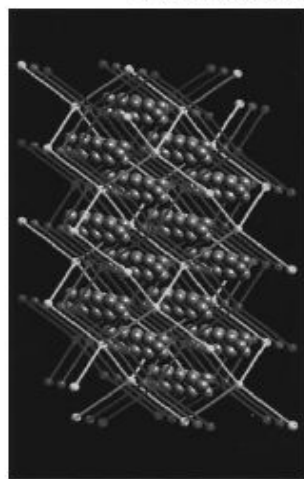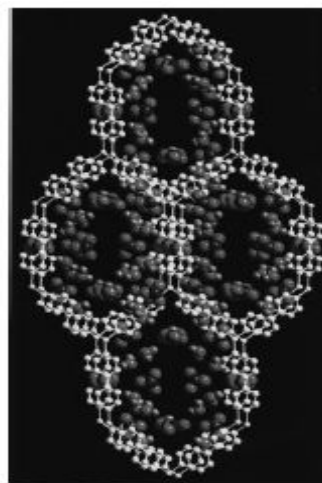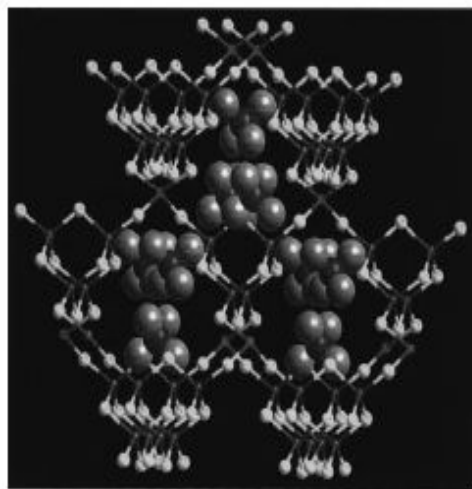# SYNTHETIC STRATEGIES IN CHEMISTRY

**NATIONAL CENTRE FOR CATALYSIS RESEARCH
INDIAN INSTITUTE OF TECHNOLOGY, MADRAS
April 2008**

PREFACE

Synthesis has a central role in the development of Science especially in Chemistry. The strategies adopted in synthesis of molecules and materials have undergone considerable changes in recent times and it was felt that it may be necessary to assess and assimilate information on this topic in a single place. Though, no originality is claimed to the contents on this topic, the very fact that the available information on this topic is available in one place itself is considered to be a major step forward. To the best of our knowledge, such an attempt has not yet been made or available in literature, though various comprehensive assessment of various methods have been made and reported in literature.

The contents of this ebook have been generated from the lectures delivered to the summer programme for the Children's Club during April 14 to April 30, 2008 at the National Centre for Catalysis Research (NCCR). The members of the research community of NCCR are responsible for the compilation of information on each of the topics presented in this ebook.

We have felt the need for a comprehensive compilation on this topic for various reasons and we do hope the scientific community will also feel the same way. It is possible that coverage may not be comprehensive. However, it is our first attempt to tread into an unknown territory in Science and make a compilation. In this sense this can be considered as our humble first attempt. The chapters have been contributed by individuals and hence the language and style may not be uniform though we tried very little to make it uniform.

We are grateful to Mr. Narayanaswamy, Secretary, Children's Club, Mylapore, Chennai 600 004 for his continuous faith in us and also for providing us opportunity year after year to conduct such programmes. The members of NCCR consider this as a privilege and wish to record their grateful thanks to him. They also acknowledge the support provided by the administration of IIT, Madras to conduct such programmes.

We do hope this ebook will receive the attention it deserves. We shall be grateful for any useful feedback on this exercise, so that we will be able to implement them in our future endeavours.

Chennai 600 036
April 18, 2008   B.Viswanathan

Content

Chapter - 1

INTRODUCTION TO SYNTHETIC STRATEGIES IN CHEMISTRY

Prof. B. Viswanathan

INTRODUCTION

One of things that make chemistry unique among the sciences is the synthesis. Chemists make things, new pharmaceuticals, food additives, materials, agricultural chemicals, coatings, adhesives, and all sorts of useful new molecules. The chemists prepare them from simpler more readily available starting materials. There are two aspects to organic synthesis first the development of a synthetic strategy or plan of action and the second the actual implementation of that plan in a chemical laboratory.

Synthesis of molecules and materials are important aspect of the development of science. In the past, synthesis is based on some of the Name reactions in organic and Inorganic chemistry. The attempts to synthesis new molecules and materials have always depended on the experience and extrapolation of the existing knowledge to new situations and new synthesis of molecules. However in the last two decades, the synthesis has become a well established science going beyond the recollection and adoption of the existing procedures. The normal procedures so far adopted for the synthesis of materials are

(i)   precipitation based on solubility principle (based on thermodynamic quantities)

(ii)   Bond formation and bond breaking usually brought about by reagents, participating species and leaving entities (these are often kinetically controlled);   processes depending on the strength of binding already existing or being formed.

(iii) simple solid state reactions often controlled by diffusion

(iv)   ligating or binding species

These procedures have been satisfying the normal curiosity of the chemists for new molecules. However today, Chemistry is the study of molecules, materials of functionalities and hence they have to be synthesized, built, and architectured and designed

Today the molecules and materials are   for many applications.. Every sector of life requires molecules/materials with functionalities, stability, as well as durability under adverse conditions. Molecules of highly active functionalities with stability, durability and appropriate stress- strain relationship (global properties of dissolution, digestion, attachment to species and others) are the demands of today.   Most often the materials required have to be in the meta stable state but should be stable enough to be useful in devices.   The exploitable properties must be able to be controlled by Size, shape, orientation and morphology.   Over the last thirty years, synthetic chemists have developed an assortment of routes to obtain optically pure compounds. Many strategies include the use of pure starting materials with chiral centres. In addition, the utilization of chiral auxiliary groups have been implemented to achieve an increase in stereo-selectivity and to simplify the purification process. Lastly, asymmetric catalysis using enzymes or inorganic catalysts has also been used to afford the desired stereochemistry.

At this stage the important questions to be faced are:

1. In the case of organic chemistry how can one build the desired carbon skeleton?
2. How does one introduce the necessary functional groups?
3. How does one control the regio- and stereochemistry of reactions?

These questions can be expanded to any extent depending on the need for molecules and materials.

The chemical synthesis of complex organic molecules is integral to many advances that enhance the quality of life, such as novel disease treatments, agrochemicals with improved properties and advanced materials for high performance technology and biotechnology. The methods for synthesizing complex organic molecules have traditionally pieced molecules together in a linear manner, gradually building complexity into the molecule. This can be a very time consuming process, and synthetic routes to molecules can end up being incredibly long, requiring extensive resources and manpower.

Since 2000 pioneering approaches to synthesis that combines two-directional synthesis and tandem reactions. Linear symmetrical trifunctional compounds are synthesized through use of two-directional synthesis and a range of tandem reactions are then applied to generate a range of diverse structures from these simple substrates. Two-

directional synthesis, when used in combination with tandem reactions, can lead to significantly faster strategies for the synthesis of complex molecules.
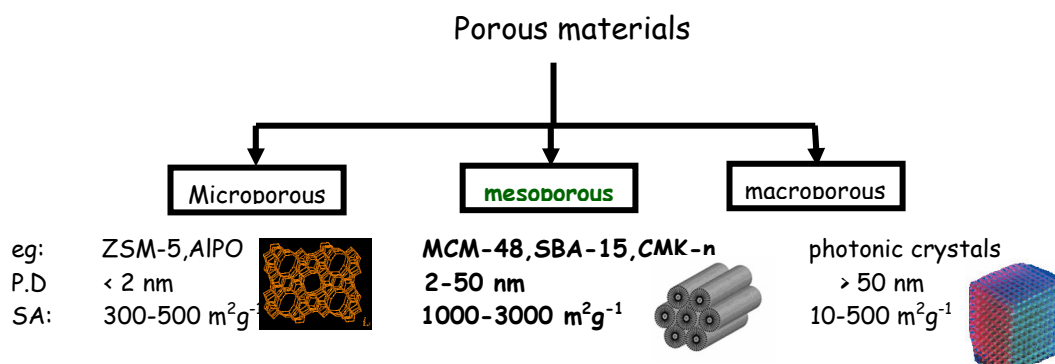
The recognition of the strong dimensionality-dependent physical-chemical properties of inorganic matter at the nanoscale has stimulated efforts toward the fabrication of nanostructured materials in a systematic and controlled manner. Surfactant-assisted chemical approaches have now advanced to the point of allowing facile access to a variety of finely size- and shape-tailored semiconductor, oxide and metal nanocrystals (NCs) by balancing thermodynamic parameters and kinetically-limited growth processes in liquid media. While refinement of this synthetic ability is far from being exhausted, further efforts are currently made to provide nanocrystals with higher structural complexity as means to increase their functionality. By controlling crystal miscibility, interfacial strain, and facet-selective reactivity at the nanoscale, hybrid nanocrystals are currently being engineered, which consist of two or more chemically different domains assembled together in a single particle through a permanent inorganic junctions.

POROUS MATERIALS

This is one class of materials which has seen a tremendous advancement in the synthetic strategies. Porous solids have high scientific and technological interest. They are able to interact with atoms, ions and molecules at surfaces and throughout the bulk of material.

Distribution of sizes, shapes and volumes of the void spaces in porous materials are directly related to their ability to perform desired function in particular application. High SA/volume ratio provides a strong driving force to speed up thermodynamic processes that minimize free energy
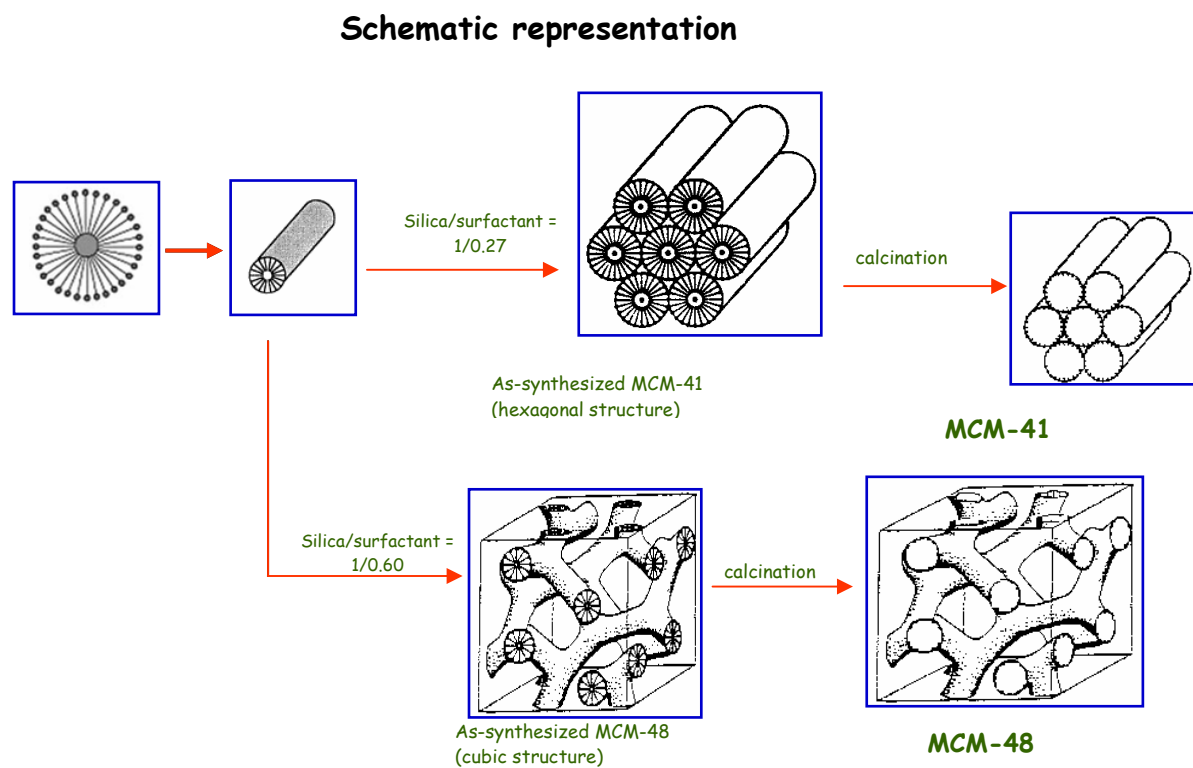
In high surface area materials the active sites are more isolated. Materials with uniform pores can separate molecules on basis of size. They are also employed as adsorbents, catalyst supports, and electrode materials.

The porous solids can be classified according to the range of pore sizes available in them. A simple classification is shown in Scheme 1.1.

Porous materials

	Microporous	mesoporous	macroporous
eg:	ZSM-5,AlPO	MCM-48,SBA-15,CMK-n	photonic crystals
P.D	< 2 nm	2-50 nm	> 50 nm
SA:	300-500 m^2g^{-1}	1000-3000 m^2g^{-1}	10-500 m^2g^{-1}

Scheme 1.1 A simple classification of porous substances.

The porous architecture is normally built in various ways.   One such methodology is shown in Fig.1.

Schematic representation

Silica/surfactant = 1/0.27

calcination

As-synthesized MCM-41
(hexagonal structure)

MCM-41

Silica/surfactant = 1/0.60

calcination

As-synthesized MCM-48
(cubic structure)

MCM-48

J. S. Beck, J.C. Vartuli, W. J. Roth, M. E. Leonowiez, C. T. kresge, K. D. Schmitt, C. Chu, D. H. Oison, and E. W. Sheppard. S. B. McCullen, J.L. Schlenker. *J. Am. Chem. Soc.*, 114 (1992) 10834

Fig. 1.1. The formation of mesoporous Mobil composition of materials (MCM) formed as a result of template mechanism (the details will be discussed in chapter 6)

Conventionally the template route is understood in terms of space filling mechanism as shown in Fig. 2.2 by the template molecules, template molecular aggregates or structure directing agents.

The role of quaternary directing agents

Small individual alkyl chain length quaternary directing agents generate the formation of micro-porous solids

Long alkyl chain length quaternary directing agents self-assemble to supramolecular Species which can generate the formation of mesoporous molecular sieves
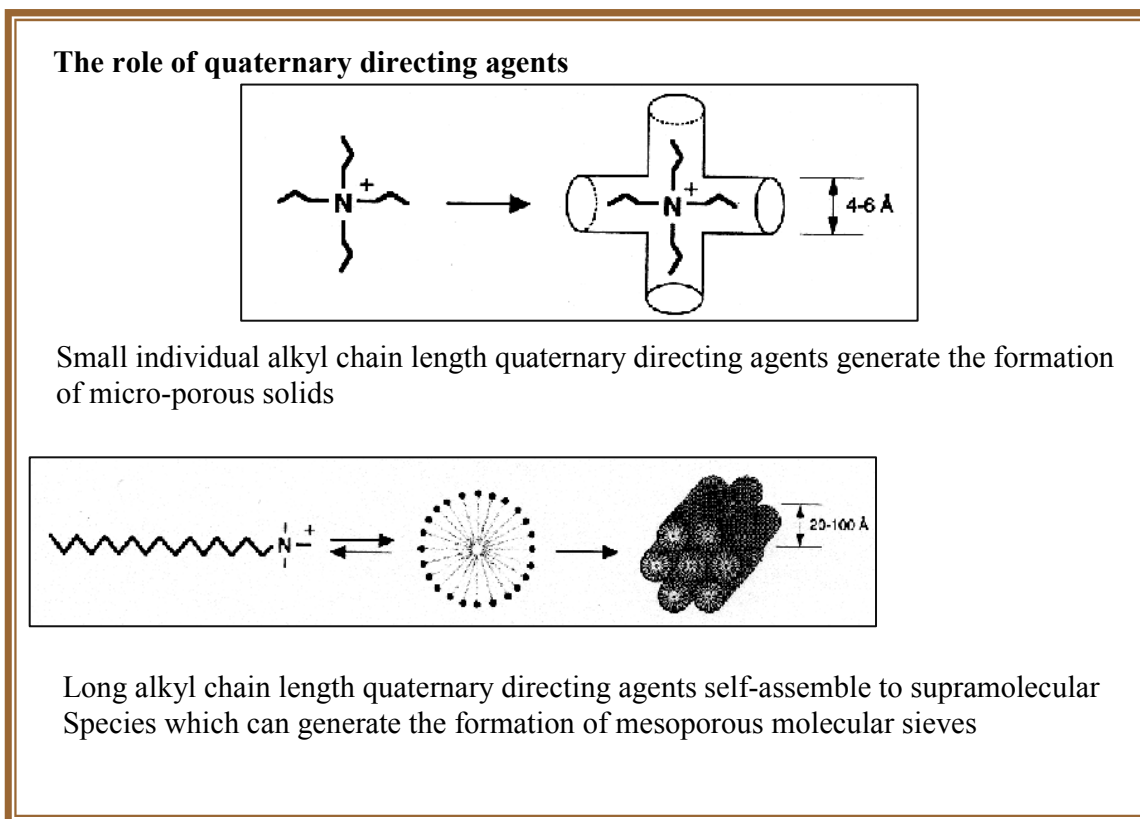
Thomos J. Barton et al., Chem Mater., 11 (10) (1999) 2633

Fig. 1.2. Simple mechanism for the formation of porous solids

Generally the interactions in formation of materials can be understood in terms of bonding interactions. One such classification is given in Scheme 1.2.

ORGANIC SYNTHESIS

Classic examples of synthesis can be found in the area of organic Chemistry. Strategies and Tactics in Organic Synthesis provide a forum for investigators to discuss their approach to the science and art of organic synthesis. Rather than a simple presentation of data or a second-hand analysis, one is provided with stories that vividly demonstrate the power of the human endeavour known as organic synthesis and the creativity and tenacity of its practitioners. First hand accounts of each project tell us of the excitement of

conception, the frustration of failure and the joy experienced when either rational thought and/or good fortune give rise to successful completion of a project. Synthesis is really done and are educated, challenged and inspired by these stories, which portray the idea that triumphs do not come without challenges. We also learn that we can meet challenges to further advance the science and art of organic synthesis, driving it forward to meet the demands of society, in discovering new reactions, creating new designs and building molecules with atom and step economies that provide solutions through function to create a better world.   These are usually termed as Name reactions in organic chemistry. These aspects will be dealt with in separate chapters.

Type of interaction	Surfactant	Inorganic precursor	Notation	Examples
Ionic (Direct pathways)	Cationic	+ Anionic	S^+-----I^-	M41S, M-MCM-41, 48
	Anionic	+ Cationic	S^------I^+	M-M41S,
Ionic (Mediated pathways)	Cationic	+ Cationic	$S^+ X^- I^+$	SBA, APM
	Anionic	+ Anionic	$S^- M^+ I^-$	Metal Oxides
Hydrogen bonding (Neutral)	Neutral Amine	+ Neutral	S^0-----I^0	HMS
	Neutral Polymer	+ Neutral	S^0-----I^0	SBA
Covalent	Neutral	+ Neutral	S-----I	TMS

Scheme 1.2. Possible interactions in the Synthetic Strategies for Porous Materials

META STABLE STATE OF THE MATERIALS

For many device and other applications, one is required to make materials in the meta stable state.   Meta stable state can be obtained in materials by a variety of routes. The possible list of the methods can be:

- Organization
- Templating – bonding and structural
- Auto-thermal

- Transport CVD, PVD
- Field induced (electro-deposition, T induced)
- Moulding and blowing
- Extrusion (geometry control)

The list given is not complete but it gives an idea of what methods can generate the meta stable of materials.

INORGANIC MATERIALS

Inorganic materials occupy a unique place and they can be synthesized by various methods. Some well known methods include

Sol gel techniques

Co-ordination chemistry

Weak interactions

bonding interactions

These methods are described in detail in subsequent chapters. The purpose of the present book is to assimilate available information on synthetic strategies in Chemistry. Though one can not claim comprehensiveness on this topic, it is the endeavour to bring some of the available knowledge in one place. It is hoped from that point of view, the synthetic chemists may find this book useful.

Chapter – 2

SYNTHETIC METHODS BASED ON ACTIVATING THE REACTANT

P. Ramana Murthy

INTRODUCTION:

In organic synthesis, activating the reactant has a crucial role to play. Conventionally, the activating of the reactant is carried out thermally, photochemically; catalytically, or by change in the concentration of the reactant, and /or acid and base. The effects of these parameters on the reactant and also reaction conditions have been studied.

**HALOGENATION OF BENZENE**:

Substitution Reactions:

Benzene reacts with chlorine or bromine in the presence of a catalyst, replacing one of the hydrogen atoms of the ring by a chlorine or bromine atom.The reaction take place at room temperature. The catalyst is either aluminium chloride (or aluminium bromide if one were to react benzene with bromine) or iron. Strictly speaking iron is not a catalyst, because it gets permanently changed during the reaction. It reacts with some of the chlorine or bromine to form iron (III) chloride, $FeCl_3$, or iron (III) bromide, $FeBr_3$.

$$2Fe + 3Cl_2 \longrightarrow 2FeCl_3$$
$$2Fe + 3Br_2 \longrightarrow 2FeBr_3$$
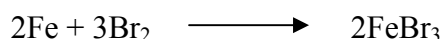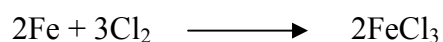
These compounds act as catalyst and behave exactly like aluminium chloride, $AlCl_3$, or aluminium bromide, $AlBr_3$, in these reactions.
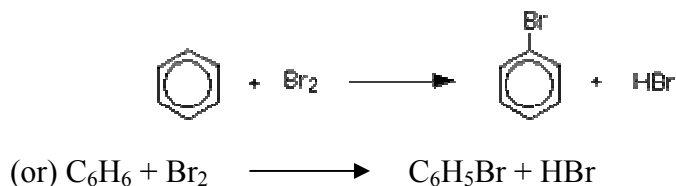
The reaction with chlorine:

The reaction between benzene and chlorine in the presence of either aluminium chloride or iron gives chlorobenzene.

$$(or) \ C_6H_6 + Cl_2 \longrightarrow C_6H_5Cl + HCl$$
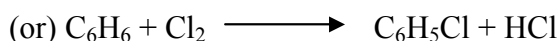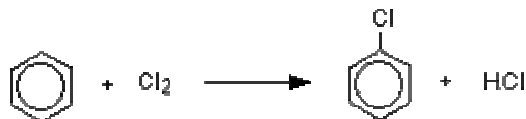
The Reaction with Bromine:

The reaction between benzene and bromine in the presence of either aluminium bromide or iron gives bromobenzene. Iron is usually used because it is cheaper and more readily available.

(or) $C_6H_6 + Br_2 \longrightarrow C_6H_5Br + HBr$

Addition Reactions:

In the presence of ultraviolet light (but without a catalyst), hot benzene will also undergo an *addition* reaction with chlorine or bromine. The ring delocalisation is permanently broken and a chlorine or bromine atom adds on to each carbon atom.

For example, if one were to bubble chlorine gas through hot benzene exposed to UV light for an hour, one gets 1,2,3,4,5,6-hexachloro-cyclohexane.
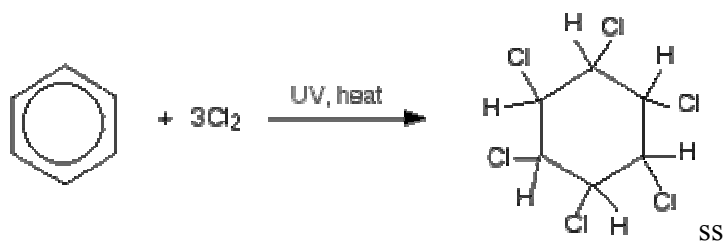
Bromine would behave similarly.

One of these isomers was once commonly used as an insecticide known variously as BHC, HCH and Gammexane. One of the "chlorinated hydrocarbons" caused much environmental harm.

THE HALOGENATION OF METHYLBENZENE:

Substitution Reactions:

It is possible to get two quite different substitution reactions between methylbenzene and chlorine or bromine depending on the conditions used. The chlorine or bromine can substitute into either the ring or the methyl group.

Substitution into the Ring:

Substitution in the ring happens in the presence of aluminium chloride (or aluminium bromide if one were to use bromine) or iron, and in the absence of UV light. The reactions takes place at room temperature. This is exactly the same as the reaction with benzene, except that one has to worry about where the halogen atom attaches in the ring relative to the position of the methyl group

Methyl groups are 2,4-directing, which means that incoming groups will tend to go into the 2 or 4 positions on the ring - assuming that the methyl group is in the first position. In other words, the new group will attach to the ring next door to the methyl group or opposite it. With chlorine, substitution into the ring gives a mixture of 2-chloromethylbenzene and 4-chloro-methylbenzene.
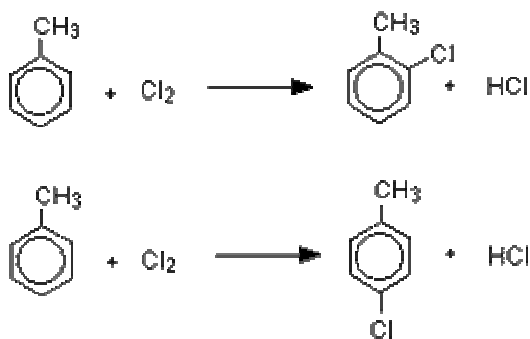
Substitution into the Methyl group:

If chlorine or bromine react with boiling methylbenzene in the absence of a catalyst but in the presence of UV light, substitution takes place in the methyl group rather than the ring.

For example, with chlorine (bromine would be similar):
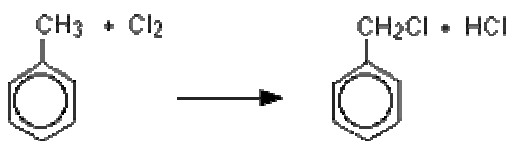
The organic product is (chloromethyl)benzene or benzyl chloride. The brackets in the name emphasise that the chlorine is part of the attached methyl group, and is not in the ring.

One of the hydrogen atoms in the methyl group has been replaced by a chlorine atom. However, the reaction does not stop there, and all three hydrogens in the methyl group can in turn be replaced by chlorine atoms.

That means that one could also get (dichloromethyl)benzene and (trichloromethyl)benzene as the other hydrogen atoms in the methyl group are replaced one at a time.
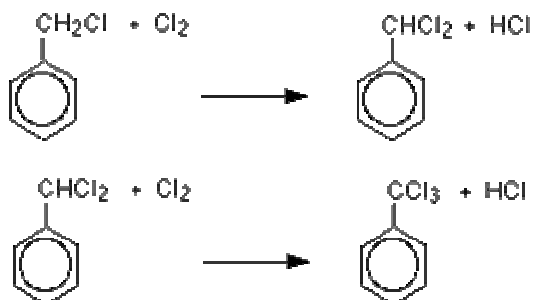
SUBSTITUTION REACTIONS OF BENZENE AND OTHER AROMATIC COMPOUNDS

The remarkable stability of the unsaturated hydrocarbon benzene has been discussed. The chemical reactivity of benzene contrasts with that of the alkenes in that substitution reactions occur in preference to addition reactions, as illustrated in the following diagram (some comparable reactions of cyclohexene are shown in the green box).
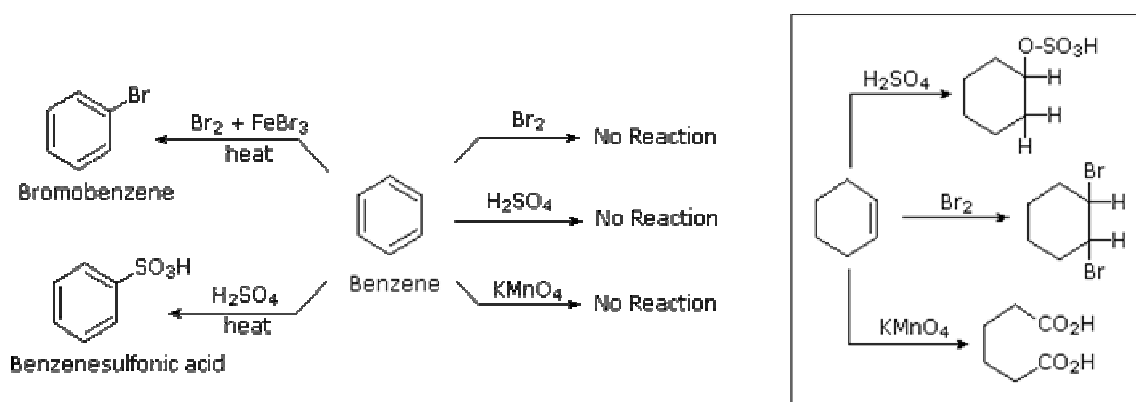
 Many other substitution reactions of benzene have been observed,
five most useful are listed below in Table 2.1. Since the reagents and conditions employed in these reactions are electrophilic, these reactions are commonly referred to as

Electrophilic Aromatic Substitution. The catalysts and co-reagents serve to generate the strong electrophilic species needed to effect the initial step of the substitution. The specific electrophile believed to function in each type of reaction is listed in the right hand column.

Table 2.1 Substitution reactions of Benzene

Reaction Type		Typical Equation	Electrophile $E^{(+)}$
Halogenation:	C_6H_6	+ Cl_2 & heat FeCl$_3$ C_6H_5Cl + HCl Chlorobenzene	$Cl^{(+)}$ or $Br^{(+)}$
Nitration	C_6H_6	catalyst +HNO$_3$ & heat, $C_6H_5NO_2$+ H_2O Nitrobenzene	NO_2^+
Sulfonation:	C_6H_6	H_2SO_4 Catalyst + H_2SO_4 + SO_3, & heat $C_6H_5SO_3H$ + H_2O; Benzene-sulfonic acid	$SO_3H^{(+)}$
Alkylation: Friedel-Crafts	C_6H_6	+ R-Cl & heat, AlCl$_3$ C_6H_5-R + HCl Arene	$R^{(+)}$
Acylation: Friedel-Crafts	C_6H_6	+ RCOCl & heat, AlCl$_3$ C_6H_5COR + HCl Aryl Ketone	$RCO^{(+)}$

1. **Mechanism for Electrophilic Substitution Reactions of Benzene - Nitration:**

$$C_6H_6 \ + \ HNO_3 \longrightarrow C_6H_5NO_2 \ + \ H_2O$$

(or)
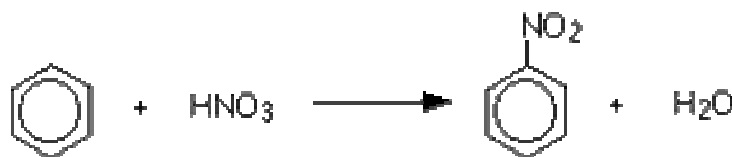
The concentrated sulphuric acid is acting as catalyst.

The formation of the electrophile

The electrophile is the "nitronium ion" or the "nitryl cation", NO_2^+. This is formed by reaction between the nitric acid and the sulphuric acid.

$$HNO_3 \ + \ 2H_2SO_4 \ \longrightarrow \ NO_2^+ \ + \ 2HSO_4^- \ + \ H_3O^+$$

The electrophilic substitution mechanism

Stage one

Stage two
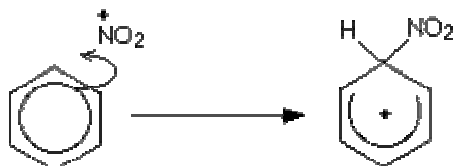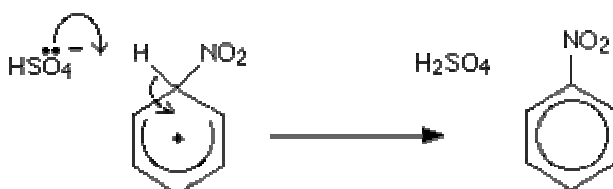

A two-step mechanism has been proposed for these electrophilic substitution reactions. In the first, slow or rate-determining, step the electrophile forms a sigma-bond to the benzene ring, generating a positively charged benzenonium intermediate. In the second, fast step, a proton is removed from this intermediate, yielding a substituted benzene ring.

2. Substitution Reactions of Benzene Derivatives

When substituted benzene compounds undergo electrophilic substitution reactions of the kind discussed above, two related features must be considered:

I. The first is the relative reactivity of the compound compared with benzene itself. Experiments have shown that substituents on a benzene ring can influence reactivity in a profound manner. For example, a hydroxy or methoxy substituent increases the rate of electrophilic Nitration substitution about ten thousand fold, as illustrated by the case of anisole. In contrast, a nitro substituent decreases the ring's reactivity by roughly a million. This activation or deactivation of the benzene ring toward electrophilic substitution may be correlated with the electron donating or electron withdrawing influence of the substituents, as measured by molecular dipole moments. In the following diagram one

can see the electron donating substituents activate the benzene ring toward electrophilic attack, and electron withdrawing substituents deactivate the ring (make it less reactive to electrophilic attack).

Activating Substituents

| 1.52 | 1.45 | 1.20 | 0.40 |

Deactivating Substituents

| 3.97 | 3.90 | 1.91 | 1.56 |
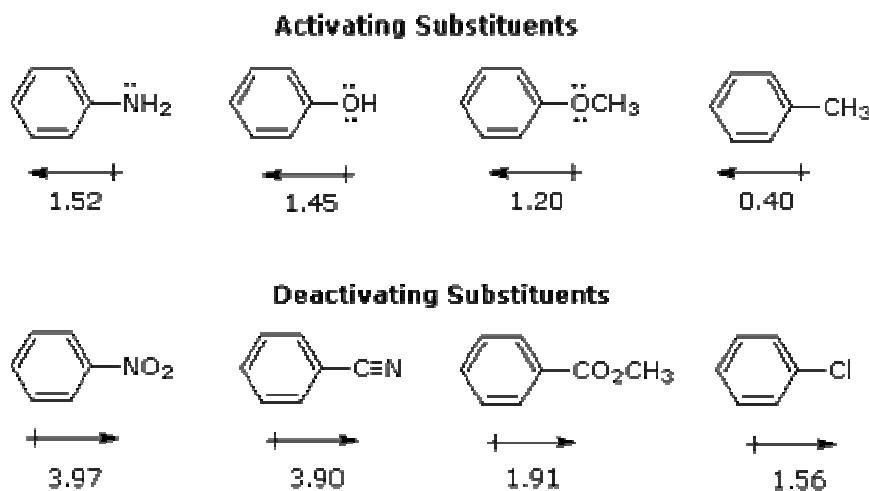
The influence a substituent exerts on the reactivity of a benzene ring may be explained by the interaction of two effects:

The first is the inductive effect of the substituent. Most elements other than metals and carbon have a significantly greater electronegativity than hydrogen. Consequently, substituents in which nitrogen, oxygen and halogen atoms form sigma-bonds to the aromatic ring exert an inductive electron withdrawal, which deactivates the ring. The second effect is the result of conjugation of a substituent function with the aromatic ring. This conjugative interaction facilitates electron pair donation or withdrawal, to or from the benzene ring, in a manner different from the inductive shift. If the atom bonded to the ring has one or more non-bonding valence shell electron pairs, as do nitrogen, oxygen and the halogens, electrons may flow into the aromatic ring by p-π conjugation (resonance), as in the middle diagram. Finally, polar double and triple bonds conjugated with the benzene ring may withdraw electrons, as in the right-hand diagram.In both cases, the charge distribution in the benzene ring is greatest at sites ortho and para to the substituent.

   Electron donation by resonance dominates the inductive effect and these compounds

show exceptional reactivity in electrophilic substitution reactions. Although halogen atoms have non-bonding valence electron pairs that participate in p-π conjugation, their strong inductive effect predominates, and compounds such as chlorobenzene are less reactive than benzene. The three examples on the left of the bottom row (in the same diagram) are examples of electron withdrawal by conjugation to polar double or triple bonds, and in these cases the inductive effect further enhances the deactivation of the benzene ring. Alkyl substituents such as methyl increase the nucleophilicity of aromatic rings in the same fashion as they act on double bonds.

II. The second factor that becomes important in reactions of substituted benzenes concerns the site at which electrophilic substitution occurs. Since a mono-substituted benzene ring has two equivalent ortho-sites, two equivalent meta-sites and a unique para-site, three possible constitutional isomers may be formed in such a substitution. If reaction occurs equally well at all available sites, the expected statistical mixture of isomeric products would be 40% ortho, 40% meta and 20% para. One can find that the nature of the substituent influences the product ratio in a dramatic fashion. Bromination of methoxybenzene (anisole) is fast and gives mainly the para-bromo isomer, accompanied by 10% of the ortho-isomer and only a trace of the meta-isomer. Bromination of nitrobenzene requires strong heating and produces the meta-bromo isomer as the chief product.
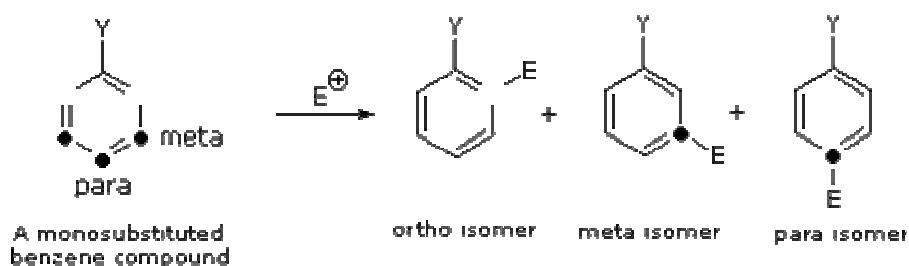
Some additional examples of product isomer distribution in other electrophilic substitutions are given in Table 2 It is important to note that the reaction conditions for the substitution reactions are not the same, and must be adjusted to fit the reactivity of the reactant C_6H_5-Y. The high reactivity of anisole, for example, requires that the first two reactions be conducted under mild conditions (low temperature and little or no catalyst).

The nitrobenzene reactant in the third example is unreactive, so rather harsh reaction conditions must be used to accomplish that reaction.

Table 2.2. Examples of product isomer distribution in electrophilic substitution

Y in C$_6$H$_5$–Y	Reaction	% Ortho-Product	% Meta-Product	% Para-Product
–O–CH$_3$	Nitration	30–40	0–2	60–70
–O–CH$_3$	F-C Acylation	5–10	0–5	90–95
–NO$_2$	Nitration	5–8	90–95	0–5
–CH$_3$	Nitration	55–65	1–5	35–45
–CH$_3$	Sulfonation	30–35	5–10	60–65
–CH$_3$	F-C Acylation	10–15	2–8	85–90
–Br	Nitration	35–45	0–4	55–65
–Br	Chlorination	40–45	5–10	50–60

These observations, and many others like them, have led chemists to formulate an empirical classification of the various substituent groups commonly encountered in aromatic substitution reactions. Thus, substituents that activate the benzene ring toward electrophilic attack generally direct substitution to the ortho and para locations. With some exceptions, such as the halogens, deactivating substituents direct substitution to the meta location. The following table summarizes this classification.

Table 2.3. Summary of the classification of the substituents

Orientation and Reactivity Effects of Ring Substituents

Activating Substituents ortho & para-Orientation		Deactivating Substituents meta-Orientation		Deactivating Substituents ortho & para-Orientation
–O$^{(-)}$	–NH$_2$	–NO$_2$	–CO$_2$H	–F
–OH	–NR$_2$	–NR$_3^{(+)}$	–CO$_2$R	–Cl
–OR	–NHCOCH$_3$	–PR$_3^{(+)}$	–CONH$_2$	–Br
–OC$_6$H$_5$	–R	–SR$_2^{(+)}$	–CHO	–I
–OCOCH$_3$	–C$_6$H$_5$	–SO$_3$H	–COR	–CH$_2$Cl
		–SO$_2$R	–CN	–CH=CHNO$_2$

The information summarized in Table 2.3 is useful for rationalizing and predicting the course of aromatic substitution reactions.

Nucleophilic Substitution Reactions

 The carbon-halogen bond in alkyl halides is polarized, placing a partial positive charge on the carbon, and a partial negative charge on the halogen. The partial positive charged carbon is therefore electrophilic and will be susceptible to attack by nucleophiles. When a suitable nucleophile attacks an alkyl halide, it can displace the halogen in a substitution reaction to release the halide an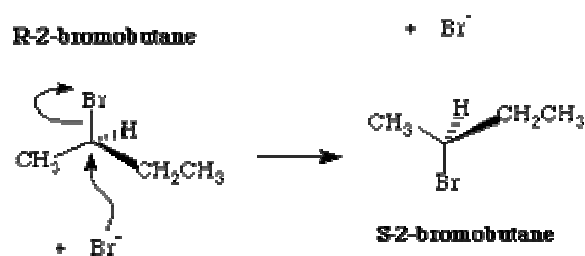ion and form a new bond to the carbon. The nucleophile is usually neutral or negatively charged and some examples are HO^-, H_2O, MeOH, EtO^-, RS^-
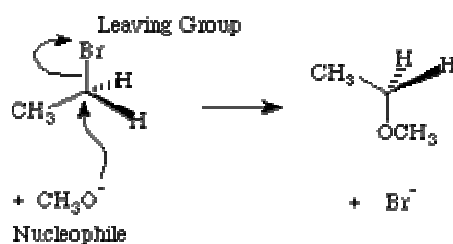
With simple primary alkyl halides reacting with simple nucleophiles, the rate at which this substitution reaction proceeds is proportional to both the concentration of the nucleophile and the concentration of the reactant alkyl halide, making the reaction second order. This type of second-order, nucleophilic displacement reaction is therefore termed an **"S_N2"** reaction (substitution, nucleophilic, bimolecular). The mechanism for this reaction is best described as concerted with the reaction coordinate passing through a single energy maximum with no distinct intermediate. The transition state for this reaction is described by the structure shown below in which partial bonds exist between the central carbon and the attacking nucleophile and departing halogen.

The geometry of this transition state, with the planar carbon in the center, requires that the central carbon undergo a **stereochemical inversion**; therefore if the central carbon is chiral, the absolute configuration of the central carbon must change. In the example shown R-2-bromobutane reacts with bromide anion to form the enantiomer, S-2-bromobutane.

Predicting the product from these types of substitution reactions simply requires that the bond to the halogen leaving group be broken and a new bond be made between the nucleophilic atom and the central carbon, inverting the absolute configuration if appropriate.

S_N2 Reaction: Kinetics

Nucleophilic substitution reactions follow different rate laws, depending on the exact mechanism. The rate law for an S_N2 reaction is: Rate = k [RX] [Nuc] where k is the rate constant, RX is the alkyl halide and Nuc is the nucleophile. The reaction rate is therefore second order overall. This also tells us that the reaction is bimolecular, *i.e.* two species are involved in the rate-determining step.
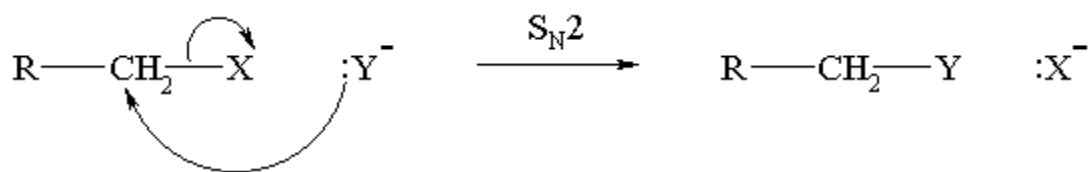
This proposed mechanism for the S_N2 reaction raises an interesting question: If the substitution occurs at a chiral carbon, does the reaction proceed with retention, inversion or loss of stereochemistry? The answer to this question lies in the direction of attack of the incoming nucleophile. Attack on the same side as the halogen would result in retention of stereochemistry. Attack from the opposite side to the halogen would result in inversion of stereochemistry. A mixture of these two possibilities would lead to loss of stereochemical integrity at the chiral carbon. Experimentally, it is found that a purely S_N2 reaction at a chiral carbon proceeds with inversion of stereochemistry.

   In 1896, German chemist Paul Walden reported the conversion of enantiopure (+)-(R)-malic acid into the enantiomer (-)-(S)-malic acid, although he did not know at which

step inversion was occurring. In the 1920s Kenyon and Philips investigated a similar process with 1-phenyl-2-propanol:
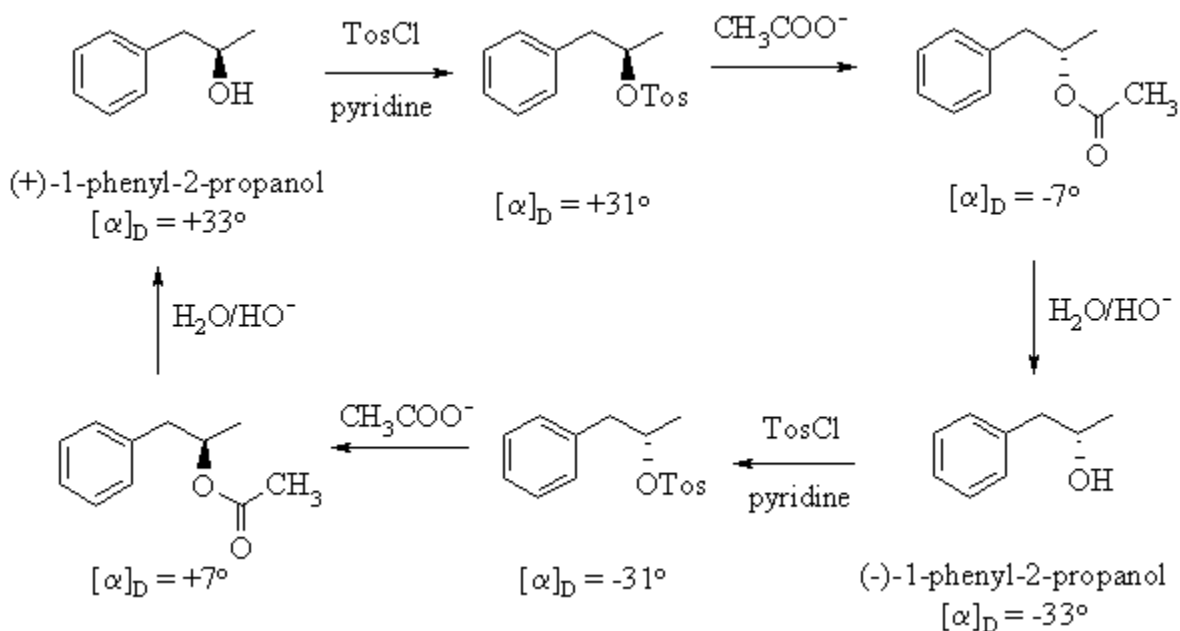
From this and several other such cycles, Kenyon and Phillips concluded that the nucleophilic substitution reaction of primary and secondary alkyl halides and tosylates always proceeds with inversion of stereochemistry. In the cycle shown above inversion takes place in the nucleophilic substitution of tosylate ion by acetate ion.

S$_N$1 Reaction

The S$_N$2 reaction is favoured by basic nucleophiles such as hydroxide ion and disfavoured by solvents such as alcohols and water. The reaction also depends on the nature of the substrate: primary substrates react rapidly, secondary substrates react more slowly and tertiary substrates are almost inert to S$_N$2 reaction. In protic media with non-basic nucleophiles under neutral or acidic conditions, tertiary substrates can be orders of magnitude more reactive than their primary or secondary counterparts. The S$_N$2 mechanism clearly cannot account for this and it can be concluded that a different mechanism can operate under these circumstances. This mechanism is called **S$_N$1** which denotes Substitution by a nucleophile, unimolecular.

That is, only **one** species is involved in the rate-determining step.

Kinetics

The S_N1 reaction is first order and the rate varies only as the concentration of the alkyl halide: Rate = k [RX]. The rate of reaction is found to be independent with respect to the concentration of the nucleophile. In other words, the nucleophile does not take part in the rate-determining step.   Any proposed mechanism for the reaction must therefore have the alkyl halide undergoing some change **without** the aid of the nucleophile. The first step must therefore be cleavage of the C-X bond to form a carbocation, followed by reaction with the nucleophile to give the substitution product.
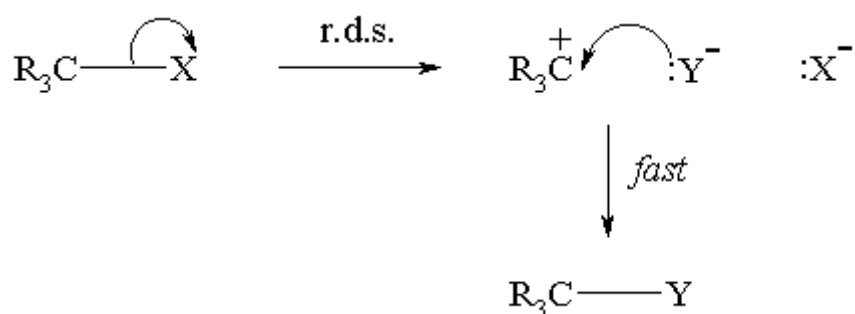
This mechanism is clearly different from the S_N2 pathway and the stereo-chemical outcome should also differ. Carbocations are sp^2 hybridized, planar species - at first glance it would appear that the nucleophile, Y⁻ could attack from either face of the carbocation, with an equal probability. One would predict that this should lead to complete racemisation, if the starting alkyl halide were optically pure. In practice, complete racemisation is rarely observed and usually, a minor excess (up to ~20%) of inversion is observed. One explanation for this was provided by Winstein, an eminent physical organic chemist. It was proposed that an ion-pair, between the carbocation and the leaving group X⁻ is present, which partly blocks attack of the nucleophile from one face. Thus, inversion slightly dominates.

 Factors which Influence the Reaction Pathway

S_N2

- **Steric Effects**: The transition state in the S_N2 reaction involves partial bonding between the nucleophile and the substrate. The bulkier the substrate, the more difficult it is for the transition state to be reached. The reactivity order is $1° > 2° > 3°$.

- **The Nucleophile**: By definition, a nucleophile must have an unshared pair of electrons, whether it is charged or neutral. Nucleophilicity follows approximately basicity, so pKa values can be used. Nucleophilicity usually increases going down a group in the periodic table. The reactivity order of the more common nucleophiles is: $CN^- > I^- > MeO^- > HO^- > Cl^- > H_2O$.

- **The Leaving Group**: The leaving group is normally ejected with a negative charge. Therefore the best leaving groups are those which can best stabilise a negative charge. Weak bases (TsO^-, I^-, Br^-) are generally good leaving groups, whereas strong bases (F^-, HO^-, RO^-) are generally poor leaving groups.

- **The Solvent**: Polar aprotic solvents are best for S_N2 reactions. These include acetonitrile (CH_3CN), dimethyl sulphoxide (Me_2SO) and *N,N*-dimethylformamide (Me_2NCHO). Proticsolvents tend to form a 'cage' around the nucleophile, decreasing its reactivity.

S_N1:

- **The Substrate**: Substrates which can form relatively stable carbocation intermediates favour S_N1 reactions The order of stability of carbocations is: $3^o > 2^o > benzyl > allyl > 1^o$.

- **The Nucleophile**: The nucleophile is not involved in the rate-determining step in an S_N1 reaction but the S_N1 pathway is more likely to be followed if the nucleophile is poor, *e.g.* H_2O.

- **The Leaving Group**: The leaving group is also involved in the rate-determining step for an S_N1 reaction, so the same reactivity order as for S_N2 is followed.

- **The Solvent:** The solvent can have an effect on the rate of the S_N1 reaction, but for different reasons. Solvent effects arise from stabilisation of the **transition state** and not the reactants themselves. The rate of S_N1 reaction is increased in a polar solvent such as water or aqueous ethanol.

Esterification Reaction:

This is a reaction of formation of esters from carboxylic acids and alcohols in the presence of concentrated sulphuric acid acting as the catalyst. It uses the formation of ethyl ethanoate from ethanoic acid and ethanol as a typical example.

Mechanism

Ethanoic acid reacts with ethanol in the presence of concentrated sulphuric acid as a catalyst to produce the ester, ethyl ethanoate. The reaction is slow and reversible. To reduce the chances of the reverse reaction happening, the ester is distilled off as soon as it is formed.

$$CH_3COOH + CH_3CH_2OH \underset{conc\ H_2SO_4}{\rightleftharpoons} CH_3COOCH_2CH_3 + H_2O$$
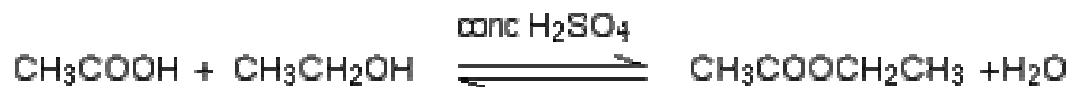
Step 1

In the first step, the ethanoic acid takes a proton (a hydrogen ion) from the concentrated sulphuric acid. The proton becomes attached to one of the lone pairs on the oxygen which is double-bonded to the carbon.
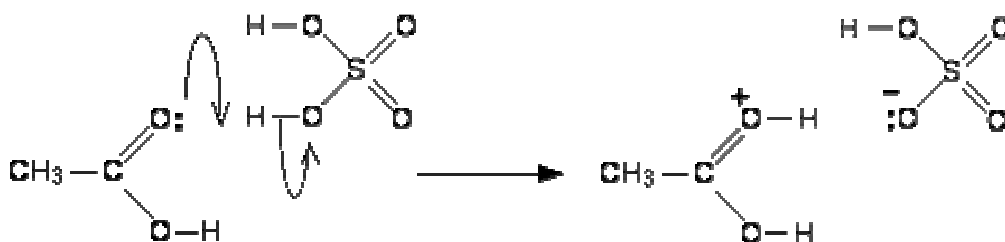
The transfer of the proton to the oxygen gives it a positive charge.   The positive charge is delocalised over the whole of the right-hand end of the ion, with a fair amount of positive charge on the carbon atom. In other words, one can think of an electron pair shifting to give the structure:
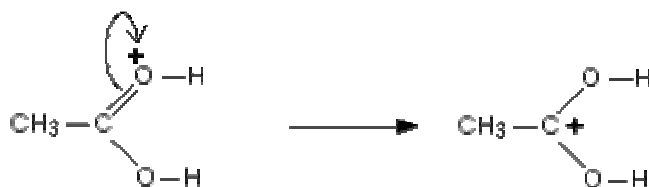
One could also imagine another electron pair shift producing a third structure:
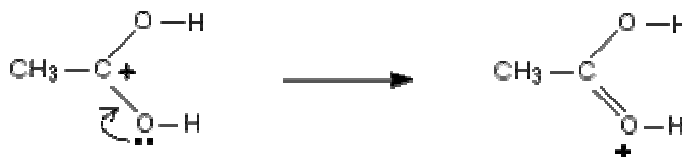
So which of these is the correct structure of the ion formed? None of them! The truth lies somewhere in between all of them. One way of writing the delocalised structure of the ion is:
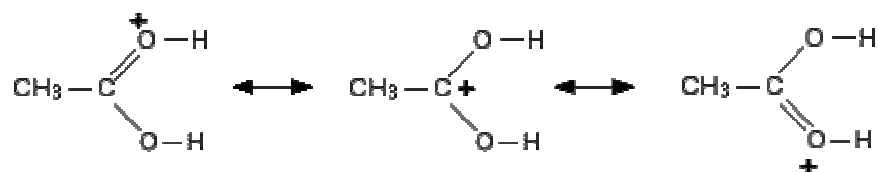
The double headed arrows means you that each of the individual structures makes a contribution to the real structure of the ion. They do not mean that the bonds are flipping back and forth between one structure and another. The various structures are known as resonance structures or canonical forms.

There will be some degree of positive charge on both of the oxygen atoms, and also on the carbon atom. Each of the bonds between the carbon and the two oxygens will be the same - somewhere between a single bond and a double bond.

For the purposes of the rest of this discussion, we are going to use the structure where the positive charge is on the carbon atom.

Step 2

The positive charge on the carbon atom is attacked by one of the lone pairs on the oxygen of the ethanol molecule.
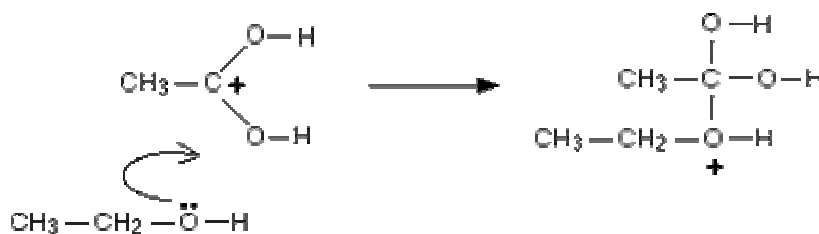
Step 3

What happens next is that a proton (a hydrogen ion) gets transferred from the bottom oxygen atom to one of the others. It gets picked off by one of the other substances in the

mixture (for example, by attaching to a lone pair on an unreacted ethanol molecule), and then dumped back onto one of the oxygens more or less at random.

The net effect is:

Step 4

Now a molecule of water is lost from the ion.
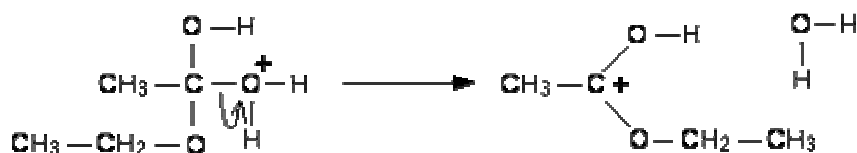
The positive charge is actually delocalised all over that end of the ion, and there will also be contributions from structures where the charge is on the either of the oxygens:
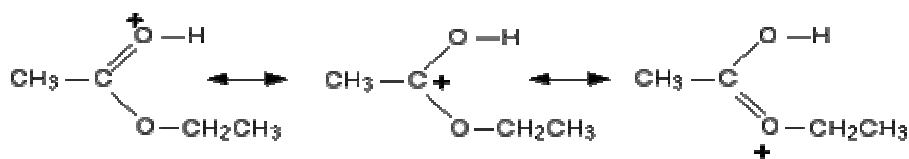
Step 5

The hydrogen is removed from the oxygen by reaction with the hydrogensulphate ion which was formed way back in the first step.
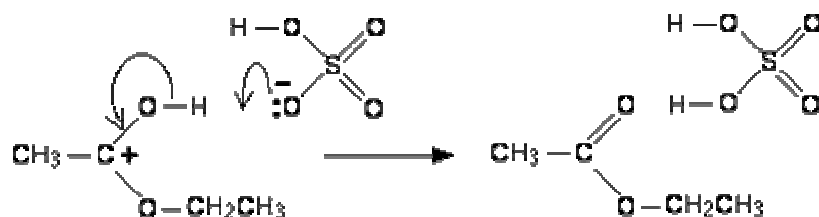
And there we are! The ester has been formed, and the sulphuric acid catalyst has been regenerated.

Reimer-Tiemann Reaction:

The Reimer-Tiemann reaction is a used for the ortho-formylation of phenols. The reaction was discoverd by Karl Ludwig Reimer and Ferdinand Tiemann.
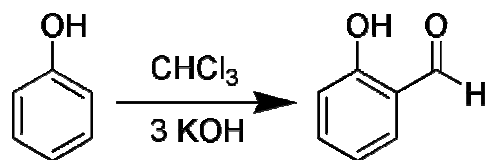
Reaction mechanism:

(1) reacts with strong base to form the chloroform carbanion (**2**), which will quickly alpha-eliminate to give dichlorocarbene (**3**). Dichlorocarbene will react in the ortho- and para- position of the phenate (**5**) to give the dichloromethyl substituted phenol (**7**). After basic hydrolysis, the desired product (**9**) is formed.
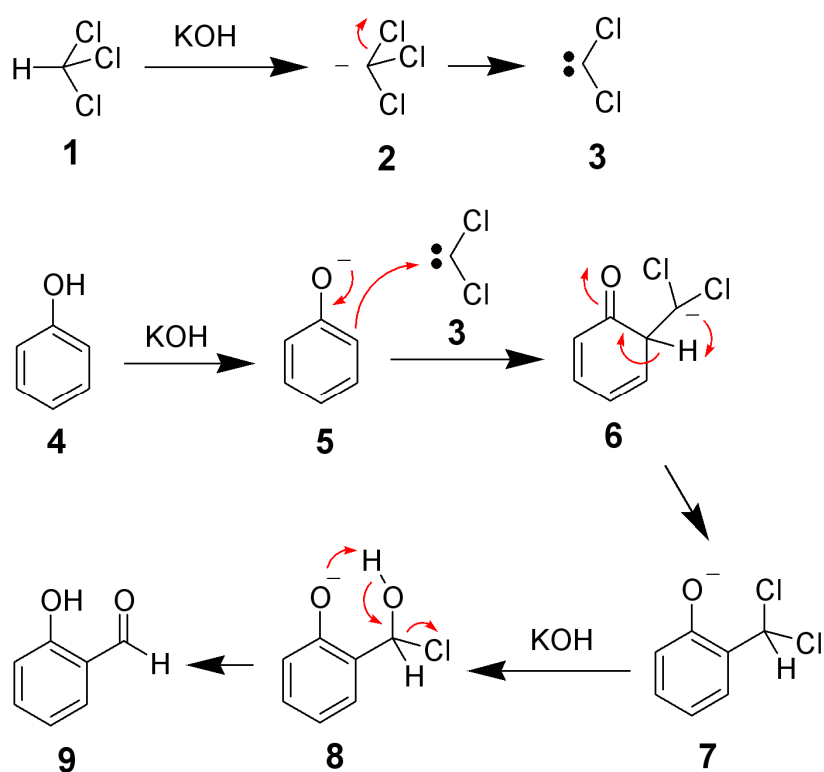
The Aldol Condensation of Aldehydes :

$$RCH_2-\overset{\overset{O}{\|}}{C}-H \xrightarrow{\text{NaOH}} R\overset{..}{\overset{\overset{O}{\|}}{C}}H\overset{\overset{O}{\|}}{C}-H \xrightarrow{RCH_2-\overset{\overset{O}{\|}}{C}-H} H-\overset{\overset{O}{\|}}{C}-\overset{\alpha}{C}H-\overset{\overset{\beta}{O}H}{C}H$$

enolate

β-hydroxyaldehyde
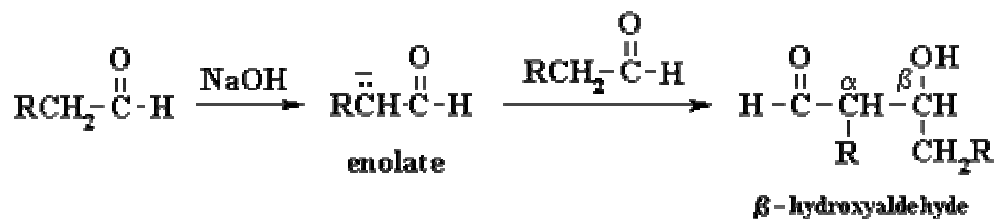
Reaction type : Nucleophilic addition : Summary

- Reagents : commonly a base such as NaOH or KOH is added to the aldehyde.

- The reaction involves an enolate reacting with another molecule of the aldehyde.

- Remember enolates are good nucleophiles and carbonyl C are electrophiles.

- Since the pKa of an aldehyde is close to that of NaOH, both enolate and aldehyde are present.

- The products of these reactions are ̃hydroxyaldehydes or **ald**ehyde-alcoh**ols** = **aldols**.

- The simplest aldol reaction is the condensation of ethanal. This is shown below in 2 different representations.

$$2\ CH_3-\overset{\overset{O}{\|}}{C}-H \xrightarrow{HO^-} H-\overset{\overset{O}{\|}}{C}-CH_2-\overset{\overset{OH}{|}}{C}H\diagdown CH_3$$
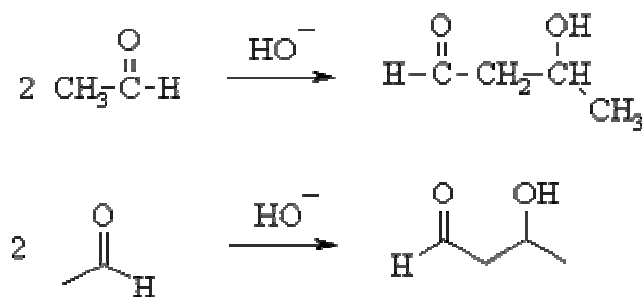
Step 1:
First, an acid-base reaction. Hydroxide functions as a base and removes the acidic-hydrogen giving the reactive enolate.

Step 2:
The nucleophilic enolate attacks the aldehyde at the electrophilic carbonyl **C** in a nucleophilic addition type process giving an intermediate alkoxide.

Step 3:
An acid-base reaction. The alkoxide deprotonates a water molecule creating hydroxide and the ̃hydroxyaldehydes or **aldol** product
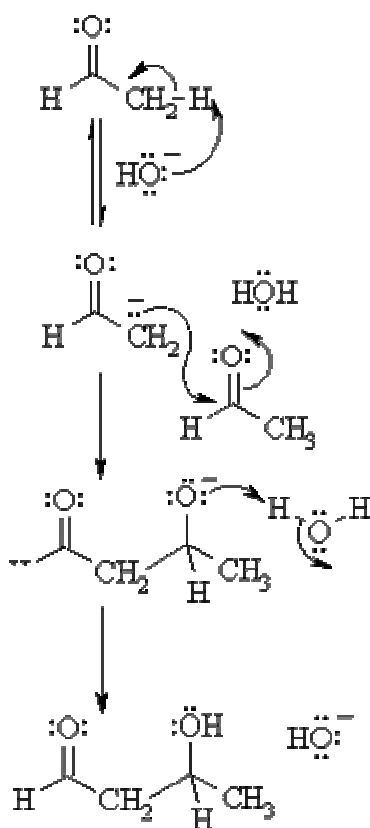
Benzoin Condensation:
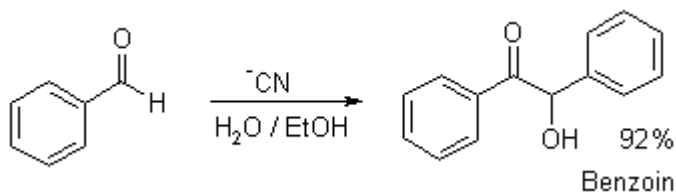
The Benzoin Condensation is a coupling reaction between two aldehydes that allows the preparation of α-hydroxyketones. The first method is only suitable for the conversion of aromatic aldehydes.

Mechanism

Addition of the cyanide ion to create a cyanohydrin effects an umpolung of the normal carbonyl charge affinity, and the electrophilic aldehyde carbon becomes nucleophilic after deprotonation.
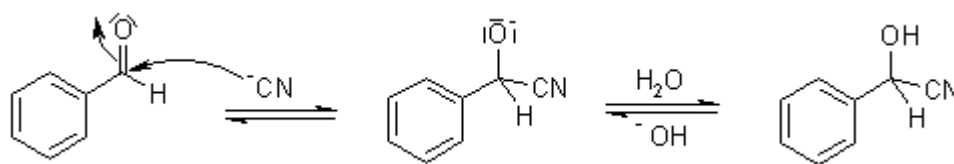
A strong base is now able to deprotonate at the former carbonyl C-atom:
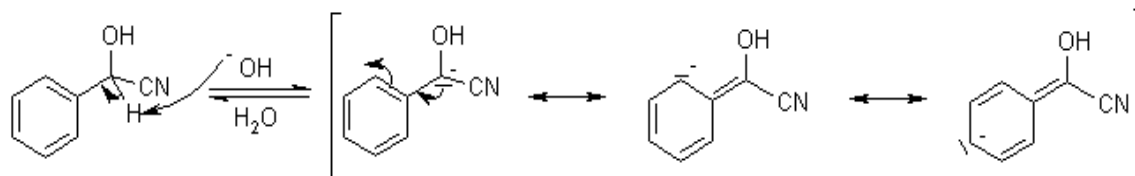
A second equivalent of aldehyde reacts with this carbanion; elimination of the catalyst regenerates the carbonyl compound at the end of the reaction:
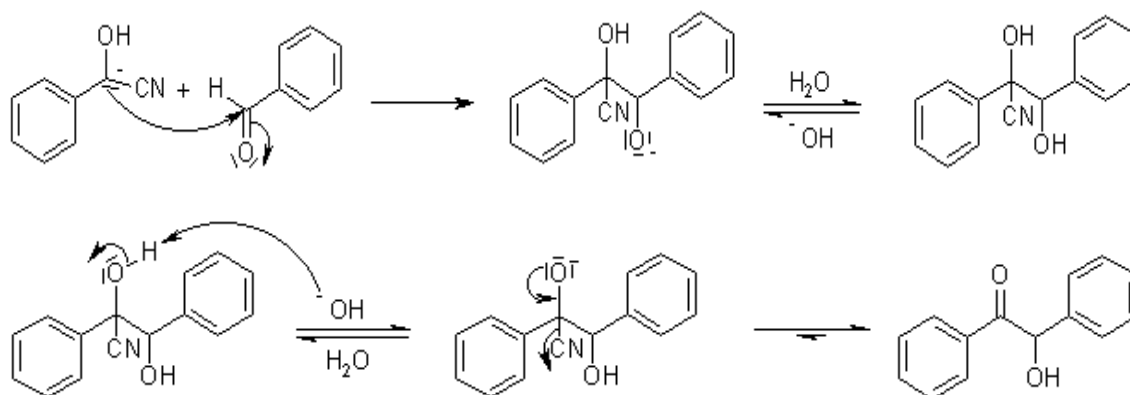
Neighbouring group participation:

The direct interaction of the reaction centre (usually, but not necessarily, an incipient carbenium centre) with a lone pair of electrons of an atom or with the electrons of a □- or □-bond contained within the parent molecule but not conjugated with the reaction centre. A distinction is sometimes made between n-, □- and □-participation. When NGP is in operation it is normal for the reaction rate to be increased.

A rate increase due to neighbouring group participation is known as 'anchimeric assistance'. 'Synartetic acceleration' is the special case of anchimeric assistance ascribed

to participation by electrons binding a substituent to a carbon atom in a □-position relative to the leaving group attached to the □-carbon atom.

A classic example of NGP is the reaction of a sulfur or nitrogen mustard with a nucleophile, the rate of reaction is higher for the sulfur mustard and a nucleophile than it would be for a primary alkyl chloride without a heteroatom.
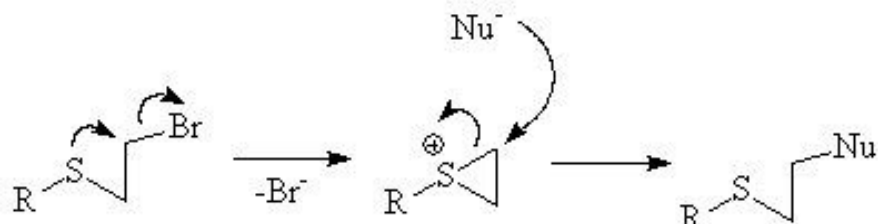
The π orbitals of an alkene can stabilize a transition state by helping to delocalize the positive charge of the carbocation. For instance the unsaturated tosylate will react more quickly with a nucleophile than the saturated tosylate.

The carbo-cationic intermediate will be stabilized by resonance where the positive charge is spread over several atoms.
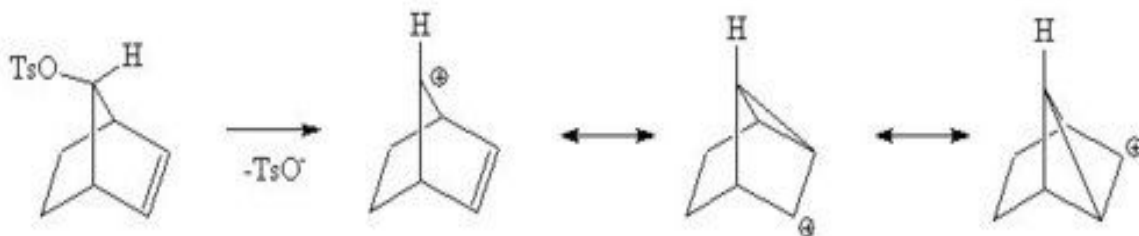
PHOTOCHEMICAL REACTIONS:

Any chemical reaction can be caused by absorption of light (including visible, ultraviolet, and infrared). The light excites atoms and molecules (shifts some of their electrons to a higher energy level) and thus makes them more reactive. In comparison to ordinary reactions using thermal energy alone, photochemical reactions can follow different routes and are more likely to produce free <u>radicals</u>, which can trigger and sustain <u>chain reactions</u>.

Some photochemical reactions like photoadditions, photocycloadditions, photoeliminations, photoenolizations, photo-Fries rearrangements, photoisomerizations, photooxidations, photoreductions, photosubstitutions, etc.

The Reaction between hydrogen and chlorine:

$$H_2(g) + Cl_2(g) \square\ 2HCl(g)$$
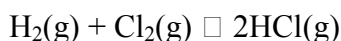
A mixture of hydrogen and chlorine gases kept in the dark reacts only very slowly if at all. Now subject it to a pulse of ultraviolet light and an explosive reaction takes place.

Initiation, Propagation and Termination

The reaction of hydrogen and chlorine is a typical photochemical chain reaction involving radicals. The reaction involves three stages: initiation, propagation, and termination. It requires photons of light only to get it started (Initiation of the reaction) after which it rapidly reaches completion. These photons, absorbed by a few of the chlorine molecules, cause the Cl-Cl bonds to break homolytically.

Step 1 $\quad\quad Cl_2 + h\square\ \square\ 2Cl\cdot$ $\quad\quad$ Initiation
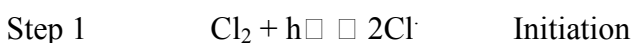
The reaction now has to keep going, or propagate itself. The next two steps in the mechanism involve **propagation**. A propagation reaction involves the loss of a radical, but also the formation of another radical. Two propagation steps are required otherwise the reaction would come to a stop before completion.

Step 2 $\quad\quad Cl\cdot + H_2 \square\ H\cdot + HCl$ $\quad\quad$ Propagation

Step 3 $\quad\quad H\cdot + Cl_2 \square\ HCl + Cl\cdot$ $\quad\quad$ Propagation

The propagation steps repeat over and over in a **chain reaction**. Radicals also come together forming covalent bond in termination steps.

Step 4 $H^. + Cl^. \rightarrow HCl$ Termination

The Chlorination of Methane

The chlorination of methane is another photochemical radical chain reaction. The reaction is a substitution reaction; a hydrogen atom of methane is swapped for a chlorine atom.

$$CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$$

Here is the mechanism for the reaction.. Step 1 $Cl_2 + h\nu \rightarrow 2Cl^.$ Initiation

Step 2 $CH_4 + Cl^. \rightarrow {^.}CH_3 + HCl$ Propagation

Step 3 ${^.}CH_3 + Cl_2 \rightarrow CH_3Cl + Cl^.$ Propagation

Step 4 ${^.}CH_3 + Cl^. \rightarrow CH_3Cl$ Termination
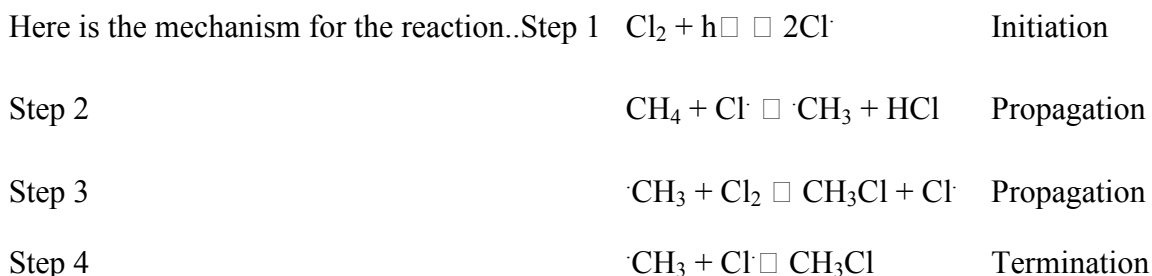
In the reaction of methane and chlorine, chloromethane (CH_3Cl) is not the only organic product. A mixture of organic products (also CH_2Cl_2, $CHCl_3$, CCl_4) is obtained, corresponding to the substitution of each of the hydrogen atoms of methane. The formation of these arises from steps 2 and 3 above repeating. The formation of the disubstituted derivative, dichloromethane (CH_2Cl_2) is shown:

$$CH_3Cl + Cl^. \rightarrow {^.}CH_2Cl + HCl$$

$${^.}CH_2Cl + Cl_2 \rightarrow CH_2Cl_2 + Cl^.$$
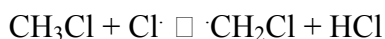
Finally, to be more precise about the name of the mechanism for this reaction: it is a radical substitution reaction.

REFERENCES:

1. O. D. Tyagi, M. Yadav, A Textbook of Organic Reaction Mechanism, Anmol Publications Pvt. Ltd., 2002.

2. O. P. Agarwal, Unified Course in Chemistry, Volume II, Jai Prakash   Nath & Co., (2003).

3. Pure and Applied Chemistry, 1994, 66, 1077.

Glossary of terms used in Physical Organic Chemistry, (IUPAC Recommendations 1994).

4. www.chemguide.co.uk

Chapter - 3

METHODS BASED ON ACTIVATING THE REACTING SUBSTANCE

R. Mahalakshmy

1. INTRODUCTION

The art of carrying out efficient chemical transformations is a major concern in modern organic synthesis. Two aspects are of utmost importance when considering the outcome of a reaction, viz., selectivity and efficiency (optimization of yields). The new procedures developed should also be compatible with our environment and thus facilitate preserving our resources. The right activation mode is, therefore, development of methods that promote an efficient chemical transformation. In this article, activation should be understood in a rather wide sense. In one-way it is described as a sort of catalysis facilitating the course of the reaction by lowering the activation energy. Another way it is explained in relation to non-catalytic path.
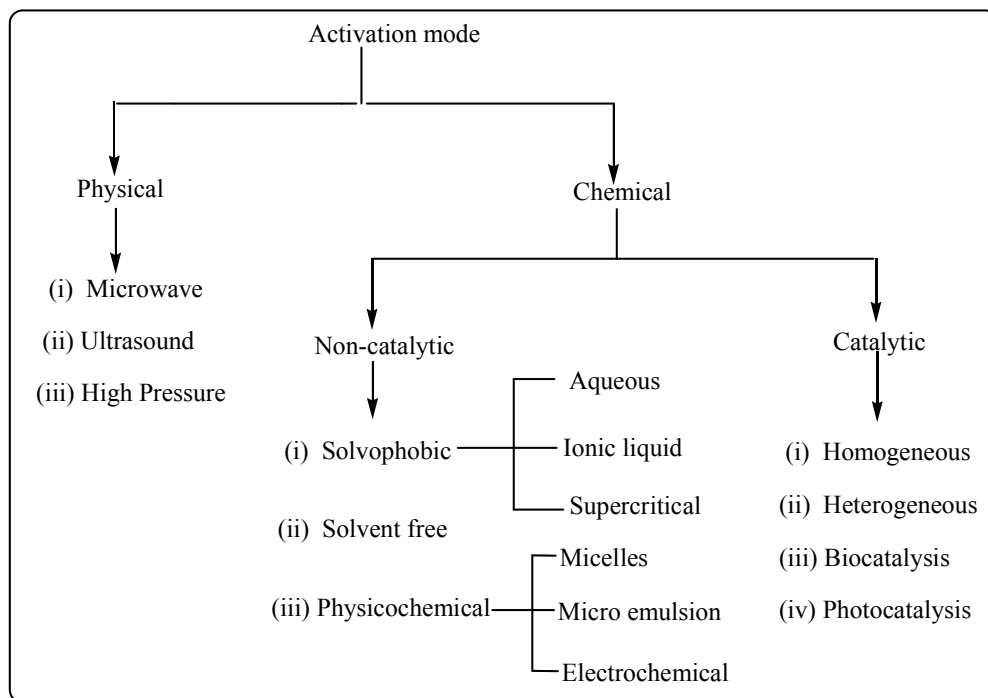
Scheme 3.1. Types of activation mode

Activation is achieved in different ways, which may be classified into physical, chemical or biochemical, physicochemical modes. Although exhaustivity is not the aim, this article tries to give a survey on the most recent advances in either traditional modes (pressure, light,

chemical catalysis) or in novel techniques (microwaves, sonication, biocatalysis). The various activation modes discussed in this article are shown in scheme 3.1.

2. PHYSICAL METHODS FOR THE ACTIVATION OF REACTING SUBSTANCE

2.1. Activation by Microwave

Microwaves are a form of electromagnetic waves (wavelength between 1cm and 1m). When molecules with a permanent dipole are placed in an electric field, they become aligned with that field. If the electric field oscillates, then the orientations of the molecules will also change in response to each oscillation. Most microwave ovens operate at 2.45 GHz, wavelength at which oscillations occur 4.9×10^9 times per second. Molecules subjected to this microwave radiation are extremely agitated as they align and realign themselves with the oscillating field, creating an intense internal heat that can escalate as quickly as $10°$ C per second. This technique proves to be excellent in cases where traditional heating has a low efficiency because of poor heat transmission and, hence, local overheating is a major inconvenience.

Microwave energy is fast becoming the method of choice for both industrial and academic chemists for driving reactions to completion, as it offers the safest, most effective way to increase reaction rates and improve product yields, while promoting green chemistry. Reactions that previously took hours, or even days, to complete can now be performed in minutes. Decreasing reaction times offers teaching opportunities: students have more time for design, optimization, characterization and analysis of reaction processes and products. Additionally, microwave-assisted reactions are often performed in aqueous solutions or neat, minimizing the need for organic solvents, simplifying the work-up process, and providing "green" reaction conditions.

Is microwave assisted organic synthesis green and safe?

It's time to think of the environment and our impact on it. Microwave energy is an inherently efficient way to transfer energy to a reaction, as it transfers kinetically rather than thermally. Because of this quality, it is the ideal energy source for driving reactions and it also has the following advantages.

- Use water, ethanol or other environmentally benign solvents
- Neat reactions/high conversions help eliminate waste
- Non-hazardous reagents help students design safer syntheses
- Use catalysts, not stoichiometric reagents

Not only is microwave-assisted chemistry is good for the environment, it is also safer for chemists. Microwave synthesis systems designed for the laboratory offer an

- Unmatched level of safety.
- Eliminate hot plate burns
- Reactions return to room temperature before removing from microwave

A few representative examples of microwave assisted chemical conversions are considered.

(i) Oxidation of Primary and Secondary Alcohol

A fast and facile microwave accelerated oxidation of primary alcohols to carboxylic acids and secondary alcohols to ketones were carried out under organic/aqueous biphasic conditions using 30% aqueous H_2O_2 in the presence of sodium tungstate and tetrabutylammonium hydrogen sulfate (TBAHS) as a phase-transfer catalyst[1]. The experimental procedure involves a simple mixing of an alcohol, $Na_2WO_4, 2H_2O$ and TBAHS followed by the addition of 30% aqueous H_2O_2 in 25:1:1:125 molar ratios for primary and 25:1:1:40 molar ratio for secondary alcohols in an open vessel. Then the reaction mixtures were placed inside a monomode microwave reactor and irradiated under a reflux condenser for specific time. The best results were obtained when the temperatures of reaction mixtures were set to 90° C and 100° C for primary and secondary alcohols, respectively.
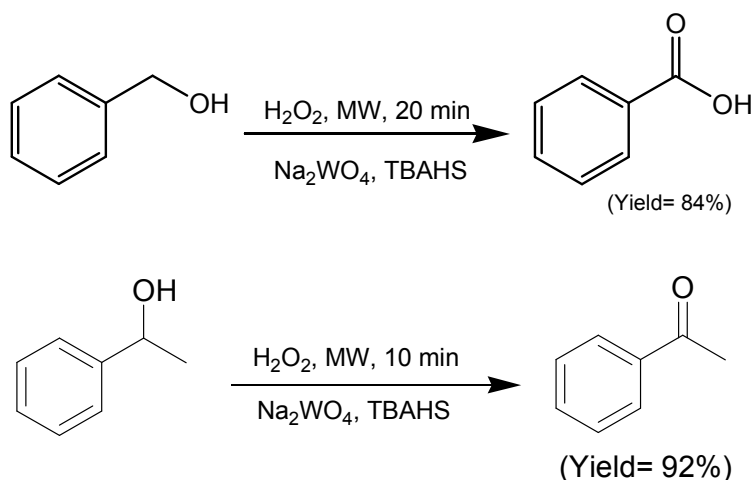
(ii) Nucleaphilic Substitution Reaction

The synthesis of arylamines through direct nucleophilic substitution of aryl halides typically requires highly polar solvents such as DMF and DMSO at high temperatures even with highly activated aryl halides. A novel and efficient synthesis of N-arylamines by the reaction of activated p-bromonitrobenzene with secondary amines (morpholine and N-phenylpi-

perazine) in the presence of basic Al_2O_3 under microwave irradiation was carried out under solvent-free conditions in a simple domestic oven [2].
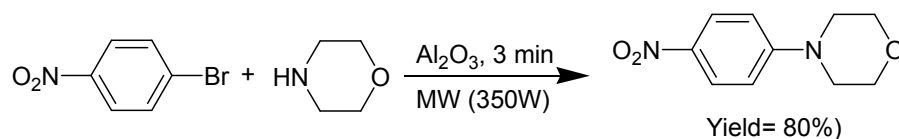
Both alumina and amines are polar so they absorb microwaves effectively and consequently the reaction is completed in a short time.

Thus, the microwave irradiation has been successfully applied in organic chemistry. Spectacular accelerations, higher yield under milder reaction conditions and higher product purities have all been achieved so far. More over, by using this technique, a number of reactions has been carried out successfully that do not occur by conventional heating and even modifications of selectivity (chemo, regio and stereoselectivity) are obtained.

2.2. Activation by Ultrasound

Ultrasounds are acoustic waves with frequencies ranging from 20 to 100 MHz. They are mechanical waves that are not absorbed by solid and, therefore, they do not induce heating. They are transmitted through any substances – solid, liquid or gas, which possesses elastic properties.

How does ultrasound accelerate a chemical reaction?

The energy of ultrasound is insufficient to cause chemical reactions, but when it travels through media a series of compressions and rarefactions are created, the rarefaction of liquids leading to cavities. During rarefaction, the negative pressure developed by the power of ultrasound is enough to overcome the intermolecular forces binding the fluid and tear it, producing cavitation bubbles. The succeeding compression cycle can cause the micro bubbles to collapse almost instantaneously with the release of large amounts of energy. The enormous rise in local temperatures and pressures produces a dramatic beneficial effect of reaction acceleration, with relatively short times being required for completing the reaction such that the decomposition of thermally labile products is minimised. A schematic representation of cavitaional erosion of solid is given in Fig. 3.1.
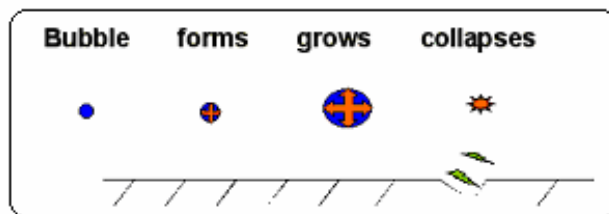
Fig. 3.1. Cavitational erosion of solid

How to carry out a chemical reaction in an ultrasonic bath?

A number of common reactions used in synthetic organic chemistry can be carried out more efficiently using ultrasound. These reactions can be performed by immersing a reaction vessel into an ultrasonic bath (Fig. 3.2) or by immersing an ultrasonic probe (horn) into a reaction medium.
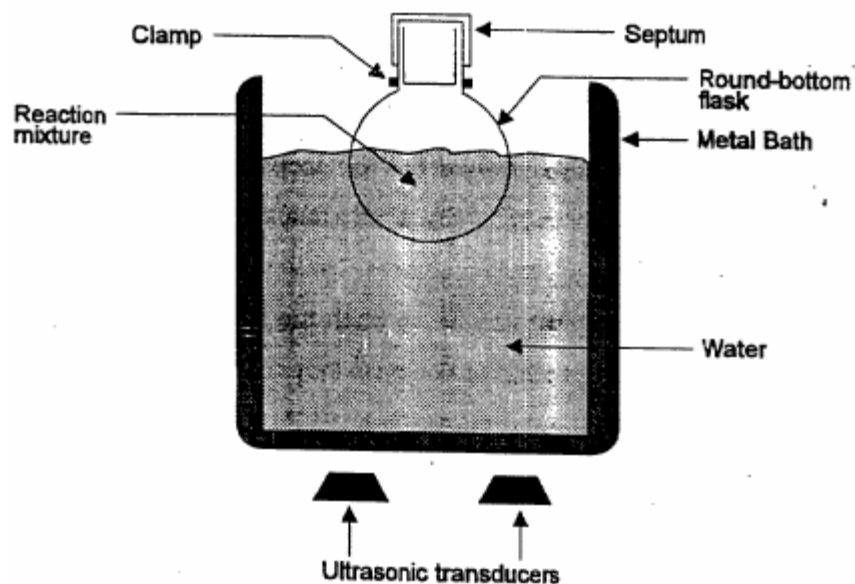
Fig. 3.2. Apparatus for carrying out a reaction in an ultrasonic cleaning bath

(Reproduced from a general article entitled, "Ultrasound: A Boon in the Synthesis of Organic Compounds" published in *Resonance*, 1998, *3*, 56)

There are several advantages of this method and they are:

    (i)   It increases the yield and the percentage of by-products decreases.

    (ii)   Reactions occur faster, so that lower temperatures can be used.

    (iii)   Reaction times decrease by a factor five to fifty for identical isolated yields.

    (iv)   It provides alternative pathways for reactions, due to the formation of high-energy intermediates.

In the following text several specific applications of Sonochemistry are given [3].

(i) Preparation of organometallic reagents

Sonochemistry enables reactions involving organometallic reagents to be carried out safely. The reaction of magnesium with ethyl, butyl and phenyl bromides in aqueous diethyl ether or in n-dibutyl ether containing 50% benzene or light petroleum is accelerated by utilising ultrasound.

$$R\text{-}X + Mg \xrightarrow{\text{)))))}} R\text{-}Mg\text{-}X$$
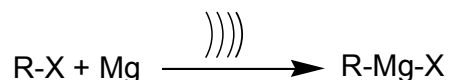
$R = C_2H_5$, $n–C_4H_9$, C_6H_5

$X = Cl, Br$

(ii) Oxidation of alcohol

The oxidation of alcohols by solid potassium permanganate in hexane and benzene is significantly enhanced by sonication in an ultrasonic bath.
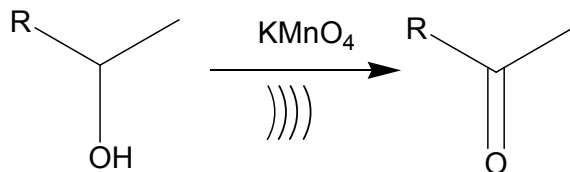
(iii) Reformatsky reaction

The Reformatsky reaction can be carried out in high yield (98 %) in just 30 minutes at $25–30^{o}$ C as compared to conventional method, which gives only 50% yield after 12 hours at 80° C.

$$C_4H_8C\text{=}O + BrCH_2COOEt + Zn \xrightarrow[\text{)))))}]{NaX} C_4H_8C(OH)CH_2COOEt$$
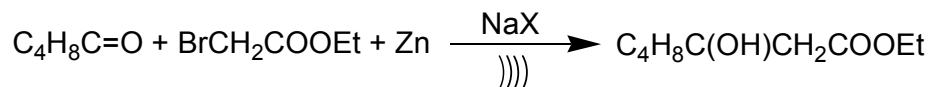
(iv) Breakdown of polymeric organometallic compound

The breakdown of polymeric organotin fluoxides is carried out by sonication method. For this reaction, there is 900-fold increase in rate as compared to conventional reflux.

$$[R_3SnF]_n \xrightarrow{\text{)))))}} nR_3SnX$$
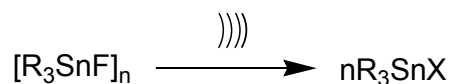
$R=Me, n–Bu$ or Ph

$X=Cl, Br, NCO$

(*Note: In the above examples the symbol)))) *represents the sonication method*)

In addition to the types of reactions mentioned, ultrasound has also been used in the case of enzyme catalysed reactions, polmer chemistry and coal liquification. Extension of combination of sonochemistry with other specific methods, such as photochemistry and electrochemistry appear to be promising. Since it is an upcoming and a recent field of interest, there is a great deal more to explore in ultrasonics as an important tool in order to tap its full potential for the discovery of new reactions utilising highly energetic sound waves. The sonochemical boom is turning out to be a real boon for synthetic chemistry.

2.3. Activation by high pressure

Pressure represents a mild non-destructive activation mode, generally respecting the molecular structure by limiting decomposition or further evolution of the products. The specific effects of high pressure can be of important value for organic synthesis. The kinetic pressure effect is primarily determined by the variation of volume due to changes in the nuclear positions of the reactants during the formation of the transition state. Related to volume requirements are steric effects since the bulkiness of the molecules involved in the transition state conditions the magnitude of the steric interactions. As a consequence, pressure affects volume changes and should have an effect on steric congestion.

    As a mild activation mode, pressure may be considered of value in the synthesis of thermally fragile molecules, permitting a lowering of the temperature. In addition, the selectivity is generally preserved or even improved under such conditions. High-pressure chemistry is now recognized as a powerful method to achieve synthetic organic reactions, which are not readily accessible by usual means. The applications of this technique to organic reactions like Diels-Alder [4] and Cyclo addition [5] are discussed.

(i) Diels-Alder reaction

The high pressure (0.8 GPa) Diels-Alder reaction of N-methyl-2(1H)-pyridones with cyclooctyne at 90° C affords 1:1 cycloadducts in 60 - 80% Yield. No adduct is recovered at normal pressure due to the extrusion of methyl isocyanate.
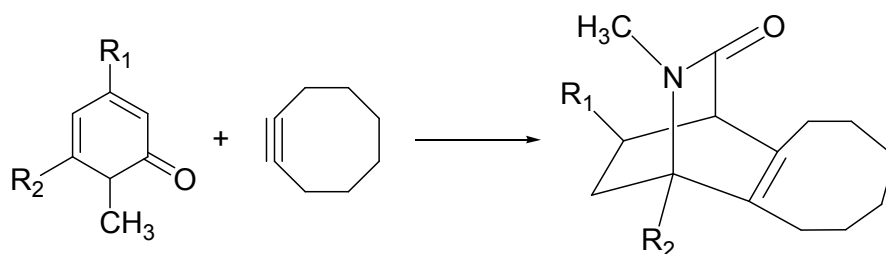
(ii) Cycloaddition reaction

Cycloaddition of mesityl oxide to isoprene is also carried out at high pressure in LiClO$_4$/Diethy ether medium.

20 MPa, 100 C, 24 h

LiClO$_4$/Diethyether

Yield:52%   Yield:19%
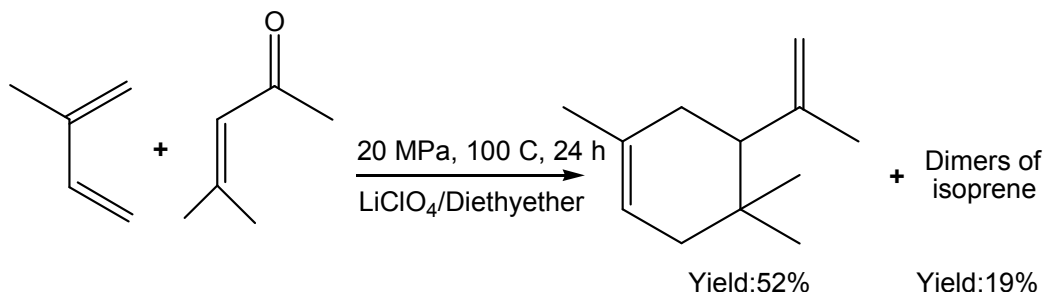
When traditional synthetic strategies appear forbiddingly difficult or fail utterly, the pressure parameter, possibly associated with other activation methods may be considered. Other salient features of this method include:

(i)   Extreme simplicity of the method

(ii)   Capacity to induce ionogenesis

(iii)   Capacity to remove steric inhibition

Thus the notable advantages of this method materialize in new or improved synthetic routes, and it adds another important dimension to the existing synthetic activation modes.

3. CHEMICAL METHODS FOR THE ACTIVATION OF REACTING SUBSTANCE

3.1. Non-catalytic activation

3.1.1. Solvophobic activation

3.1.1a. Reaction in water

In the most recent decades, the use of water as a reaction solvent or co-solvent has received much attention in synthetic organic chemistry, with sometimes surprising and unforeseen results. It plays an essential role in life processes; however its use as a solvent has been limited in organic synthesis. Despite the fact that it is the cheapest, safest and most non-toxic solvent in the world, its presence is generally avoided through the dehydrative drying of substrates and solvents. But still it can be considered as a unique solvent. Moreover, water is the 'solvent of Nature' and therefore the use of water as a medium for organic reactions is one of the latest challenges for modern organic chemists.

There are many potential reasons to replace the classical organic solvents by water. They are

(i)   Cost, safety and environmental concern.

(ii)   Aqueous procedures are often referred to as green, environmentally friendly, or benign.

(iii)   The unique solvation properties of water have been shown to have beneficial effects on many types of organic reactions in terms of both the rate and selectivity.

(iv)   Experimental procedures may be simplified, since isolation of organic products and recycling of water-soluble catalysts and other reagents can be achieved by simple phase separation.

Selected few organic reactions run in an aqueous medium are considered.

(i) Wittig Reaction

Bergdahl and co-workers published the first report in the literature describing that Wittig reactions of stabilised (and poorly water-soluble) ylides with aldehydes are unexpectedly accelerated in an aqueous medium [6].
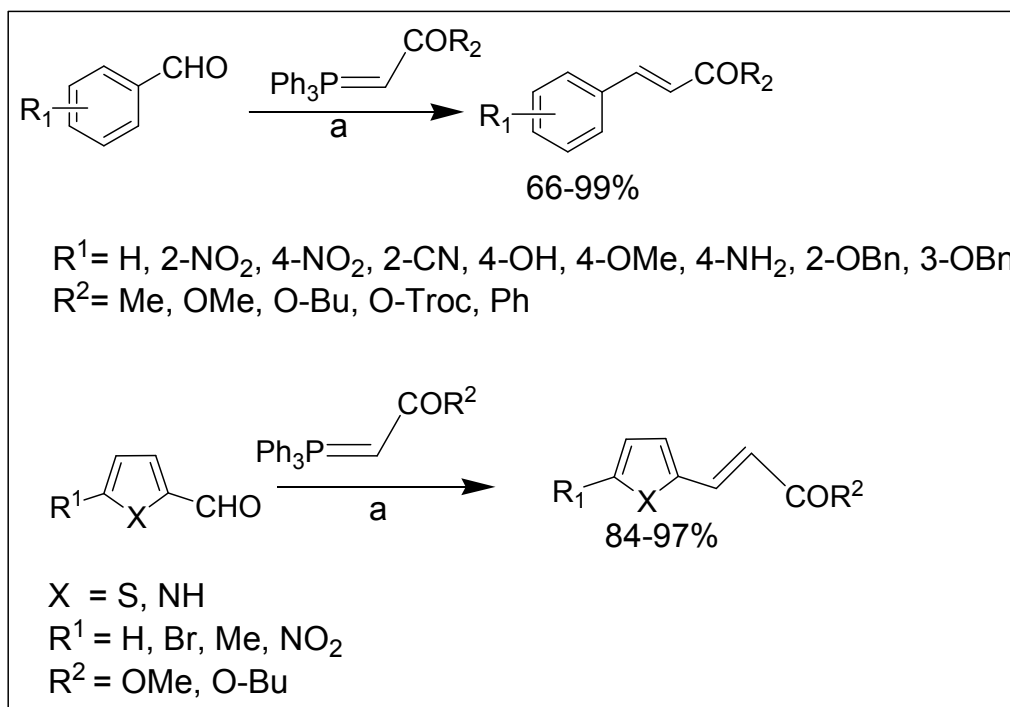
a) aldehyde (1 mmol), ylide (1.2-1.5 mmol), H_2O (5 mL), 20-90°C, 5 min - 4 h. Troc= 2,2,2-trichloroethoxycarbonyl.

(ii) Mannich-type Reactions

Kobayashi and co-workers published an efficient (up to 94% yield) enantio- and diastereoselective protocol for Mannich-type reactions of a hydrazono ester with silicon

enolates in aqueous medium. One example of a *syn* adduct from an (*E*)-silicon enolate and two examples of *anti* adducts from (*Z*)-silicon enolates are reported [7].
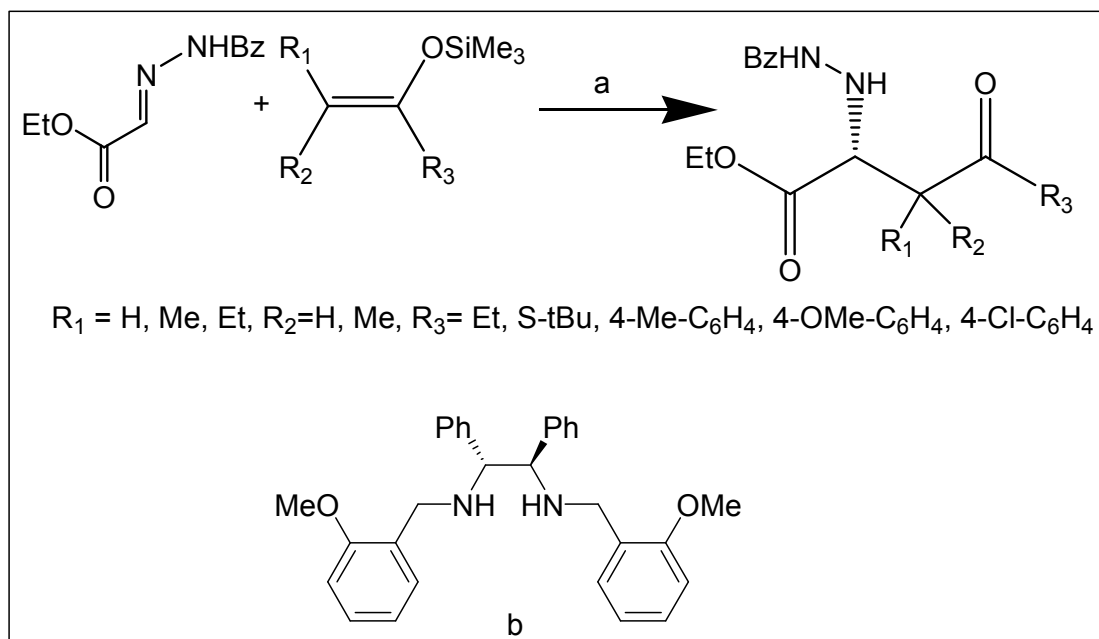
Where a = acyl hydrazono ester (0.4 mmol), silyl enol ether (1.2 mmol), ZnF_2 (100 mol%), **b** (10 mol%), CTAB (0.02 mmol), H_2O (1.95 mL), 0 °C, 20 h. CTAB= cetyltrimethylammonium bromide.

(iii) Deprotection of Functional Groups

Methods for selective deprotection of functional groups are key tools for organic chemists. The following examples, performed in water, open new possibilities for the use of this challenging medium. Konwar and co-workers [8] reported a simple protocol for the deprotections of oximes and imines under neutral conditions (yields up to 90%) using a I_2/surfactant/water system
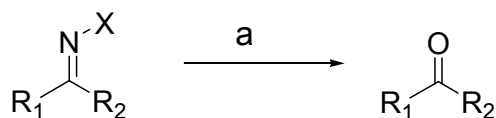
X= OH, Ph
R^1, R^2 = alkyl
R^1,R^2= aryl
R^1= H, alkyl, R^2=aryl

where a= oxime or imine (1 mmol), I_2 (20 mmol%), H_2O (15 mL), SDS (0.2 mmol), 25-40°C, 3.5-8 h.

The main obstacle to the use of water as reaction solvent is the negligible solubility of the majority of organic compounds in water. This problem can be addressed by using aqueous organic solvents or phase-transfer agents.

3.1.1b. Reaction in ionic liquid

Ionic liquids are low-melting-point salts that have attracted considerable attention recently as greener alternatives to classical environmentally damaging solvents. "The interest is mainly due to their peculiar properties such as absence of flammability, lack of measurable vapor pressure, and good ability to dissolve organic, organometallic, and even some inorganic compounds. These unique chemical and physical characteristics of ionic liquids are increasingly enticing chemists to explore their use as media for organic synthesis.

Ionic liquids offer numerous advantages over conventional organic solvents for carrying out organic reactions. They are,

- (i)   Easy product recovery
- (ii)   Catalysts can be recycled
- (iii)   Ionic liquids can be reused
- (iv)   Their thermodynamic and kinetic behavior is different
- (v)   Rates of reaction are often enhanced and
- (vi)   Selectivity is frequently better

*Examples for **Ionic** Liquids*

The most common classes of ionic liquids are alkylammonium salts, alkylphosphonium salts alkylpyridinium salts, and N, N´-dialkylimidazolium salts. Few examples of cationic and anionic ionic liquids are given in Fig. 3.3.
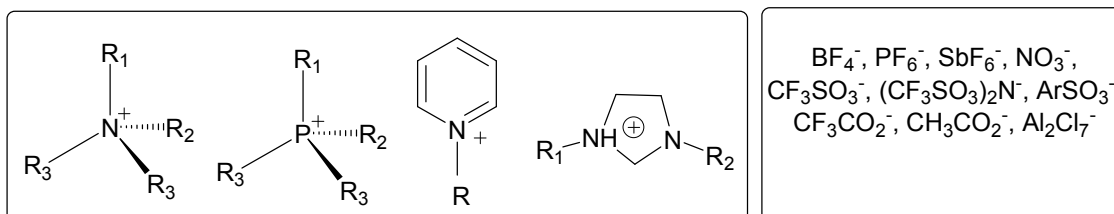
Fig. 3.3. Cationic and anionic ionic liquids

Synthesis and applications of halide based ionic liquid

Halide-based ionic liquids ILX (IL represents cations such as 1, 3-dialkylimidazolium, 1-alkylpyridinium and tetraalkylammonium; X represents halide anions) can be used as reagents in nucleophilic substitution for the conversion of alcohols to alkyl halides. This reaction provides an alternative way of preparing other types of ionic liquids (ILA) based on the conjugate bases of acids (HA) [9].

$$ILX + HA + ROH \xrightarrow{-H_2O} ILA + RX$$
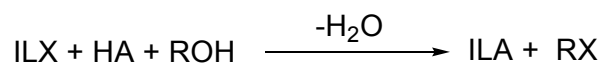
Where,

ILX: halide-based ionic liquids; X=Cl, Br, I; HA: acids; ROH: alcohols

ILA: new ionic liquids with conjugate bases of HA

These halide-based ionic liquids (ILX) can also be used as reaction media for copper-catalyzed nucleophilic aromatic substitution reaction for formation of aryl nitriles (ArCN).

$$ArY + NaCN \xrightarrow[ILX, -NaY]{Cu\ catalyst} ArCN$$
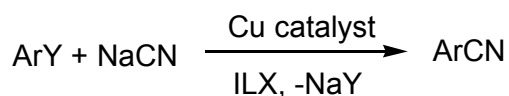
ArY: Aryl halides, Y= I or Br, ILX: halide-based ionic liquid

X= Cl, Br, I; Cu catalysts: CuX, X= Cl, Br, I, CN

Trihalide-based ionic liquids (ILX_3) that can be used as reagents as well as reaction media in halogenation reactions

$$ILX + 2HX + H_2O_2 \xrightarrow{-2H_2O} ILX_3$$
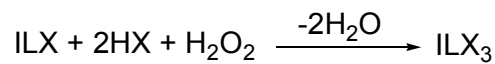
ILX: halide-based ionic liquids, X= Cl, Br, I

HX: hydrogen halides

"The rapid growth of interest in ionic liquids is mainly limited to people in academia and national laboratories," "There is a lot of skepticism among industrial chemists, probably because our understanding of these materials is limited. Before we see industrial chemists enthusiastically involved in exploring the field, a lot of work has to be done. We need information on the toxicity and safety of these materials and their effect on the environment, as well as an assessment of their life cycles. Also, we need cost analyses compared with existing technologies. In addition, it is important to develop a good database of all the information available on ionic liquids. Unless we have all this information, the growth will be limited to a few sectors only."

3.1.1c. Reaction in supercritical media

What is a supercritical fluid?

Supercritical fluids may be defined as the state of a compound, mixture or element above its critical pressure (Pc) and critical temperature (Tc), but below the pressure required to condense it into a solid. It possesses the characteristics of both fluid and gaseous substances: the fluid behavior of dissolving soluble materials, and the gaseous behavior of excellent diffusibility. They occupy a point where pure and applied science meets head on. This is a feature that has attracted many workers to the field. A general phase diagram for critical fluid is given in Fig. 3.4.
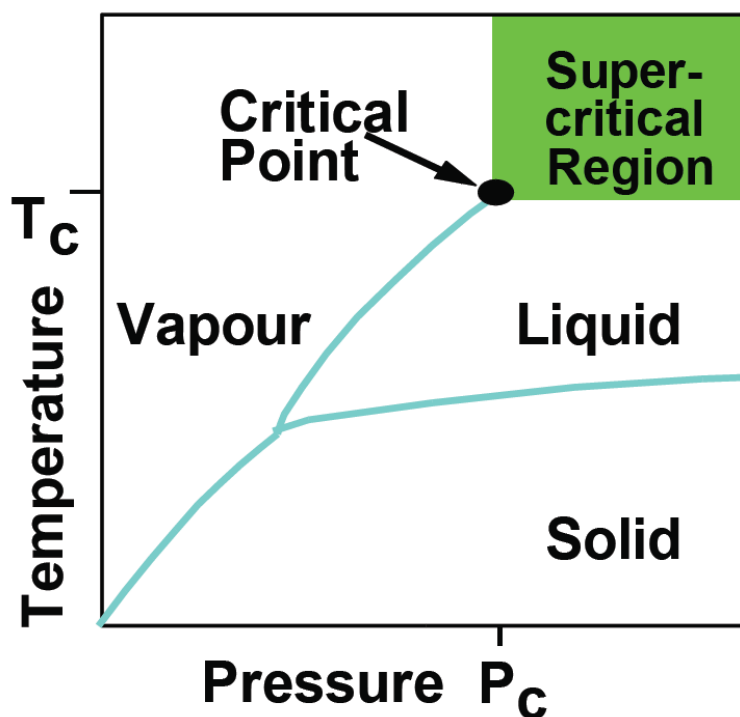
Fig. 3.4. General phase diagram for super critical fluid

(Reproduced from the web page: http://www.ed406.upmc.fr/cours/shaldon.pdf)

Reactions under supercritical conditions have been used for large-scale industrial production for most of the twentieth century, but the application of supercritical fluids (SCFs) in the synthesis of complex organic molecules is only just emerging. Research in this field has been particularly active in the last decade of this century, because the following special properties of SCFs make them attractive solvents for modern synthetic chemistry.

- Increased reaction rates and selectivities resulting from the high solubility of the reactant gases
- Rapid diffusion of solvents
- Weakening of the solvation around the reacting species and the local clustering of reactants or solvents.
- These fluids are easily recycled and allow the separation of dissolved compounds by a gradual release of pressure
- Sequential and selective precipitations of the catalyst and product would be possible.

Example for Carbon–carbon bond formation reactions in supercritical fluids

(i)   Diels-Alder reaction

The Diels–Alder reaction is the most widely-used synthetic method for the synthesis of polycyclic ring compounds. Kolis et al [10] have reported the possibility of performing Diels–Alder reactions in superheated and scH$_2$O due to the unique properties of scH$_2$O [11]. The reactions tested were the cycloadditions of cyclopentadiene (1) with diethyl furmarate (2) and diethyl maleate (4) using scH$_2$O as the solvent. They obtained yields of 10 and 86% for 3 and 5, respectively, after 1 h. Although the yield of the endo/exo-2, 3-diethyl ester of 5-norbornene 3 was low, equal amounts of both isomers of 5 were formed in good yield from the cis diene.
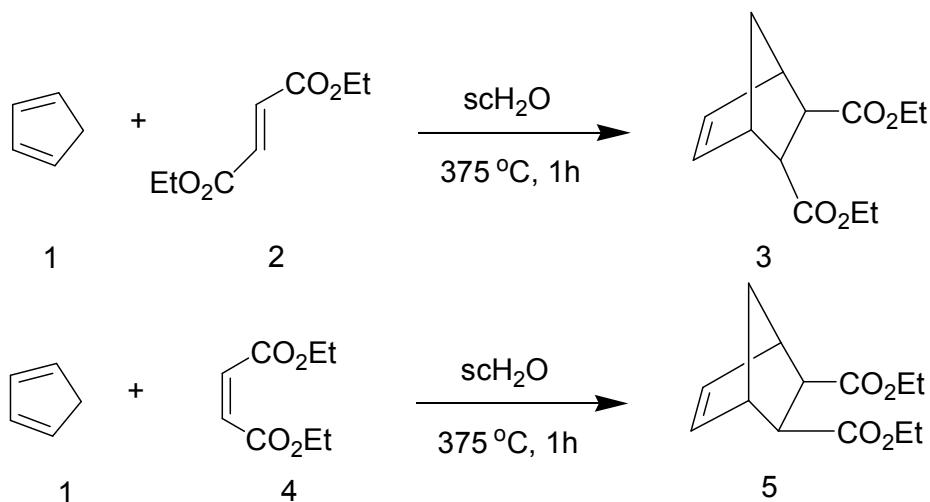
3.1.2.   Solvent Free or Solid State Reaction

A solvent-free or solid-state reaction may be carried out using the reactants alone or incorporating them in clays, zeolites, silica, alumina or other matrices. Thermal process or irradiation with UV, microwave or ultrasound can be employed to bring about the reaction.

Solvent-free reactions obviously reduce pollution, and bring down handling costs due to simplification of experimental procedure, work up technique and saving in labour. These would be especially important during industrial production.

Often, the products of solid state reactions turn out to be different from those obtained in solution phase reactions. This is because of specific spatial orientation or packing of the reacting molecules in the crystalline state. This is true not only of the crystals of single compounds, but also of co-crystallized solids of two or even more reactant molecules. The host-guest interaction complexes obtained by simply mixing the components intimately also adopt ordered structure. The orientational requirements of the substrate molecules in the crystalline state have provided excellent opportunities to achieve high degree of stereoselectivity in the products. This has made it possible to synthesize chiral molecules from prochiral ones either by complexation with chiral hosts or formation of intermediates with chiral partners.

Experimental method

If two or more substrates are involved in the reaction, they are thoroughly ground together in a glass mortar or cocrystallized, and allowed to stay at room temperature or transferred to a suitable apparatus and heated carefully in an oil bath or exposed to appropriate radiation until the reaction is complete. More sophisticated reaction procedures are also adopted, if necessary. TLC can monitor the progress of the reaction. In some cases, a small quantity of water or a catalyst may be added. If it is a single-compound reaction, it is subjected to heat or radiation directly. Care is to be taken to collect the volatile products, if they are produced. In this article illustrative examples representing a number of organic syntheses performed under both thermal and photochemical conditions are described [12].

Examples

(i) Solid-state reactions are not really a new concept. They have been reported even in undergraduate text books. In fact, the historically significant first organic synthesis of urea by Wöhler achieved in 1828 belongs to this class

$$NH_4NCO \xrightarrow[\triangle]{\text{Solid}} NH_2\text{-}CO\text{-}NH_2$$
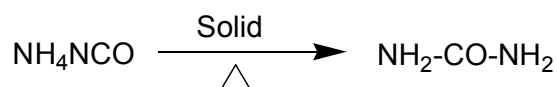
(ii) Pyrolytic distillation of barium or calcium salts of carboxylic acids to prepare ketones is even now a commonly used procedure.

$$(Ph\text{-}CH_2\text{-}COO)_2Ba \xrightarrow{\triangle} Ph\text{-}CH_2\text{-}CO\text{-}CH_2\text{-}Ph + BaCO_3$$
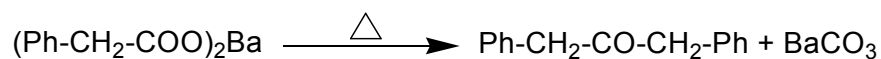
(iii) Michael Addition

The addition of a nucleophile to a carbon-carbon double bond with a strong electron-withdrawing group at the vinylic position is known as Michael addition.
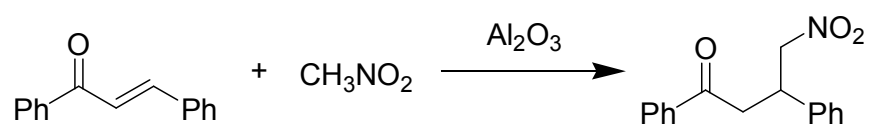
(iv) Aldol Reaction

Aldol condensation is an important reaction of aldehydes and ketones in forming carbon-carbon bonds. The addition of an enol or enolate ion of an aldehyde or a ketone to the carbonyl group of an aldehyde or a ketone is aldol addition, or aldol condensation, if water is eliminated in a subsequent step to produce a, b-unsaturated aldehyde or ketone. Many variations of this reaction are known and are called by different names.

$$ArCHO + Ar'\text{-}CO\text{-}CH_3 \xrightarrow[\substack{\text{5 min; 97\%}}]{\substack{\text{NaOH} \\ \text{Solid r.t}}} Ar\text{-}CHOH\text{-}CH_2\text{-}CO\text{-}Ar' + Ar\text{-}CH=CH\text{-}CO\text{-}Ar'$$
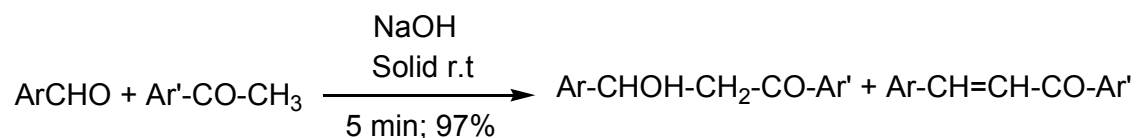
(In solution only 11% yield was realized in 5 min)

(v) Oxidations of alcohol to ketone/aldehyde
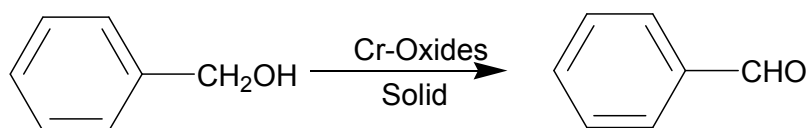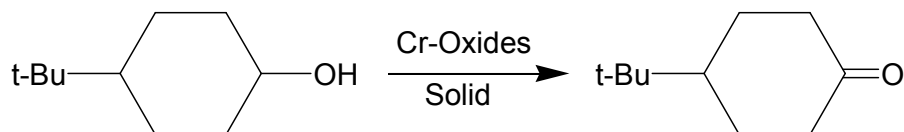
3.1.3. Activation by Physicochemical Methods

3.1.3a. Reaction in Micellar media

Micelles are dynamic colloidal aggregates formed by amphiphilic surfactant molecules. These molecules can be ionic, zwitterionic, or non-ionic, depending on the nature of their head groups, their micelles being classified in the same way. In dilute solutions, amphiphile molecules exist as individual species in the media and these solutions have completely ideal physical and chemical properties. As the amphiphile concentration increases, aggregation of monomers into micelles occurs and, as a consequence, these properties deviate gradually from ideality. This concentration is called the critical micellisation concentration. During the formation of micelles, head group repulsions are balanced by hydrophobic attractions and for ionic micelles, also by attractions between head groups and counterions. Hydrogen bonds can be also formed between adjacent head groups.

It is well known that performing the reactions in micellar media instead of pure bulk solvents can alter the rates and pathways of all kinds of chemical reactions.   Micelles are able to

(a) Concentrate the reactants within their small volumes,

(b) Stabilise substrates, intermediates or products and

(c) Orientate substrates so that ionization potentials and oxidation–reduction properties, dissociation constants, physical properties, quantum efficiencies and reactivities are changed.

Thus, they can alter the reaction rate, mechanism and the regio- and stereochemistry. For many reactions, rate increments of 5–100-fold over the reactions in homogeneous solutions have been reported. In some cases, rate increments may be higher and increments in the order of 106-fold have been observed.

Example

(i) Ring opening reaction of epoxide

The ring opening reaction of styrene oxide with NaCN was studied in the micellar solution of sodium dodecyl sulfate (SDS) as an anionic micelle at different concentrations in the presence of catalytic amounts of Ce(OTf)[13].

$$Ph\text{-epoxide} \xrightarrow[\text{Ce(OTf)}_4,\ \text{Cat, rt, NaCN}]{\text{Micelle(SDS)}} PhCH(OH)CH_2CN + PhCH(CN)CH_2OH$$

                                                                          8%   92%
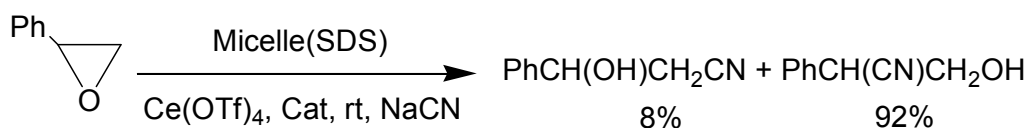
The CMC of SDS= 8.1×10^{-3} M

Thus, it is established that, in many cases, performing the reactions in micellar media instead of organic solvents can alter rates and the pathways of the reactions.

3.1.3b. Reaction in Microemulsion Media

When water is mixed with an organic liquid immiscible with water and an amphiphile, generally a turbid milky emulsion is obtained which, after some time, separates again into an aqueous and an organic phase. On the water-rich side, the mixtures consist of stable dispersions of oil droplets in water, which coagulate with rising temperature. A sponge like structure is obtained if the mixtures contain approximately equal amounts of water and oil. On the oil-rich side, dispersed water droplets are found, which coagulate with decreasing temperature. The size of the domains is a function of the amphiphile concentration and the volume fractions of water and oil. Since microemulsions contain both a polar component (water) and a non-polar component (oil), they are capable of solubilising a wide spectrum of substrates. The mechanism of solubilisation is similar to that in micellar solutions. The micelles are replaced by the oil domains, which are capable of solubilising all kinds of hydrophobic substances. The solubilisation of polar substances takes place analogously through the aqueous domains of the microemulsion. The solubilisation capacity of microemulsions is generally superior to that of the micellar solutions and can therefore, affect the rate and course of a certain reaction.

The use of microemulsions as media for organic reactions is a way to overcome the reagent incompatibility problems that are frequently encountered in organic synthesis. In this sense, microemulsions can be regarded as an alternative to phase transfer catalysis. The microemulsion approach and the phase transfer approaches can also be combined, i.e. the reaction can be carried out in a microemulsion in the presence of a small amount of phase transfer agent. A very high reaction rate may then be obtained. The reaction rate in a microemulsion is often influenced by the charge at the interface and this charge depends on the type of surfactant used. For instance, reactions involving anionic reactants may be accelerated by cationic surfactants. The surfactant counterion also plays a major role for the reaction rate. The highest reactivity is obtained with small counterions, such as acetate, that are only weakly polarizable. Large polarizable anions, such as iodide, bind strongly to the interface and may prevent other anionic species to reach the reaction zone.

Example

(i)   Nucleophilic substitution reactions were performed in H_2O/CO_2 (w/c) microemulsions formed with an anionic perfluoropolyether ammonium carboxylate (PFPE COO-NH_4^+) surfactant. These reactions between hydrophilic nucleophiles and hydrophobic substrates were accomplished in an environmentally benign microemulsion without requiring toxic organic solvents or phase transfer catalysts.

(ii)   The reaction between benzyl chloride and potassium bromide to form benzyl bromide is the first organic reaction performed in w/c microemulsion [14]. This reaction between a nonaqueous compound soluble in CO_2 and a CO_2-insoluble salt may be expected to take place at or near the surfactant interface.
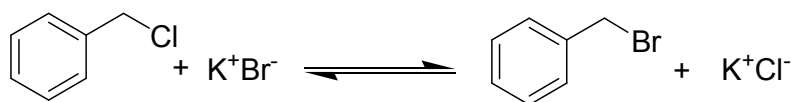
3.1.4c. Electrochemical Activation

Reactive intermediates such as carbocations, carbanions, radicals and radical ions can be electrochemically generated from various electroactive species. Those intermediates may react chemically (C) or electrochemically (E) according to EC, ECE mechanisms. Anodic oxidations produce acidic or electrophilic species, which can react with nucleophiles or (and) eliminate protons or electrophiles. Cathodic reductions afford basic or nucleophilic species, which can react with protons or electrophiles or (and) eliminate nucleophiles. In this way, using direct electrolytes can selectively perform functional group conversion, substitution reactions, addition reactions, cleavage reactions and coupling reactions. Activation by transition metal catalysts is required when the organic substrate is not electroactive or leads to non desired reactions. The metal-catalysed electrosynthesis proceeds by a double activation: i) chemical activation of the organic substrate by the electrogenerated active form of a transition metal catalyst that generates an organometallic species more easily reduced than the organic substrate, ii) followed by activation by electron transfer of the organometallic species formed in the previous chemical activation step. This double chemical and electrochemical activation causes new reactions to proceed, which involve either, the classical organic reactive species, produced in any electrochemical steps (carbanions) or organometallic complexes (anionic or neutral) as the basis of new reactivity.

Example

Allylations of aldehyde

Using a recyclable electrochemical process (up to five cycles with excellent yield), a tin-mediated protocol for the allylation of aldehydes (95-100% yield) is developed [15].

R= Alkyl, aryl
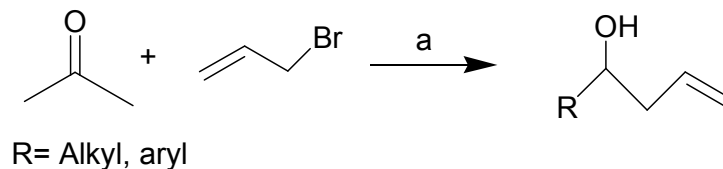
Where a = graphite electrode (2.0 V), aldehyde (5 mmol), allyl bromide (8 mmol), $SnCl_2$ (10 mmol), H_2O (10 mL), r.t., 6-10 h.

3.2. Catalytic Method of Activation

The word catalysis came from the two Greek words, the prefix, cata meaning down, and the verb lysein meaning to split or break. A catalyst breaks down the normal forces that inhibit the reactions of the molecules; a widely accepted definition of catalyst being, 'a substance that increases the rate of approach to equilibrium of a chemical reaction without itself being substantially consumed in the reaction process'. Catalysis is the phenomenon of a catalyst in action, wherein lowering of the activation energy is a fundamental principle that applies to all forms of catalysis – homogeneous, heterogeneous or enzymatic.

Broadly catalysis can be divided into five categories:

  (i)   *Homogeneous Catalysis:* Both the reactant and catalysts are present in the   same phase

  (ii)   *Heterogeneous Catalysis:* Reactant and catalysts are present in separate phase, the catalyst is solid and the reactant either liquid or gas

  (iii)   *Bio Catalysis:* Also known as enzyme-catalysis.

  (iv)   *Photo Catalysis:* Energy for reactions is from light source (hv) (e.g. TiO_2 photocatalytic purification and treatment of H_2O)

3.2.1. Homogeneous catalysis

Homogeneous catalysis is a chemistry term which describes catalysis where the catalyst is in the same phase (ie. solid, liquid and gas) as the reactants and products.

The hydrolysis of esters by acid catalysis is an example of this - all reactants and catalyst are dissolved in water:

   $CH_3CO_2CH_3(aq) + H_2O(l) \leftrightarrow CH_3CO_2H(aq) + CH_3OH(aq)$ - *with H^+ catalyst.*
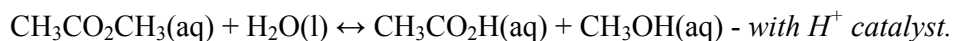
Example
Hydrogenation of maleic acid to succinic acid
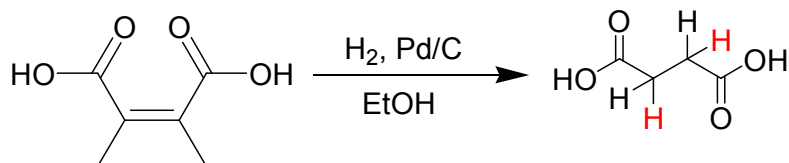
Advantage and drawbacks

- Highly efficient in terms of slectivity (i.e. regioselectivity. enantiomeric excesses) and reaction rates, due to ther monomolecular nature.
- Catalyst recovery can be very difficult (due to the homogeneous nature of the solution).
- Product contamination by residual catalyst or metal species is a problem.

3.2.2. Heterogeneous Catalysis

Heterogeneous catalysis is a chemistry term which describes catalysis where the catalyst is in a different phase (ie. solid, liquid and gas, but also oil and water) to the reactants and products. Heterogeneous catalysts provide a surface for the chemical reaction to take place on.

Example

(i) Synthesis of Ammonia by Haber process

$$3H_2(g) + N_2(g) \leftrightarrow 2NH_3(g) \text{ - } \textit{catalysed by Fe(s).}$$
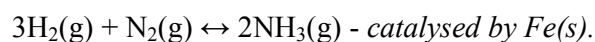
In the Haber process to manufacture ammonia, finely divided iron acts as a heterogeneous catalyst. Active sites on the metal allow partial weak bonding to the reactant gases, which are adsorbed onto the metal surface. As a result, the bond within the molecule of a reactant is weakened and the reactant molecules are held in close proximity to each other. In this way the particularly strong triple bond in nitrogen is weakened and the hydrogen and nitrogen molecules are brought closer together than would be the case in the gas phase, so the rate of reaction increases

(ii) Hydrogenation of ethene on a solid support

In order for the reaction to occur one or more of the reactants must diffuse to the catalyst surface and adsorb onto it. After reaction, the products must desorb from the surface and diffuse away from the solid surface. Frequently, this transport of reactants and products from one phase to another plays a dominant role in limiting the reaction rate. Understanding these

transport phenomena and surface chemistry such as dispersion is an important area of heterogeneous catalyst research. Catalyst surface area may also be considered. A pictorial representation of hydrogenation of ethane on solid support is shown in Fig. 3.5.

$$CH_2=CH_2 \xrightarrow{\text{Ni or Pd catalyst}} CH_3\text{-}CH_3$$
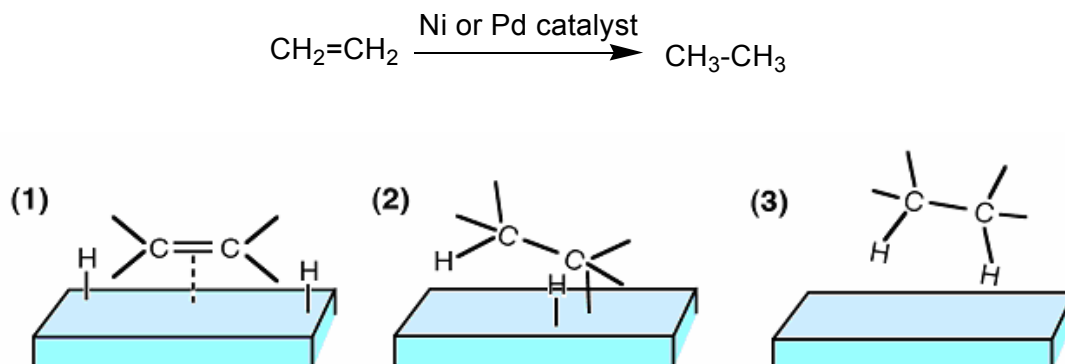
Fig. 3.5. Pictorial representation of hydrogenation of ethene on solid surface
(Reproduced from the web page: http://en.wikipedia.org/wiki/Heterogeneous_catalysis)

Advantages and drawbacks

- Heterogeneously catalyzed reactions allow easy and efficient separation of high value products from the catalyst and metal derivatives.
- However, selectivity and rates are often limited by the multiphasic nature of this system and/or variations in active site distribution from the catalyst preparation.

3.2.3. Enzyme or biocatalysis

Biocatalysis can be defined as the utilization of natural catalysts, called enzymes, to perform chemical transformations on organic compounds. Both enzymes that have been more or less isolated or enzymes till residing inside living cells are employed for this task.

The most important conversion in the context of green chemistry is with the help of enzymes. Enzymes are known as biocatalyst and the transformations are referred to as biocatalytic conversions. Enzymes are now easily available and are an important tool in organic synthesis. Biocatalytic conversions have many advantages in relevance to green chemistry. Some of these are:

- Most of the reactions are performed in aqueous medium at ambient temperature and pressure.
- Biocatalytic conversions normally involve only one step.
- Protection and deprotection of functional groups is not necessary

- Reactions are fast reactions.
- Conversions are stereospecific.
- Special advantage of biochemical reaction is that they are chemoselective, regioselective and stereo selective.

A number of diverse reactions are possible by biocatalytic processes, which are catalysed by enzymes.   The major six classes of enzymes and the type reactions they catalyse are discussed.

(i) *Oxidoreductases*: These enzymes catalyst oxidation-reduction reactions. This class includes oxidases (direct oxidation with molecular oxygen) and dehydrogenases (which catalyse the direct removal of hydrogen from one substrate and pass it on to a second substrate.

(ii) *Transferases:* These enzymes catalyse the transfer of various functional groups. Eg. Transaminase

(iii*) Hydrolases:* This group of enzymes catalyses hydrolytic reactions. Eg. Esterase (esters)

(iv) *Lyases:* These are of two types, one which catalyses addition to double bond and the other which catalyses removal of double bond. Both addition and elimination of small molecules are on sp^3 hybridised carbon.

(v) *Isomerases:* These catalyse various types of isomerisation, e.g. racemases, epimerases etc.

(vi) *Ligases:* These catalyse the formation or cleavage of sp^3 hybridised carbon.

The enzymes are specific in their action. This specificity of enzymes may be manifested in one of the three ways:

a. An enzyme may catalyze a particular type of reaction, e.g. esterases hydrolyses only ester. Such enzymes are called reaction specific. Alternatively, an enzyme may be specific for a particular class of compounds. These enzymes are referred to as substrate specific, e.g., Urease hydrolyses only urea and phosphatases hydrolyse only phosphate esters.

b. An enzyme may exhibit kinetic specificity. For example, esterase hydrolyse all esters but at different rates.

c. An enzyme may be stereospecific. For example, maltase hydrolyses alpha-glycosides but not beta-glycosides. On the other hand emulsin hydrolyses beta glycosides but not the alpha gluycosides.

      d. It should be noted that a given enzyme could exhibit more than one
        specificities.

The oxidation accomplished by enzymes or microorganisms excel in regiospecificity, stereospecificity and enantioselectivity.   An unbelievably large number of enzymatic oxidations have been accomplished.

Examples:

(i) Conversion of alcohol into acetic acid by bacterium acetic in presence of air (the process is now known as quick-vinegar process)

$$CH_3CH_2OH + O_2 \xrightarrow{\text{Bacterium acetic}} CH_3COOH + H_2O$$
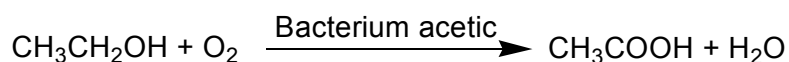
(ii) Conversion of sucrose into ethyl alcohol by yeast (this process is used for the manufacture of ethyl alcohol.

$$C_{12}H_{22}O_{11} + H_2O \xrightarrow[\text{Yeast}]{\text{Invertase}} 2C_6H_{12}O_6$$

$$C_6H_{12}O_6 \xrightarrow[\text{Yeast}]{\text{Invertase}} 2C_2H_5OH + 2CO_2$$
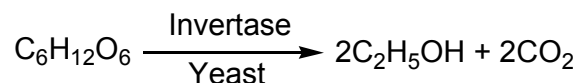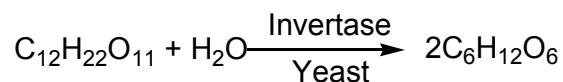
(iii) Oxidation of Galactose

Galactose oxidase (GO) is a fungal enzyme that catalyzes the two-electron oxidation of D. galactose to the corresponding aldehyde with the concomitant reduction of molecular oxygen to hydrogen peroxide.
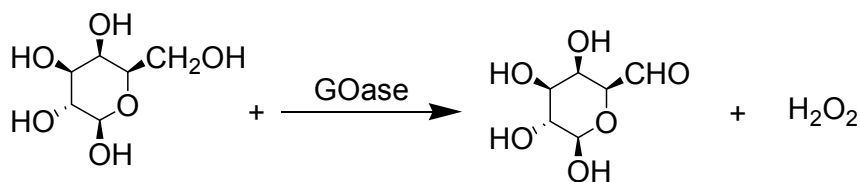
(iv) Hydroxylation of aromatic rings

Benzene undergoes oxidation with Pseudomonus putida in presence of oxygen and gives the cis-diol.

Cis-3,5-cyclohexdiene-1,2-diol
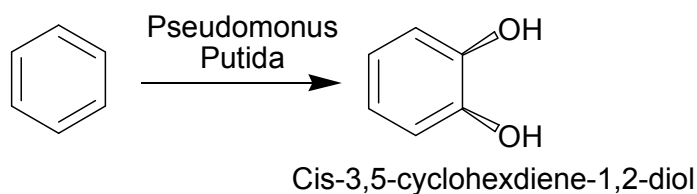
The path to new chemical entities often shows the limitations of existing tools both in biocatalysis and organic chemistry. Organic synthetic procedures to prepare a compound in a target-oriented synthesis can damage other functional parts of the molecule. Protection-deprotection schemes can lead to a dead end, when a certain protecting group cannot be cleaved off. In biocatalysis, on the other hand, the required biocatalytic toolbox and methodology might not be readily available, therefore limiting a biocatalytic approach. New toolboxes, ingredients, and methodologies at the interface of classical organic synthesis and biocatalytic reactions bridge the gap between these two areas. Since product isolation and purification involves a substantial amount of time in the preparation of chemicals, methodologies to simplify these tasks are necessary to get the pure product into the bottle with less work-up time.

Efficient and safe new pharmaceuticals, intermediates and analytical reagents need to be prepared under certain safety, health, and environmental and economical boundary conditions. Biocatalytic reactions have been shown to overcome these limitations successfully and are becoming increasingly important in industrial manufacturing. Building bridges between biocatalysis and organic synthesis will therefore create roads to new synthetic strategies and technological frontiers of both fundamental and practical interest.

3.2.4. Photocatalysis

Photocatalysis is the acceleration of a photoreaction in the presence of a catalyst. In catalysed photolysis, light is absorbed by an adsorbed substrate. In photogenerated catalysis the photocatalytic activity (PCA) depends on the ability of the catalyst to create electron–hole pairs, which generate free radicals (hydroxyl ions; OH-) able to undergo secondary reactions. Its comprehension has been made possible ever since the discovery of water electrolysis by means of the titanium dioxide. Commercial application of the process is called Advanced Oxidation Process(es) (AOP). There are several methods of achieving AOP's that can but do not necessarily involve TiO_2 or even the use of UV. Generally the defining factor is the production and use of the hydroxyl ion.

Example

(i) Chlorophyll as photocatalyst

Chlorophyll of plants is a type of photocatalyst. Photocatalysis compared to photosynthesis, (Figure 6) in which chlorophyll captures sunlight to turn water and carbon dioxide into oxygen and glucose, photocatalysis creates strong oxidation agent to breakdown any organic matter to carbon dioxide and water in the presence of photocatalyst, light and water.
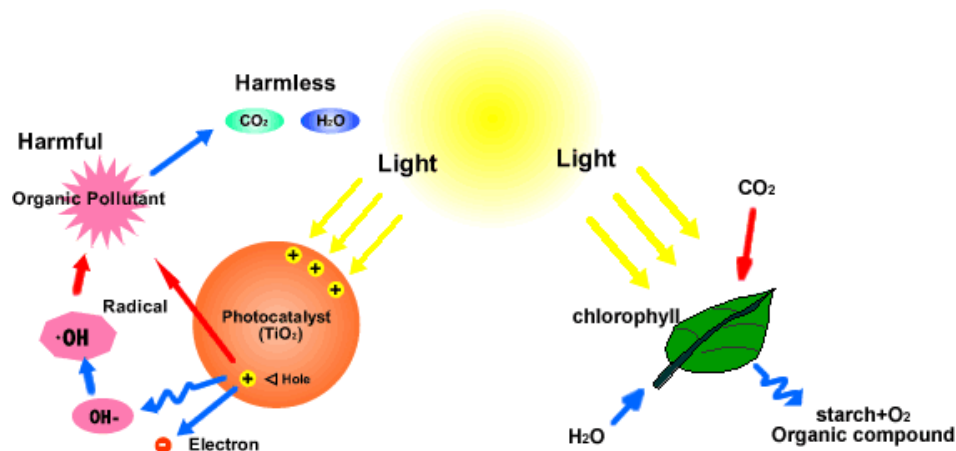
Fig. 3.6. Comparison of photocatalysis with photosynthesis
(Reproduced from the website: http://www.mchnanosolutions.com/whatis.html)

(ii) Epoxidation of trans and cis-2-hexene by TiO_2

The reaction was carried out on photoirradiated TiO_2 powder using trans-2-hexene or cis -2-hexene as the starting material. From trans-2-hexene, trans-2, 3-epoxyhexane was obtained as the main product with the ratio between trans and cis-2, 3-epoxyhexane being 98.4 to 1.6. In the case of cis-2-hexene, the ratio of trans to cis-2, 3-epoxyhexane was 12.0 to 88.0.
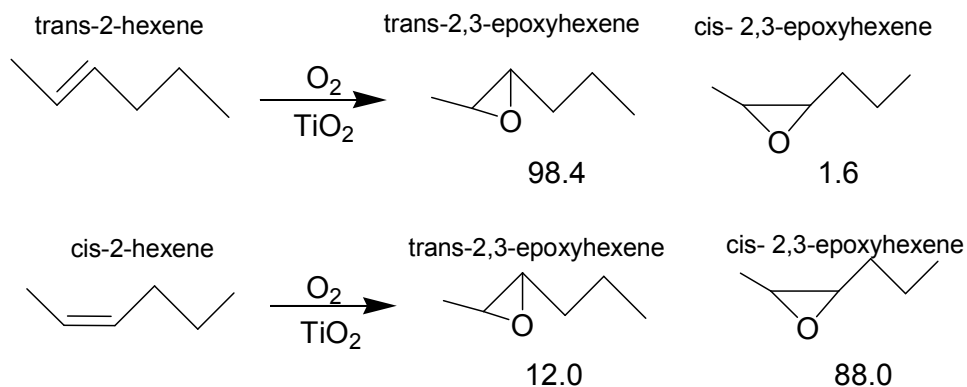
A large number of recent reports on the photo catalytic reaction of organic compounds have satisfied the basic requirement of organic synthesis, e.g isolation and identification of product. Hence photocatalystic reaction is novel synthetic tool as well as activation mode.

4. CONCLUSION

The diversity of activation methods in organic synthesis has grown noticeably in recent years. These methods have many advantages compared to traditional techniques. They also have some drawbacks. A summary of advantages and drawbacks of a few activation methods, which are discussed in this article are summarized in Table 3.1.

Table 3.1. Summary of features of activation processes

Activation mode	Advantages	Drawbacks
Microwave	Large volume reactions Fast reactions (Elimination of volatile products)	Hazardous temperature control Safety problems (reactions in solution) No reproducibility
Pressure	Simple non-destructive method No or little work-up Excellent reproduciblity	Low volume reaction Cost of equipments Limited to homogeneous reactions (difficult of mixing)
Ultrasound	Simple method Large volume reaction No or little work-up Adaptable to heterogeneous reaction	No generality Cost of equipments Hazardous temperature control
Solvophobic interactions	Considerable acceleration of rate constant, Cheap environmentally safe method	No generality Possibility of hydrolysis
Enzymatic catalysis	Low temperature efficient method Highly selective method	No generality (limited to a few specific reactions) Cost enzymes Sensitive to temperature

This article shows that the methods described are fast and efficient. Relatively high yields are achieved in a very short time. The methods and the results when compared with conventional processes are found to be inexpensive, more eco-friendly and high yielding. Therefore choosing the correct mode of activation for a particular reaction depends entirely on the knowledge of chemists in this area. In conclusion, this article reports important examples of activation modes highlighting the implementation of new synthetic strategies. It may be of great help to chemists of present and future generation.

5. REFERENCES

1. D. Bogda and M.Ukasiewicz, *Synlett, 1* (2000) 143.
2. J. S. Yadav and B. V. Subba Reddy, *Green Chemistry*, *2* (2000) 115.
3. V. Singh, K. P. Kaur, A. Khurana and G. L. Kad, *Resonance*, *3* (1998) 56.
4. K. Matsumoto, M. Ciobanu, M. Yoshita and T. Uschida, *Heterocycls*, *45* (1997) 15.
5. G. Jenner and R. Ben Salem, *Tetrahedron*, *53* (1997) 4637.
6. J. Dambacher, W. Zhao, A. El-Batta, R. Anness, C. Jiang and M, Bergdahl, *Tetrahedron Lett., 46* (2005) 4473.
7. T. Hamada, K. Manabe and S. Kobayashi, *J. Am. Chem. Soc., 126* (2004) 7768.
8.   P. Gogoi, P. Hazarika, and D. Konwar,   *J. Org. Chem., 70* (2005) 1934.
9.   R. X . Ren, J.X. Wu, *Org. Lett., 3* (2001) 3727.
10. M. B . Korzanski, and J. W. Kolis, *Tetrahedron Lett*., *38* (1997) 5611.
11. J. Gao, *J. Am. Chem. Soc., 115* (1993) 6893.
12. G. Nagendrappa, *Resonance, 7* (2002) 59.
13. N. Iranpoor, H. Firouzabadi and M. Shekarize, *Org. Biomol. Chem.*, *1* (2003) 724.
14. B. Gunilla, C. Jacobson, T. Lee and K. P. Johnston, *J. Org. Chem., 64* (1999) 1201.
15. Zha, A. Hui, Y. Zhou, Q. Miao, Z. Wang and H. Zhang, *Org. Lett., 7* (2005) 1903.

Books

1. A.S. Bommarius, B.R. Riebel, *Biocatalysis: Fundamentals and Application*, Wiley −VCH Publisher, 2007.
2. V.K. Ahluwalia, N. Kidwai, *New Trends in Green Chemistry*, Kluwer Academic Publishers and Anamaya Publishers, 2004.
3. M. Kaneko and I. Okura, *Photocatalysis: Science and Technology*, Biological and medical physics series, Springer Publishers, 2003.

Websites

1. http://www.bentham.org/aos/Samples/aos1-1.htm
2. http://books.google.co.in

Chapter - 4

SYNTHESIS OF MATERIALS BASED ON SOLUBILITY PRINCIPLE

C. M. Janet

1. INTRODUCTION

Fundamental to the success of materials science and technology is the availability of high-quality materials exhibiting specific tailor-made properties together with an appropriate shape and microstructure. Solution based methods especially water based mathods offer numerous advantages. Cheap and easy to handle precursors, low cost, simple equipments, low energy input and the eco-friendly nature are few of them. Moreover they allow the easy tailoring of synthesis parameters throughout the whole process, which may be exploited to achieve a more precise control of composition, shape and size of the resulting material. Since the synthesis route determines the properties of the material, the preparation method chosen is very important when designing materials for specific applications. Wet chemical routes for the synthesis of nanostructures are a valuable alternative to conventional processing and gas phase synthesis, with known commercial applications. Solvothermal methods and hydrothermal methods are extensively used in the synthesis of materials of novel shape and properties. The majority of the metal organic frameworks reported to date have been synthesized using solution based methods under bench-top conditions (20-80 °C, 1 atm). Hydrothermal synthesis especially has the attraction that it favors the condensation of M-OH into M-O-M bonds, allowing the preparation of materials with multidimensional metal-oxygen frameworks [1]. Recognizing that most metal salts are preferentially soluble in polar solvents, for example, water, and that the opposite is true for many organic reactants, utilizing a higher temperature and biphasic solvothermal method appears advantageous for synthesizing many classes of hybrid materials. Reaction at the interface of two immiscible solvents is a common technique for crystallizing compounds at low to moderate temperatures (<100 °C) and is commonly used to prepare hybrid inorganic-organic materials, in addition to other products. The use of biphasic solvothermal synthesis has a number of attractions over conventional hydro-/solvothermal methods. The basic concept that underlies in wet

chemical methods or solvothermal methods are the principles of solubility. Hence, it is important to have a clear understanding of the fundamentals of solubility to that its use in synthetic procedures.

2. BASICS OF SOLUBILITY

A solution is a homogeneous mixture of two or more substances. One of the substances is called a solvent (a substance in which other substance or substances are dissolved). The substances dissolved in a solvent are called solutes. A solution can exist in a solid, liquid or gas form depending on mixed substances and external conditions such as temperature and pressure. According to a chemists' perspective solubility can be understood as a maximum amount of solute that can dissolve in a solvent at so called equilibrium. In chemistry, equilibrium is a state where reactants and products reach a balance which means that no more solute can be dissolved in the solvent in the set conditions (temperature, pressure). Such a solution is called a saturated solution. There are two groups of substances in case of which solubility measure cannot be applied. These are miscible and immiscible substances. Some solvents, like water and alcohol, can be mixed together and create a homogenous phase in any proportion. A solubility measure cannot be applied to such two substances. Such substances are called miscible. On the other hand if two substances cannot be mixed together (like water and oil), they are called immiscible [2].

In the process of dissolving, molecules of the solute are inserted into a solvent and surrounded by its molecules. For this process to take place, molecular bonds between molecules of solute as well as that of solvent have to be disrupted. Both of these require energy. For example when sugar dissolves in water, new bonds between sugar and water are created. During this process energy is given off. The amount of this energy is sufficient to break bonds between molecules of sugar and between molecules of water. This example is relevant to any solute and solvent. If the bonds between the solvent and solute are too strong and there is not enough energy provided to break them while dissolving, the solute will not dissolve. The same energy rule can be applied to salts. Salts composed of positive and negative ions which are bound together by the force of attraction of their opposite charges. In cases where energy needed to break their ionic

bonds is lower, the dissolution of salts can take place only if the sufficient energy is given off by an interaction of the ions with solvent.

Salts that are considered to be soluble are Group I and ammonium (NH_4^+) compounds, nitrates, acetates, chlorides, bromides and iodides (except: silver (Ag^+), lead (II) (Pb^{2+}), mercury (I) (Hg_2^{2+}), copper (Cu^+) halides) and sulphates (except: Silver (Ag^+), lead (Pb^{2+}), barium (II) (Ba^{2+}), strontium (II) (Sr^{2+}) and calcium(II) (Ca^{2+})). Those which are insoluble are carbonates except Group I, ammonium (NH^{4+}) and uranyl compounds, sulfites except Group I and NH^{4+} compounds, phosphates except Group I and NH^{4+} compounds, hydroxides and oxides except Group I, NH^{4+}, barium (Ba^{2+}), strontium (Sr^{2+}) and thallium (Tl^+) and sulfides except Group I, Group II and NH^{4+} compounds. The solubility principle that holds well in the case of organic compounds is "Like dissolves like".

3. SOLUBILITY PRODUCT (K $_{SP}$)

Solubility product constant is a simplified equilibrium constant (K_{sp}) defined for equilibrium between a solid and its respective ions in a solution. Its value indicates the degree to which a compound dissociates in water. The higher the solubility product constant, the more soluble the compound is. The expression for K_{sp} for a salt is the product of the concentrations of the ions, with each concentration raised to a power equal to the coefficient of that ion in the balanced equation for the solubility equilibrium. Solubility product constants are used to describe saturated solutions of ionic compounds of relatively low solubility. A saturated solution is in a state of dynamic equilibrium between the dissolved, dissociated, ionic compound and the undissolved solid. For Silver chloride K_c is given in the following equation.

$$K_c = \frac{[Ag^+][Cl^-]}{[AgCl]}$$ ------------------ (1)

Where [Ag^+] and [Cl^-] reperesent concentrations of ions of Ag^+ and Cl^- and [AgCl] is a value representing the amount of moles in a liter of solid AgCl. [AgCl] is a constant and therefore, the equation can be written as

$$Kc\ [AgCl] = [Ag^+]\ [Cl^-]$$ --------------------- (2)

The product of equilibrium concentartions of Ag^+ and Cl^- is equal to a constant. This constant is called as solubility product constant or K_{sp} [3].

3.1 Significance of Le Chatelier's Principle in Solubility Concept

Once a system has reached equilibrium, the relative concentrations or pressures of the species in the reaction do not change. However, if you disturb the system in some way, the equilibrium will adjust until a new equilibrium is established. Le Chatelier's principle states that "If a system at equilibrium is disturbed by a change in temperature, pressure, or the concentration of one of the components, the system will shift its equilibrium position so as to counteract the effect of the disturbance". The ionic product (IP) is simply a measure of the ions present in the solvent. This may sound trivial but, in fact, it is not always straightforward and the concept opens up a number of interesting features of how salts behave in solution. The product of the soluble ions of a salt in solution is called the ionic product. The solubility product (Ksp) is the ionic product when the system is in equilibrium. When the ionic product exceeds the solubility product, precipitation will happen according to the Le Chatelier's principle. From equation (2) this can be understood. Any kind of precipitation is thus governed by the Lechatlier principle. One of the day to day significance of ionic and solubility products are that they are the important basic chemical phenomena underpinning the tooth mineralisation, demineralisation and stability. Addition of a common ion affects the ionic product. This has important implications in the mouth since the concentration of calcium and phosphate ions in saliva and plaque fluid can be influenced by external factors. Solubility principles in the case of gases are quite different from that of solids and liquids. As the materials of interest are mostly in solid state the solubility principles of gases are not dealt here.

3.2 Temperature and Pressure Effects on Solubility

$$\text{Heat + Solid sugar + Water = Dissolved sugar} \quad \text{------------ (3)}$$
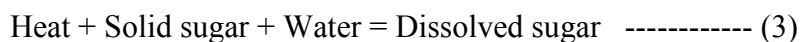
The equation (3) represents two processes: dissolution going left to right, and crystallization going right to left. When the sugar crystals are dissolving at exactly the same rate that sugar is crystallizing out of solution, the system is at equilibrium. The balance between dissolution and crystallization can be changed by changing the

temperature of the solution. Adding heat will favor dissolution. Cooling the solution will favor crystallization.

The temperature dependence of solubility is also usually explained using Le Chatelier's principle. Le Chatelier's principle predicts that heating the solution mixture will shift the equilibrium in favor of dissolution, to remove the added heat. This explains why sugar is more soluble in hot water than in cold. The solubility of a substance is its concentration in a saturated solution. Substances with solubilities much less than 1 g/100 mL of solvent are usually considered insoluble. The solubility is sometimes called "equilibrium solubility" because the rates at which solute dissolves and is deposited out of solution are equal at this concentration.

The solubility of solutes is dependent on temperature. When a solid dissolves in a liquid, a change in the physical state of the solid analogous to melting takes place. Heat is required to break the bonds holding the molecules in the solid together. At the same time, heat is given off during the formation of new solute-solvent bonds.

(a) Decrease in Solubility with Temperature:

If the heat given off in the dissolving process is greater than the heat required to break apart the solid, the net dissolving reaction is exothermic (energy given off). The addition of more heat (increases temperature) inhibits the dissolving reaction since excess heat is already being produced by the reaction. This situation is not very common where an increase in temperature produces a decrease in solubility.

(b) Increase in solubility with Temperature

If the heat given off in the dissolving reaction is less than the heat required to break apart the solid, the net dissolving reaction is endothermic (energy required). The addition of more heat facilitates the dissolving reaction by providing energy to break bonds in the solid. This is the most common situation where an increase in temperature produces an increase in solubility for solids.

The use of first-aid instant cold packs is an application of this solubility principle. A salt such as ammonium nitrate is dissolved in water after a sharp blow breaks the containers for each. The dissolving reaction is endothermic - requires heat. Therefore the heat is drawn from the surroundings, the pack feels cold. The Fig. 4.1 represents the

effect of temperature on the solubility of three different salts. Solubility of nitrate salt of K is more compared to that of chlorides as the temperature increases.
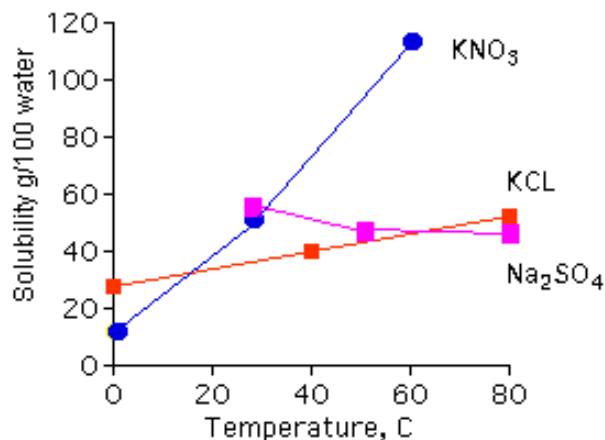
Fig. 4.1. Temperature dependence of solubility of different salts (ref. 2)

4. HETEROGENEOUS EQUILIBRIA AND PRECIPITATION

Phase transitions such as sublimation, deposition, melting, solidification, vaporization, and condensation are heterogeneous equilibria, so are the formation of crystals from a saturated solution, because a solid and its solution are separated phases. The equilibrium constants for saturated solution and solid formation (precipitate) are already defined as solubility product, Ksp. For unsaturated and supersaturated solutions, the system is not at equilibrium, and ion products, Q_{sp}, which have the same expression as K_{sp} is used.

An oversaturated solution becomes a saturated solution by forming a solid to reduce the dissolved material. The crystals formed are called a precipitate. Often, however, a precipitate is formed when two clear solutions are mixed. For example, when a silver nitrate solution and sodium chloride solution are mixed, silver chloride crystals AgCl(s) (a precipitate) are formed. Na^+ and NO_3^- are by-stander ions.

$$Ag^+(aq) + Cl^-(aq) \rightarrow AgCl(s) \quad (precipitate)$$
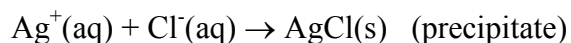
Silver chloride is one of the few chloride that has a limited solubility. A precipitate is also formed when sodium carbonate is added to a sample of hard water,

$$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightarrow CaCO_3(s) \quad (precipitate).$$
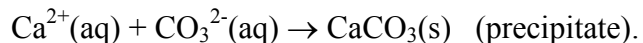
4.1 Solubility Products, Ksp, and Ion Products Qsp

Formations of precipitates are chemical equilibria phenomena, and we usually write these heterogeneous equilibrium in the following manner, and call the equilibrium constants solubility products, Ksp. If the solution is not saturated, no precipitate will form. In this case, the product is called the ion product, Q_{sp}.

4.2 Qsp, Ksp and Saturation

For some substances, formation of a solid or crystallization does not occur automatically whenever a solution is saturated. These substances have a tendency to form oversaturated solutions. For example, syrup and honey are oversaturated sugar solutions, containing other substances such as citric acids. For oversaturated solutions, Q_{sp} is greater than K_{sp}. When a seed crystal is provided or formed, a precipitate will form immediately due to equilibrium of requiring Q_{sp} to approach K_{sp}.

Sodium acetate trihydrate, $NaCH_3COO^.3H_2O$, when heated to 370 K will become a liquid. The sodium acetate is said to be dissolved in its own water of crystallization. The substance stays as a liquid when cooled to room temperature or even below 273 K. As soon as a seed crystal is present, crystallization occur rapidly. In such a process, heat is released, and the liquid feels warm. Thus, the relationship among Q_{sp}, K_{sp} and saturation is given below [3]:

Qsp < Ksp Unsaturated solution

Qsp = Ksp Saturated solution

Qsp > Ksp Oversaturated solution

5. NANOPARTICLES THROUGH HOMOGENEOUS NUCLEATION

For the formation of nanoparticles by homogeneous nucleation, a supersaturation of growth species must be created. A reduction in temperature of an equilibrium mixture, such as saturated solution would lead to supersaturation. Formation of metal quantum dots in glass matrix by annealing at moderate temperatures is a good example of this approach. Another method is to generate a supersaturation through *in situ* chemical reactions by converting highly soluble chemicals into less soluble chemicals. For example semiconductor nanoparticles are commonly produced by pyrolysis of organometallic precursors. Nanoparticles can be synthesized through homogeneous

nucleation in three mediums: liquid, gas and solid: however, the fundamentals of nucleation and subsequent growth processes are essentially the same. Before discussing the detailed approaches for the synthesis of uniformly sized monodispersed nanoparticles, it is essential to review the fundamentals of homogeneous nucleation and subsequent growth [4].

5.1 Fundamentals of Homogeneous Nucleation

When concentration of a solute in a solvent exceeds its equilibrium solubility or when temperature decreases below the phase transformation point, a new phase appears. A solution with solute exceeding the solubility or supersaturation possesses a high Gibbs free energy. The overall energy of the system will be reduced by segregating solute from the solution.
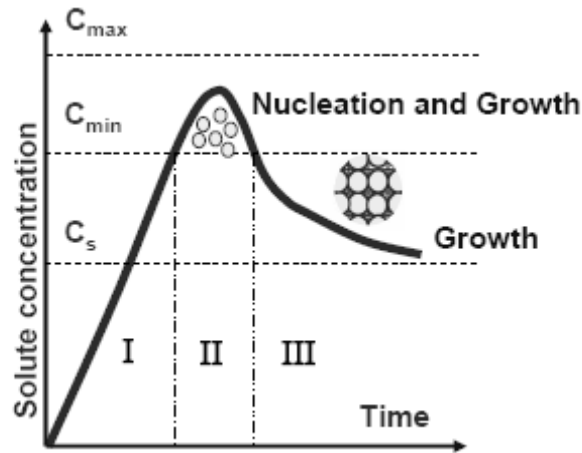
Fig. 4. 2. Nucleation and subsequent growth (ref. 4)

When the concentration of a solute increases as a function of time no nucleation would occur even above the equilibrium solubility. Nucleation occurs only when the supersaturation reaches a certain value above the solubility. Homogeneous nucleation is important for the formation of particles of uniform size and shape.

5.2 Examples of Nucleation

Pure water freezes at $-42\,°C$ rather than at its freezing temperature of $0\,°C$ if no crystal nuclei, such as dust particles, are present to form an ice nucleus. Presence of cloud condensation nuclei is important in meteorology because they are often in short supply in the upper atmosphere.

Fig. 4.3. Nucleation of carbon dioxide bubbles around a finger (ref. 5)

Nucleation in boiling can occur in the bulk liquid if the pressure is reduced so that the liquid becomes superheated with respect to the pressure-dependent boiling point. More often nucleation occurs on the heating surface, at nucleation sites. Typically, nucleation sites are tiny crevices where free gas-liquid surface is maintained or spots on the heating surface with lower wetting properties. Substantial superheating of a liquid can be achieved after the liquid is de-gassed and if the heating surfaces are clean, smooth and made of materials well wetted by the liquid. The creation of a nucleus implies the formation of an interface at the boundaries of the new phase. Some energy is consumed to form this interface, based on the surface energy of each phase. If a hypothetical nucleus is too small, the energy that would be released by forming its volume is not enough to create its surface, and nucleation does not proceed. The critical nucleus size can be denoted by its radius, and it is when r=r* (or r critical) that the nucleation proceeds [5].

6. SOLUBILITY AND CRYSTAL GROWTH

Crystal formation is made up of three phases: nucleation, growth, and cessation of growth. During nucleation, the slowest and most difficult phase in crystal growth, the smallest crystal capable of growth forms. The barrier to formation of these smallest crystals results from differences in the stability between molecules at the core and those on the surface of the crystal. During nucleation, the average stability of a molecule in a crystal is very low because the attraction between the molecule and the crystal is often less than that between the molecule and the solvent. Thus, it is significantly easier to

successfully stimulate the birth of a crystal by introducing a smaller crystal (seeding) than by merely supersaturating a solution. Once nucleation has been accomplished, the growth phase of crystal formation begins, a phase characterized by the addition of molecules to the existing crystal. Two opposing forces impact this process: enthalpy and entropy. Growth of a crystal reduces the entropy (a measure of randomness) of the system because a molecule free in solution has greater entropy than one tethered to a crystal's growing surface. Although entropy favors dissolution of crystals, it is energetically favorable for a molecule to be added to a crystal. Above a critical saturation point, enthalpy overcomes entropy, and crystal formation can occur.

6.1 Crystal Kinks and Ledges

In addition to temperature and concentration, the geometry of a growing crystal's surface influences growth. Imagine a spherical molecule approaching a planar surface of a crystal. In this case, the addition of the molecule is not energetically favorable because there is only one point of contact. Next, consider a spherical molecule approaching a "ledge" surface of a crystal. In this case, the addition of the molecule is more energetically favorable because the molecule is stabilized by two points of contact at which intermolecular forces hold the molecule to the crystal. In the third case, the "kink" structure provides three points of contact. The kink structure is the ideal surface geometry for crystal growth. Because kinks are sparse on a crystal's surface, the addition of even a small amount of impurities that effectively clog the kink sites is capable of killing crystal growth. In order for crystal growth to be maintained, "ledges" or kinks must remain available for molecules to be added to the crystal. At one point in the field of crystal research, scientists observed that nucleation occurs too quickly to be explained solely by the addition of molecules to a planar crystal surface. As a result, the spiral dislocation (SD) theory arose, stating that molecules are added to the surface of a crystal in a manner resulting in the creation of new ledges or kinks so that crystal growth can continue. With the development of atomic force microscopy (AFM) for physically detecting changes in depth on the atomic scale, it was possible to study changes associated with a ledge on a crystal. To observe crystal formation, the lab uses an atomic force microscope to gather data on the movement of ledges as organic crystals grow and dissolve. This method allows the investigator to observe the rate and geometry of ledge movement at various

concentrations of solute and in the presence of impurities. It was noticed that dissolution is not exactly the opposite of growth. During dissolution, the ledges are smooth and regular, while they are rough and irregular during growth. Although there are several theories on how the irregularity may be conducive to crystal growth, the differences have not been fully explained.

6.2 Practical Significance of Solubility and Crystal Growth

Understanding the growth and dissolution of crystals is valuable in a variety of contexts. Crystallization is an effective and economical purification process, and, in some cases where substances cannot be purified by distillation, it is the only practical method. More importantly, approximately eighty percent of all pharmaceutical agents are pure crystalline solids. Understanding the dissolution of a particular crystalline drug could allow chemists to alter the drug's dissolution rate. Moreover, understanding the conditions of crystallization may allow chemists to predict whether drugs crystallize within the body. In 2004, the journal Heart reported a case of a large crystal forming in the heart of woman given a continuous dose of a drug for ventricular tachycardia. A better understanding of this drug's crystallization could have prevented the incident. Clearly, much of this research is not yet crystal-clear.

7. SOLUTION BASED SYNTHETIC STRATEGIES

Solution based synthetic strategies involve mainly sol gel process, hydrothermal synthesis, solvothermal synthesis and reduction in solution. Among which solvothermal synthesis and hydrothermal synthesis are discussed in detail in the present chapter.

7.1 Solvothermal Synthesis

Solvothermal synthesis utilizes a solvent under pressures and temperatures above its critical point to increase the solubility of solid and to speed up reaction between solids. Most materials can be made soluble in proper solvent by heating and pressuring the system close to its critical point. This method allows the easy control on the solubility of a solute. And it leads to lower super saturation state which is necessary for the precipitation to happen. The reaction set-up used for solvothermal synthesis is given in Fig. 4.4.
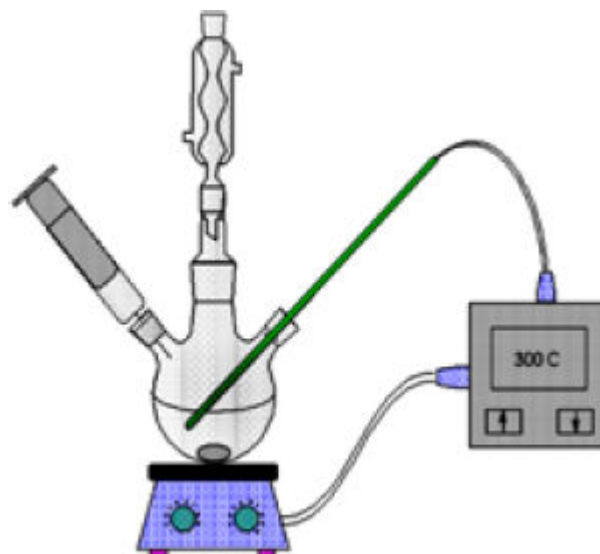
Fig. 4.4. Solvthermal synthesis set-up (ref. 6)

7.1.1 Synthesis of Semiconductor Chalcogenides

In general, semiconductor chalcogenides of different sizes and shapes are prepared using solvothermal synthesis. In our laboratory we have synthesized CdS nanostructures especially nanorods through solvothermal synthesis using a solid precursor CdC_2O_4. The reagent used to precipitate CdS was $(NH_4)_2S$. The reaction observed was represented in the equation 6. Here the solvent used was ethylene glycol and the reaction temperature was 60 °C and the reaction was carried under a constant flow of an inert gas [7].

$$CdC_2O_4 + (NH_4)_2S \rightarrow CdS + (NH_4)_2C_2O_4 \quad \text{----------} \quad (6)$$
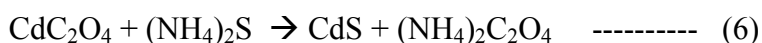
CdC_2O_4 is an insoluble solid and $(NH_4)_2S$ was liquid. But the solvothermal synthesis at low temperatures allowed in this case a slow replacement reaction of the ligand forming the nanostructures of CdS. The TEM images of the CdS nanorods are given in the Fig. 4.5. By changing the solvents, temperature and the precursor variety of sizes and shapes can be produced through this method. When ethylene diamine is used the material formed was also found to be nanorods with high aspect ratio. But, when pyridine was used CdS nanoparticles are only formed.
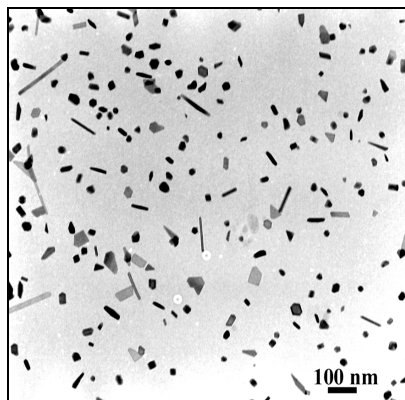
Fig. 4.5. TEM image of CdS prepared from CdC_2O_4 using solvothermal method in ethylene glycol (ref. 7)
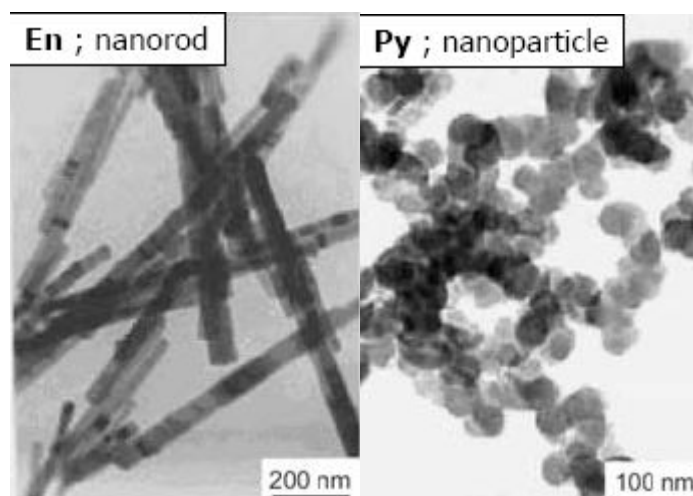
Fig. 4.6. TEM image of CdS prepared from CdC_2O_4 using solvothermal method in ethylene diamine and pyridine (ref. 6)

7.1.2 Synthesis of Metal Nanoparticles

Pt and Pd nanoparticles were synthesized by microwave-assisted solvothermal method. The only difference is the heating source is microwave. PVP with an average molecular weight of 40'000 was used as a capping agent in the experiments. H_2PtCl_6, and Palladium(II)2,4-pentanedionate were used as metal precursors. PVP was dissolved in methanol or ethanol and then the metal salts were added. The reactants were heated for 60 min at 90 °C when methanol was used as a reducing agent and at 120 °C when ethanol was used as a reducing agent for 60 min under microwave irradiation [8].
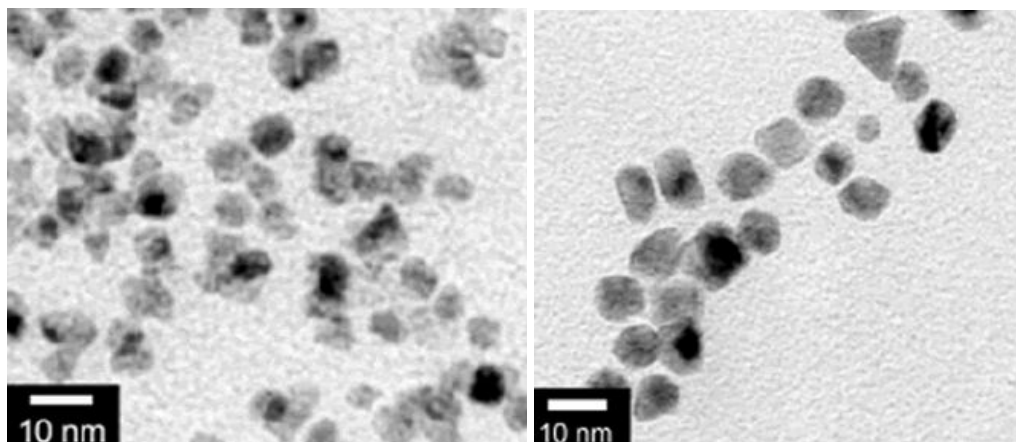
Fig. 4.7. TEM images of the obtained Pt and Pd nanoparticles under microwave-assisted solvothermal conditions (ref. 8).

7.1.3 Synthesis of Metal Nitrides and Oxides

In another approach single source precursors of halides of Al, Ga and In were prepared with urea complexation and further solvothermal synthesis at higher temperatures resulted in the formation of the respective nitrides. These nitrides are of special relevance in photovoltaic applications [9].

(a)   (b)   (c)
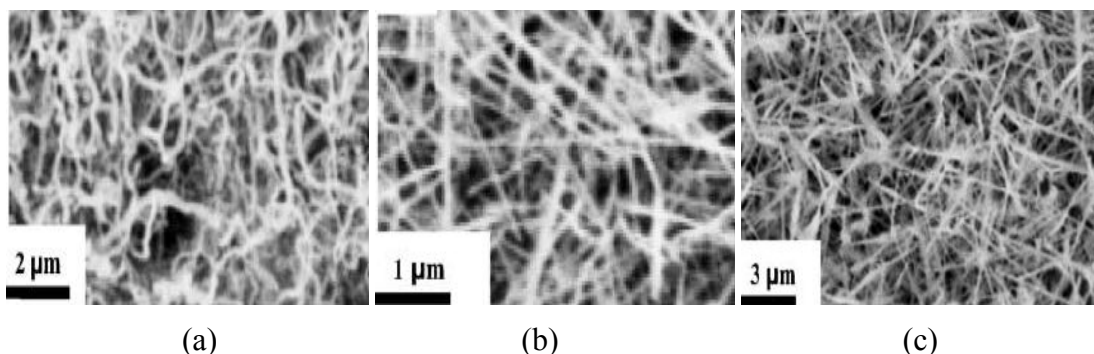
Fig. 4.8. TEM images of (a) AlN (b) GaN (c) AlN nanowires formed during solvothermal synthesis (ref. 9).

A new and facile route was developed by Suib et al., to manipulate the growth of hierarchically ordered Mn_2O_3 architectures via a solvothermal approach. Various solvents are employed to control the product morphologies and structures. Mn_2O_3 with unique cuboctahedral, truncated-octahedral, and octahedral shapes are obtained. In a typical synthesis $Mn(NO_3)_2$ was dissolved in an organic solvent followed by a vigorous stirring at room temperature for half an hour in a Teflon liner. Then the Teflon liner was transferred and sealed in an autoclave for solvothermal treatment at 120 °C for 20 h. A

variety of different solvents was used to investigate the effect of solvents on the morphology of the resultant Mn_2O_3. In order to investigate the development of Mn_2O_3 crystals, the reactions were also conducted at different temperatures using ethanol as the solvent. FESEM images of the Mn_2O_3 synthesized in different solvents and for different duration are given in Fig. 4.9 and Fig. 4.10 respectively. The images indicate the shape evolution of Mn_2O_3 polyhedra. Mn_2O_3 is used in catalytic as well as electrocatalytic applications [10].
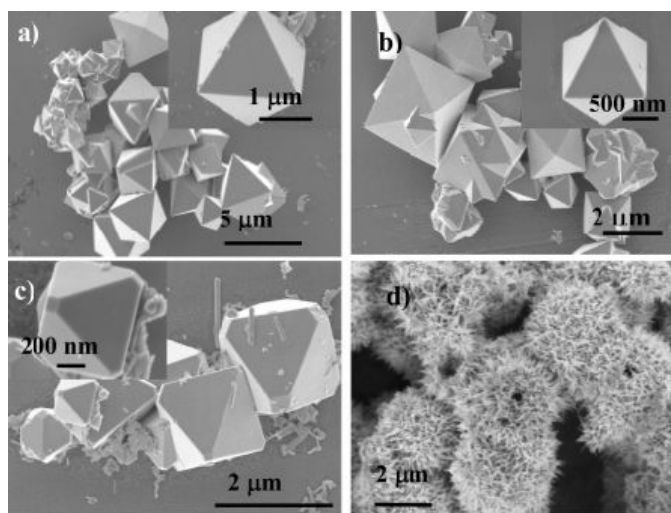
Fig. 4.9. FESEM images of products synthesized in different
solvents: (a) ethanol, (b) 1-butanol, (c) 2-butanol, and (d) acetone (ref. 10).
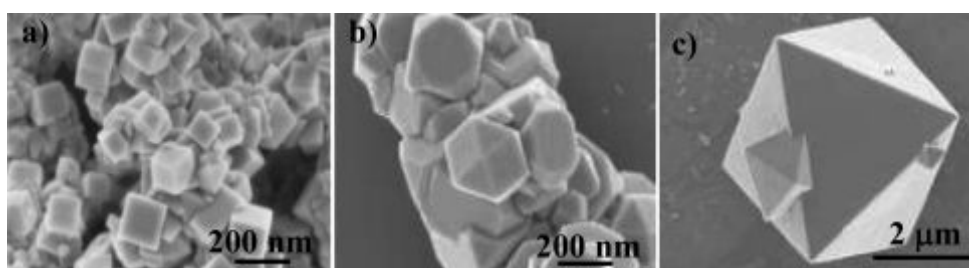
Fig. 4.10. FESEM images of products synthesized under different
reaction periods (a) 1.5 h, (b) 2 h, and (c) 3 h (ref. 10).

7.2 Hydrothermal Synthesis

Hydrothermal synthesis as the name indicates the solvent is always water. If liquid water is placed in an open container, its temperature cannot be raised above 100 °C. But, if water is heated in a sealed container, it can be heated to temperatures above 100 °C which means that supercritical properties of the water can be utilized under this

condition. The advantages of inducing supercritical behavior in hydrothermal synthesis are that it will provide a single phase behavior and give enhanced permeability, mass transport capability and dissolving capacities. Hydrothermal synthesis can be defined as a method of synthesis of single crystals which depends on the solubility of minerals in hot water under high pressure. Hydrothermal synthesis is a century old synthetic strategy and it was used for the synthesis of minerals in general. From 80's hydrothermal method was utilized extensively for newer material synthesis. Advantages of hydrothermal synthesis are in this method no post-heat treatment is needed and hence agglomeration will be less. After preparation no milling is required which will reduce impurities. Any complex chemical compositions can be synthesized by using this method. Particle size or shapes can be controlled in this approach. It can induce self assembly leading to newer and complex architectures of materials and the precursors used are relatively cheap raw materials. And hydrothermal method crystal growth includes the ability to create crystalline phases which are not stable at the melting point. Also, materials which have a high vapour pressure near their melting points can be grown by the hydrothermal method. The method is also particularly suitable for the growth of large good-quality crystals while maintaining good control over their composition. Disadvantages of the method include the need of expensive autoclaves, good quality seeds of a fair size and the impossibility of observing the crystal as it grows. Fig. 4.11 shows the reaction set-up for hydrothermal synthesis. The pressure generated inside the reactor can be read from the pressure gauge.
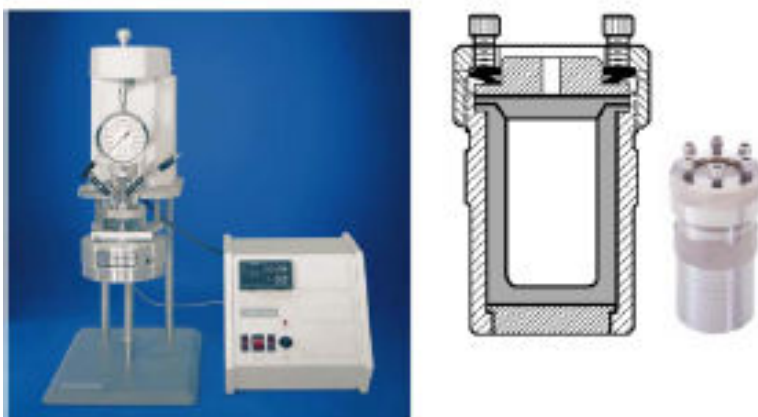
Fig. 4.11. Hydrothermal reactor set-up (ref. 6)

7.2.1 Synthesis of Oxides and Mixed Oxides

Barium titanate ($BaTiO_3$) perovskite is widely used in electronic industry in multilayered ceramic capacitors due to its high dielectric constant. Hydrothermal synthesis route is promising due to homogeneity, exact stoichiometry and spherical morphology of BT powders obtained by this synthesis method at low temperature (<200 °C). Using commercially available titania as Ti precursor (Degussa P-25) and Barium hydroxide precursor in the Ba: Ti = 1:1 ratio at a temperature as low as 120 °C for 48 h yielded $BaTiO_3$ crystals [11]. The SEM image of $BaTiO_3$ prepared is given in Fig. 4.12.
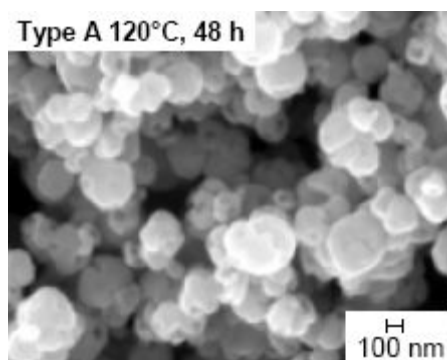
Fig. 4.12. SEM image of $BaTiO_3$ crystals (ref. 11).

Alkali treatment of commercially available TiO_2 (Degussa p-25) in hydrothermal conditions (130 °C) will result in the formation of nanotubes of TiO_2. These tubes obtained on further hydrothermal treatment at a high temperature of around 175 °C will yield nanorods of TiO_2 [12]. Thus hydrothermal synthesis provides a route to play around different morphologies of the same material by simply changing the temperature.

Hydrothermal treatment of zinc chloride hydrazene hydrate at 140 ºC for 12 h resulted in the formation of flower like microrod bundles. The solution phase is accelerating the process of self assembly through a dissolution-recrystallization-decompositiongrowth process [13]. The chemical reactions are represented in the following equations. ZnO has variety of applications in photonics and optics.

$ZnCl_2 + 2N_2H_4 \rightarrow ZnCl_2(N_2H_4)_2$ ....(1)

$Zn^{2+} + 2NH_3. H_2O \rightarrow Zn(OH)_2 + 2NH^{4+}$ ....(2)

$Zn(OH)_2 \rightarrow ZnO + H_2O$ ....(3)
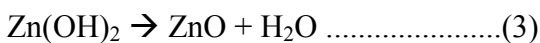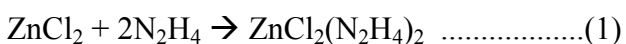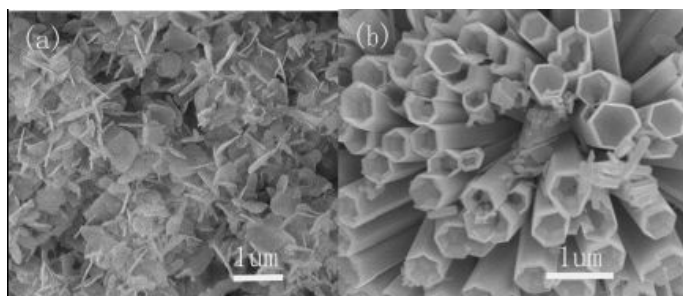
Fig. 4.13. FE-SEM images of (a) precursor $ZnCl_2(N_2H_4)_2$ obtained at room temperature (b) ZnO samples obtained at 140 °C and 12 h (ref. 13).

7.2.2 Synthesis of Noble Metal Architectures through Hydrothermal Synthesis

Polymer protected (PDDA-poly (diallyl dimethylammonium) chloride) noble-metal (including silver, platinum, palladium, and gold) nanostructures in the absence of any seeds and surfactants can be synthesized using hydrothermal method in which PDDA, an ordinary and water-soluble polyelectrolyte, acts as both a reducing and a stabilizing agent. Under optimal experimental conditions, Ag nanocubes, Pt and Pd nanopolyhedrons, and Au nanoplates are obtained. In typical synthesis, PDDA along with the respective precursors such as $AgNO_3$ (170 °C for 16 h), H_2PtCl_6 (140 °C for 40 h), H_2PdCl_4 (190 °C for 40 h) and $HAuCl_4$ (170 °C for 12 h) at specific pH was used [14].
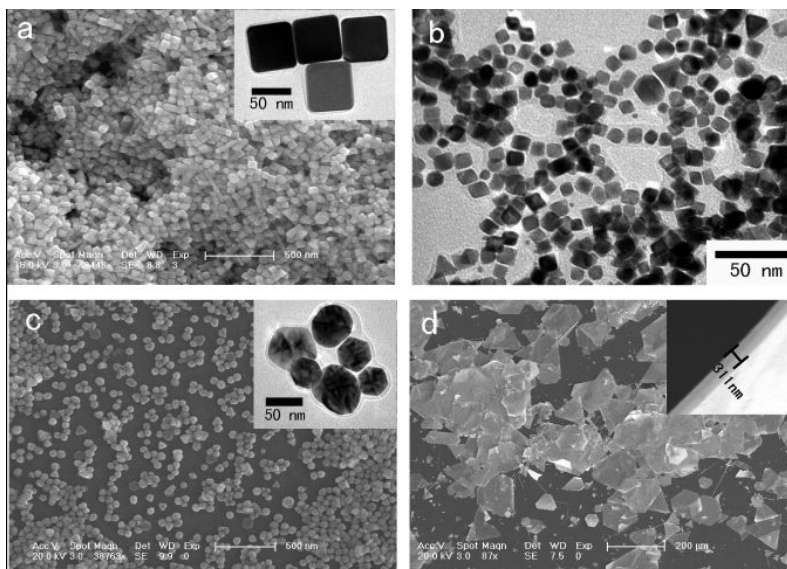
Fig. 4.14. Typical SEM and TEM images of the PDDA-protected (a) Ag nanocubes (b) Pt nanopolyhedrons (c) Pd nanopolyhedrons and (d) Au nanoplates (ref. 14).

Apart from metals and metal oxides hydrothermal synthesis method is used in the preparation of zeolites and mesoporous materials. This method was also found to be effective in the synthesis of different carbons such as nanotubes, fullerene and diamond [15].

7.2.2 Synthesis of Polymeric Materials through Hydrothermal Synthesis

Polyaniline (PANI) mesostructures have been synthesized under hydrothermal conditions. The mesostructures show different forms - fibers, dendrite fibers, textured plates, featureless plates, and spheres [16]. In a typical synthesis, a complex of $FeCl_3 \cdot 6H_2O$ and methyl orange in hydrochloric acid aqueous solution (pH = 4.0) was stirred and transferred to an autoclave with aniline monomer and kept at 120 ◦C for 24 h. The material collected was found to be PANI nanotubes [17]. The formation mechanism and the TEM images of the tubes formed are given in Scheme 1 and Fig. 4.15. A fibrillar complex of $FeCl_3$ and methyl orange (MO) acting as reactive selfdegraded templates in hydrothermal conditions was the driving force for the growth of nanotubes. MO, which contains a hydrophilic group ($-SO^{-3}$), possesses an anionic characteristic when dissolved in water. It could dimerize at a particular concentration to form higher oligomers. When aniline monomer was added into the solution, polymerization occurred on the surface of MO where the oxidant $FeCl_3$ was adsorbed and MO itself degraded automatically during the polymerization process.
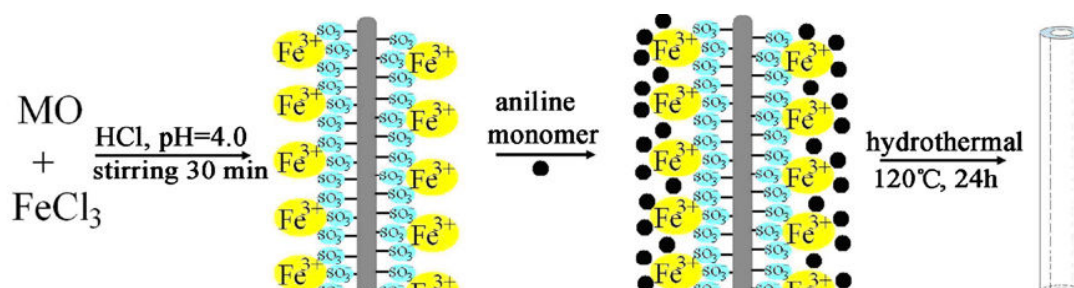
Scheme 4.1. Possible polymerization mechanism for the formation of PANI nanotubes (ref. 17)
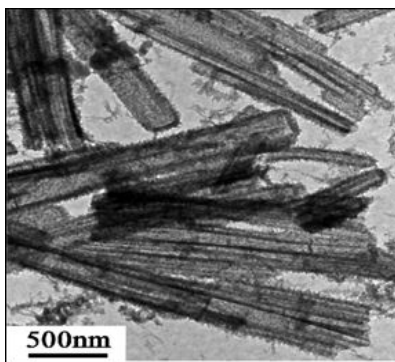
Fig. 4.15. TEM of products with pH of electrolyte (4.0) Synthesis conditions:
temperature, 120 $^{\circ}$C; FeCl$_3$, 1.5 mmol; MO, 0.075 mmol; aniline, 1.5 mmol (ref. 17).

CONCLUSIONS

The solubility of a material is having a major role while designing the synthetic strategy of any new materials. Solution phase synthesis always assisted the self assembly and gradual growth of the crystals of a variety of materials ranging from metals, metal oxides, chalcogenides, polymers, zeolites and carbon materials. Easy tailoring of the morphology and properties can be achieved if solubility concepts are suitably exploited in new material synthesis. Solution based chemistry is always important because ultimate utility of materials is going to be in any form of life chemistry which is fully based on aqueous systems. Drug delivery materials, materials in food processing and preservation, medicines and cosmetics are much trivial cases where the solubility concepts are extremely important. Hence, immense care should be taken while designing materials for day today applications through solution chemistry.

REFERENCES

1. P. M. Forster, P. M. Thomas and A. K. Cheetham, *Chem. Mater.*, 14 (2002)17.

2. http://www.elmhurst.edu/~chm/vchembook/174temppres.html

3. http://research.yale.edu/ysm/article.jsp?articleID=354

4. Nanostructures and nanomaterials, Synthesis, Properties and applications, Cao (Editor) (2004), Imperial College press, London.

5. en.wikipedia.org/wiki/Nucleation

6. D. K. Kim Nanoparticle lecture, 2003.

7. C. M. Janet and R. P. Viswanath, *Nanotechnology,* 17 (2006) 5271.

8. Q. Lu, F. Gao, D. Li and S. Komarneni, *A to Z of Journal of Materials online*, 1(2005) 1.

9. K. Sardar, M. Dan, B. Schwenzer and C. N. R. Rao, *J. Mater. Chem.*, 15 (2005) 2175.

10. W.-N. Li, L. Zhang, S. Sithambaram, J. Yuan, X.-F. Shen, M. Aindow and S. L. Suib, *J. Phys. Chem. C.*, 111 (2007) 14694-14697.

11. http://www.isotec-cluster.at/internal/uploads

12. J.-N. Nian and H. Teng, *J. Phys. Chem. B* 110 (2006) 4193.

13. C. Jiang, W. Zhang, G. Zou, W. Yu and Y. Qian, *J. Phys. Chem. B.* 109 (2005) 136.

14. H. Chen, Y. Wang, S. Dong, *Inorg. Chem.* 46 (2007) 10587.

15. http://www.sawyerresearch.com/Newsletters/May03newsletter.pdf

16. L. J. Pan, L. Pu, Y. Shi, T. Sun, R. Zhang and Y. O. Zheng, *Adv. Fun. Mater.* 16 (2005) 1279.

17. H. Huang, X. Feng and J.-J. Zhu, *Nanotechnology*, 19 (2008) 145607.

Chapter - 5
SOL-GEL TECHNIQUES

L. Hima Kumar

INTRODUCTION

Sol-gel processing generally refers to the hydrolysis and condensation of alkoxide-based precursors. It can produce ceramic and glasses with better purity and homogeneity than high temperature conventional process. Sol-gel process can be used to produce a wide range of oxides in various forms, including powders, fibers, coatings and thin films, monoliths and porous membranes. Organic/inorganic hybrids can also be made, where a gel, usually silica, is impregnated with polymer or organic dyes with specific properties. The advantage of sol-gel method is, metal oxides which are difficult to attain by conventional methods can be produced by using the sol-gel process. Another benefit is that the mixing level of the solution is retained in the final product, often in the molecular scale.

Sol-gel processing proved useful in the manufacturing of stained glass and for the preparation of oxide materials from sol-gel precursors. Sol-gel derived products have numerous applications. One of the promising application areas is for coatings and thin films used in electronics, optical and electro-optical components and devices, such as substrates, capacitors, memory devices, infrared (IR) detectors and wave guides. Antireflection coatings are also used for automotive and architectural applications. Submicron particle size powders of single and multicomponent composition can be made for structural, electronic, dental, and biomedical applications. Composite powders can also be used as agrochemicals or herbicides. Optical and refractory fibers are used for fiber optics sensors and thermal insulation, respectively. In addition, sol-gel techniques can be used to infiltrate fiber performs to make composites. Glass monoliths and coating and organic/inorganic hybrids are under development for lenses, mirror substrates, graded index optics, optical filters, chemical sensors, passive and nonlinear active waveguides, and lasers. Membranes for separation and filtration processes also are being investigated, as well as catalysts. Biomolecules (such as proteins, enzymes, antibodies, etc.) are incorporated into sol gel matrices, which can be used for the monitoring of biochemical processes, environmental testing, food processing, and drug delivery for medicine or agriculture.

Sol-gel process, starting with a metal alkoxide solution and going through various processes and operations until a final product is obtained, such as a dense film, an aerogel, a ceramic fiber was shown in Fig. 5.1.
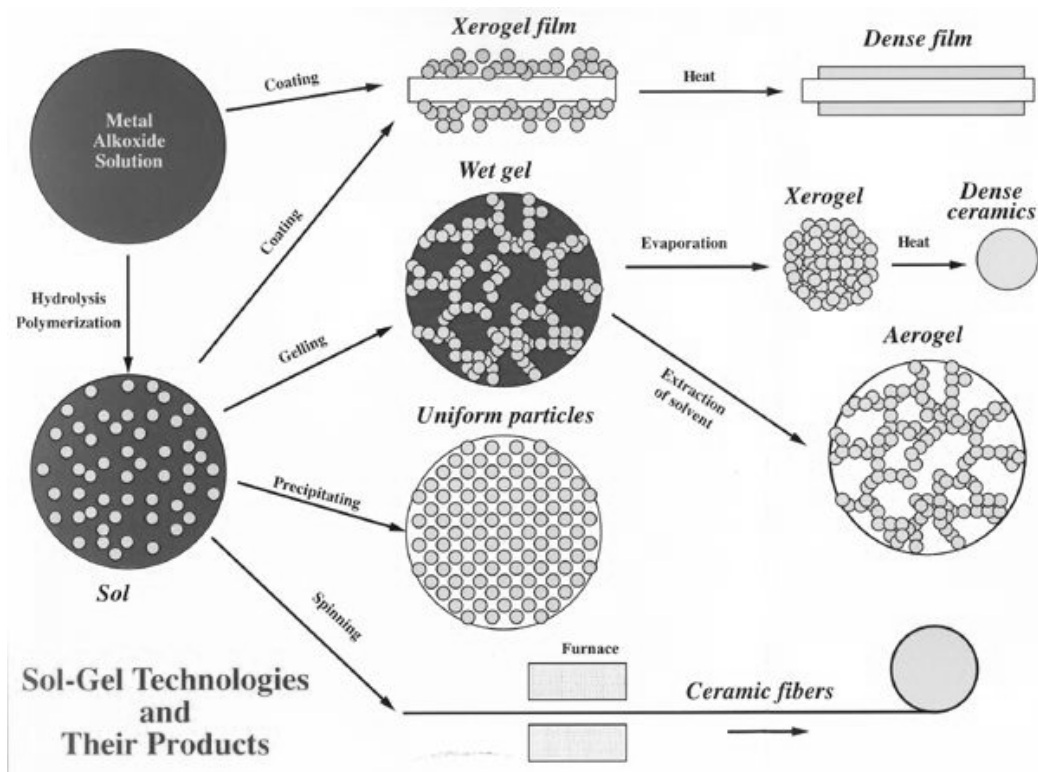
Fig. 5.1 Schematic representation of the sol-gel process (reproduced from http://www.chemat.com/assets/images/Flowchat72.jpg)

DEFINITIONS

A *colloid* is a suspension in which the dispersed phase is so small (~1-1000 nm) that the gravitational forces are negligible and interactions are dominated by short-range forces, such as van der Waals attraction and surface charges.

A *sol* is a colloidal suspension of solid particles in a liquid.

An *aerosol* is a colloidal suspension of particles in a gas.

A *gel* consists of a three dimensional continuous network, which encloses a liquid phase, in a colloidal gel, the network is built from agglomeration of colloidal particles and is limited by the size of container. In a polymer gel the particles have a polymeric sub-structure made by aggregates of sub-colloidal particles. Generally, the sol particles may interact by van der Waals forces or hydrogen bonds. A gel may also be formed from linking polymer chains.

SOL-GEL SYNTHESIS

Sol-gel synthesis is a particular approach to the preparation of glasses and ceramics at low temperatures, which may precede either by the *metallorganic route*, with metal alkoxides in

organic solvents, or by the *inorganic route*, with metal salts (chlorides, oxychlorides, nitrates, etc) in aqueous solution.

GENERAL MECHANISM

Disregarding the nature of the precursors, the sol-gel process can be characterized by a series of distinct steps.

Step 1: Formation of the 'sol' i.e. stable solutions of the alkoxide or solvated metal precursor.
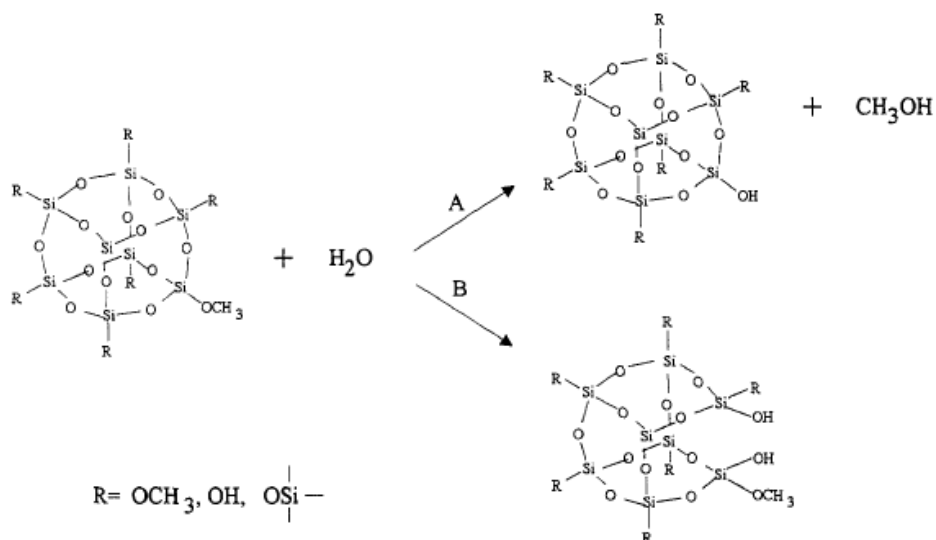
Fig. 5.2. Formation of 'sol' (reproduced form ref. 3)

Step 2: Gelation resulting from the formation of an oxide- or alcohol-bridged network (the *gel*) by a polycondensation or polyesterification reaction that results in a dramatic increase in the viscosity of the solution. If so desired, the gel may be cast into a mold during this step.

Step 3: Aging of the gel, during which the polycondensation reactions continue until the gel transforms into a solid mass, accompanied by contraction of the gel network and expulsion of solvent from the gel pores. Ostwald ripening and phase transformations may occur concurrently with syneresis. The aging process of gels can exceed 7 days and is critical to the prevention of cracks in gels that have been cast.

Step 4: Drying of the gel is, loss of water, alcohol and other volatile components, first as syneresis (expulsion of the liquid as the gel shrinks), then as evaporation of liquid from with in the pore structure with associated development of capillary stress which frequently leads to cracking. This also includes super critical drying, in which capillary stress is avoided by the use of supercritical fluids, such as CO_2, in conditions where there are no liquid/vapor densities. Drying process is complicated due to fundamental changes in the structure of the gel. The drying process has itself been broken into four distinct steps:

(i) Constant rate period, (ii) the critical point, (iii) the first falling rate period, and (iv) the second falling rate period. If isolated by thermal evaporation, the resulting monolith is termed a *xerogel*. If the solvent is extracted under supercritical or near supercritical conditions, the product is an *aerogel*.
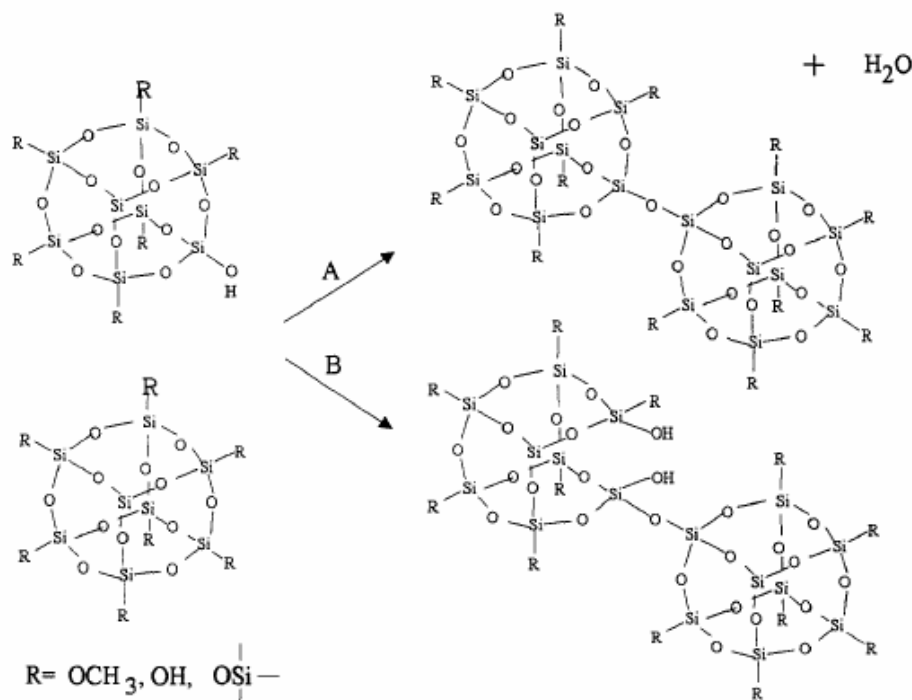
Fig. 5.3. Formation of gel (reproduced form ref. 3)
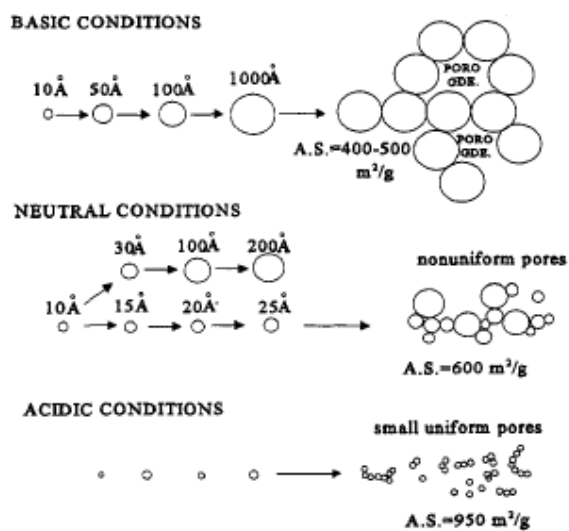
Fig. 5.4. Aging of gel (reproduced form ref. 3)

Step 5: Dehydration, during which surface-bound M-OH groups are removed, thereby stabilizing the gel against rehydration. This is normally achieved by calcining the monolith at temperatures up to 800 °C.

Step 6: Densification and decomposition of the gels at high temperatures ($T > 800$ °C). The pores of the gel network are collapsed, and remaining organic species are volatilized. This step is normally reserved for the preparation of dense ceramics or glasses.
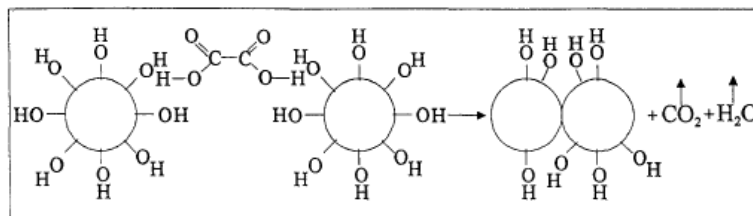
Fig. 5.5. Densification (reproduced form ref. 3)

INORGANIC ROUTE

The growth of metal-oxo polymers in a solvent inorganic polymerization reactions through hydrolysis and condensation of metal alkoxides $M(OR)_Z$, where M = Si, Ti, Zr, Al, Sn, Ce, OR is an alkoxy group and Z is the valence or the oxidation state of the metal, occur in two steps

First step: hydrolysis, Metal cations, M^{z+}, are formed by dissolving metal salts in water, are solvated by water molecules as follows:

$$M^{z+} + hH_2O \quad \rightarrow \quad [M(OH_2)h]^{z+} \quad \text{---(1)}$$
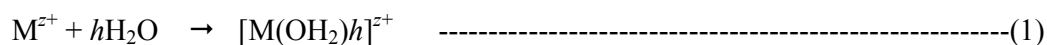
where h is the coordination number of the cation. The electron-transfer weakens the O-H interactions of bound water, and depending on the pH of the solution, various degrees of hydrolysis (deprotonation) can be induced:

$$[M(OH_2)]^{z+} \leftrightarrows [M\text{-}OH]^{(z-1)+} + H^+ \leftrightarrows [M\text{=}O]^{(z-2)+} + 2H^+ \text{----------------------------(2)}$$
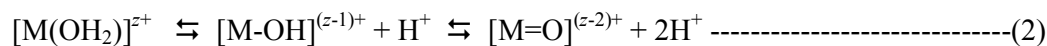
In general, hydrolysis reaction is facilitated by increase in the charge density on the metal, the number of metal ions bridged by a hydroxo or oxo ligand, and the number of hydrogens contained in the ligand. It also affected by the pH. The typical effects of charge and pH are shown in Fig. 5.6, where three domains corresponding to aquo, hrdroxy and oxo ions are

defined. Acidic conditions force the equilibria (Eq. 2) to the left and favor the formation of hydroxo ligands, whereas basic conditions will force the equilibria to the right and favor oxo ligands. The charge on the metal, however, also plays a significant role in the above equilibria with respect to pH, given that highly positive charges on the metals tend to substantially weaken the O-H bonds and favor the formation of oxo ligands.
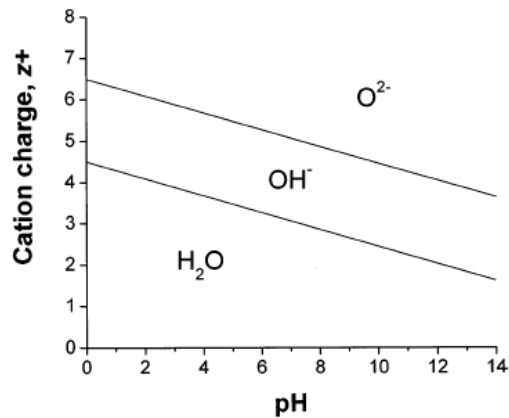
Fig. 5.6. Relationship between charge, pH and hydrolysis equilibrium of cations (reproduced form ref. 1)

Second step: polycondensation process leading to the formation of branched oligomers and polymers with a metal-oxo based skeleton and reactive residual hydroxo and alkoxy groups

M-OH + XO-M $\rightarrow$ M-O-M + XOH ---(3)
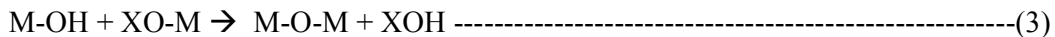
This condensation step occurs by either of the following ways

1. *Olation,* is a condensation in which a hydroxyl bridge is formed.
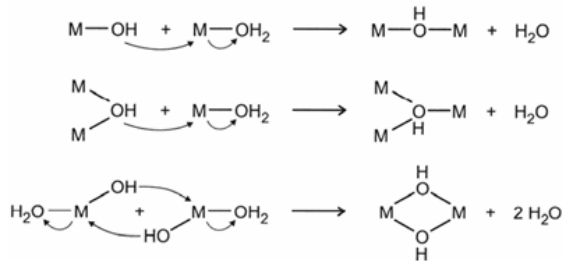
2. *Oxolation*, is condensation in which a oxo (-O-) bridge is formed.
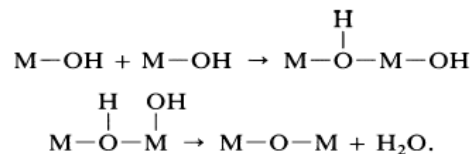
Chemical Reactivity of Metal Alkoxides

The chemical reactivity of metal alkoxides can be examined under acidic and basic conditions, as shown in Fig. 5.7.

- Acid-catalyzed
  - yield primarily linear or randomly branched polymer

- Base-catalyzed
  - yield highly branched clusters
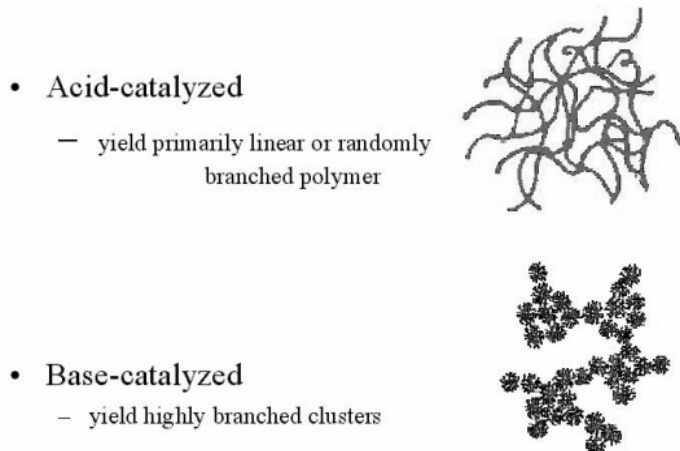
Fig. 5.7. Polymer structures formed in acid or basic environments (reproduced from ref. 1)

As with initial hydrolysis, condensation reactions may be either acid catalyzed or base catalyzed and either cases the reaction proceeds via a rapid formation of charged intermediate by a reaction with a proton or hydroxide ion, followed by slow attack of second neutral silicon species.

Under acidic conditions (e.g. with mineral acids), hydrolysis is faster than condensation, as shown in the following reaction:
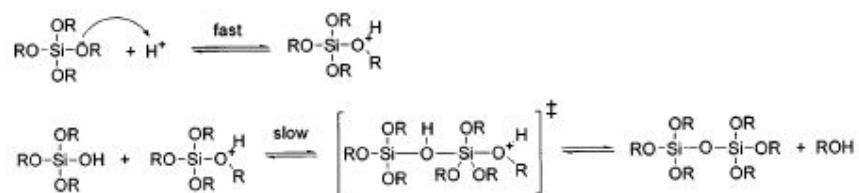
or
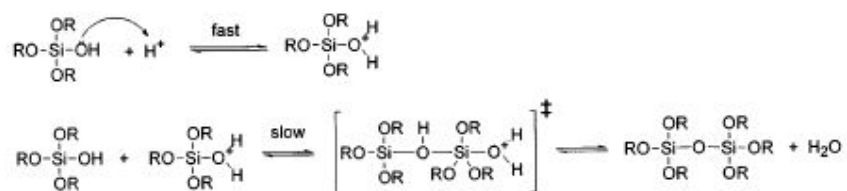
For Si(OR)$_4$-n(OH)$_n$, under acidic conditions (pH < 4), the rate of hydrolysis will always be faster than the rate of condensation due to the ability of -OR groups to better stabilize the transition states. Condensation involves the attack of silicon atoms carrying protonated silanol species on neutral Si-OH nucleophiles. A bushy network of weakly branched polymers is obtained under acidic conditions.

$$\text{RO-Si(OR)}_2\text{-O-R} + \ddot{O}H^- \rightleftharpoons \text{RO-Si(OR)}_2\text{-O}^- + \text{ROH}$$

or

$$\text{RO-Si(OR)}_2\text{-O-H} + \ddot{O}H^- \rightleftharpoons \text{RO-Si(OR)}_2\text{-O}^- + \text{H}_2\text{O}$$

followed by

$$\text{RO-Si(OR)}_2\text{-O}^- + \text{RO-Si(OR)}_2\text{-OH} \rightleftharpoons \left[\text{RO-Si(OR)}_2\text{-O-Si(OR)(RO)-OH}\right]^{\ddagger} \rightleftharpoons \text{RO-Si(OR)}_2\text{-O-Si(OR)}_2\text{-OR} + \text{OH}^-$$
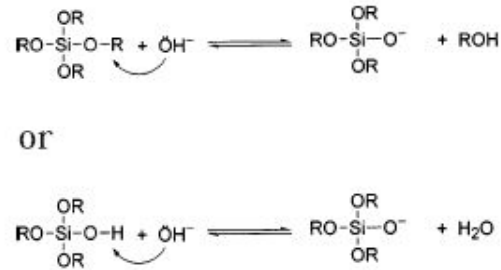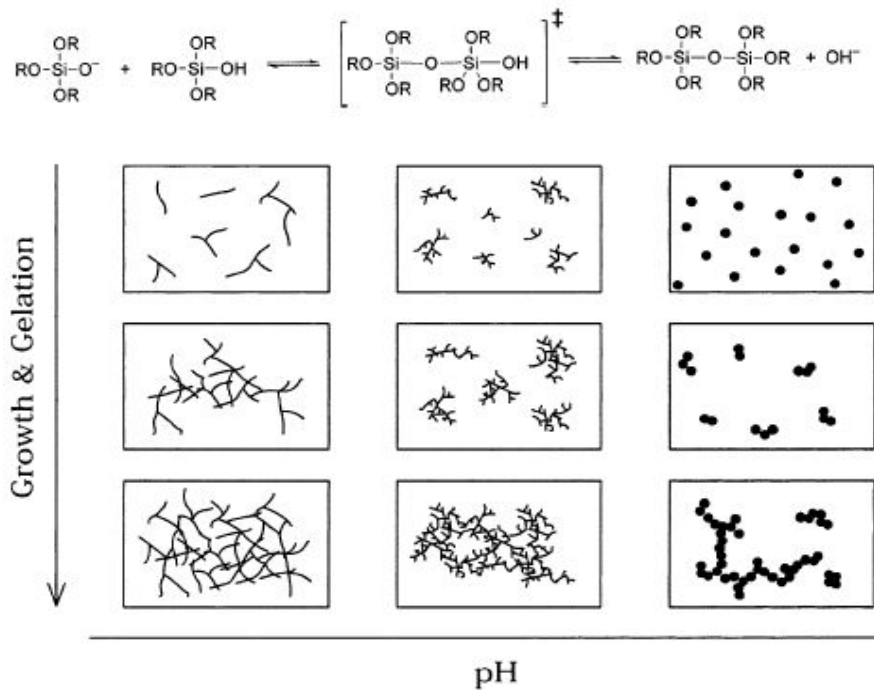
Fig. 5.8. Effect of pH on particle morphology in sol-gel reactions (reproduced from ref. 6)

The result of basic catalysis is an aggregation (monomer cluster) that leads to more compact highly branched silica networks that are not interpenetrable before drying and thus behave as

discrete species. The differences between acid and base catalyzed reactions and the consequences for particle morphology are conceptually represented in Fig. 5.8.

Gelation

Gelation is freezing in a particular structure (i.e. may be considered as a rapid solidification process). Gelation occurs when links form between silica sol particles produced by hydrolysis and condensation, to such an extent that a giant spanning cluster reaches across the containing vessel. In other words, as the sol particles grow and collide, lead to the condensation and then forming macroparticles. The sol becomes a gel when it can support a stress elastically. This is typically defined as the gelation point or gelation time. All subsequent stages of processing depend on the initial structure of the wet gel formed in the reaction bath during gelation. Under acid catalysis polymeric gels are gradually formed, as depicted in Fig. 5.8. Under basic conditions and/or with higher additions of water, more highly branched clusters are formed, which behave as discrete species. If the total concentration of alkoxysilane is low, e.g., < ~0.3 M, gelation leads to formation of colloidal silica (Stoeber process).

Aging

When a gel is maintained in its pore liquid, its structure and properties continue to change long after the gel point. This process is called aging. During aging, four processes can occur, singly or simultaneously, including polycondensation, syneresis, coarsening, and phase transformation.

Polycondensation reactions occur continuously, within the gel network as long as neighboring silanols are close enough to react. This increases the connectivity of the network and its fractal dimension. Usually in alkoxide-based gels, the chemical hydrolysis reaction is rapid, especially, when the sol is acid catalyzed, and is completed in the early stages of sol preparation. Since the chemical reaction is faster at higher temperatures, aging can be accelerated by hydrothermal treatment, which increases the rate of the condensation reaction.

Syneresis is the spontaneous shrinkage of the gel and resulting expulsion of liquid from the pores. Syneresis in alcoholic gel systems is generally attributed to formation of new bonds through condensation reactions, which increases the bridging bonds and causes contraction of the gel network. In aqueous gel systems or colloidal gels, the structure is controlled by the balance between electrostatic repulsion and attractive van der Waals forces. Therefore, the extent of shrinkage is controlled by additions of electrolyte.

Coarsening or Ostwald ripening is the irreversible decrease in surface area through dissolution and reprecipitation processes. Structural changes attributed primarily to surface energy effects. It is well known that surfaces exhibiting positive radii of curvature dissolve more readily than surfaces exhibiting negative radii of curvature. If a gel is immersed in a liquid in which it is soluble, dissolved material will tend to precipitate into regions of negative curvature. Therefore, as the dissolution rate increases, dissolution redeposition results in neck formation, causing the gel structure to become fibrillar and the pore formation. Further, when dissolution is extensive, the gel network would break down and ripen to form a colloidal sol.

During aging, there are changes in most physical properties of the gel. Time, temperature, solvent and pH conditions affect the aging process and lead to structural modifications. Heating the gel in water at 80-100 °C can strengthen the weak gel structure and generally brings about reinforcement, but does not modify the pore structure. The pH of the wash water during the washing of pore liquor out of gel is critical in the case of gels made from acid-catalyzed silicate precursors. The final properties of such gels depend on both the pH at which the gel was formed and the pH at which it was aged before drying.

Drying

Drying is nothing but removing of the solvent phase. The method is influenced by the intended use of the dried material. If powdered ceramics are desired, no special care need be exercised to prevent fragmentation; if monoliths from colloidal gels are desired, the drying procedures are largely determined by the need to minimize internal stresses associated with the volume changes on drying and the capillary forces in the gel pores.

There are three stages of drying:

• During the first stage of drying, the volume change of the gel equals the volume of evaporated liquid. The gel network is still flexible and can rearrange to accommodate the decreasing volume. The compliant gel network is deformed by the large capillary forces, which causes shrinkage of the object. All pores are filled with solvent and no liquid-air interfaces are present. In classical large-pore systems, this first stage of drying is called "the constant rate period" because the evaporation rate per unit area of the drying surface is independent of time. First stage of drying ends when shrinkage stops.

• Second stage of drying begins when the "critical point" is reached (Fig .8). The packing density of the solid phase increases with increasing the strength of the network, and resists further shrinkage. This stage is called critical point. As drying proceeds, the gel network

becomes more restricted and the removal of liquid leads to the formation of such interfaces and the development of capillary stresses. The liquid flows to the surface where evaporation takes place. The flow is driven by the gradient in capillary stress. Because the rate of evaporation decreases in second stage, classically this is termed "the first falling rate period'.
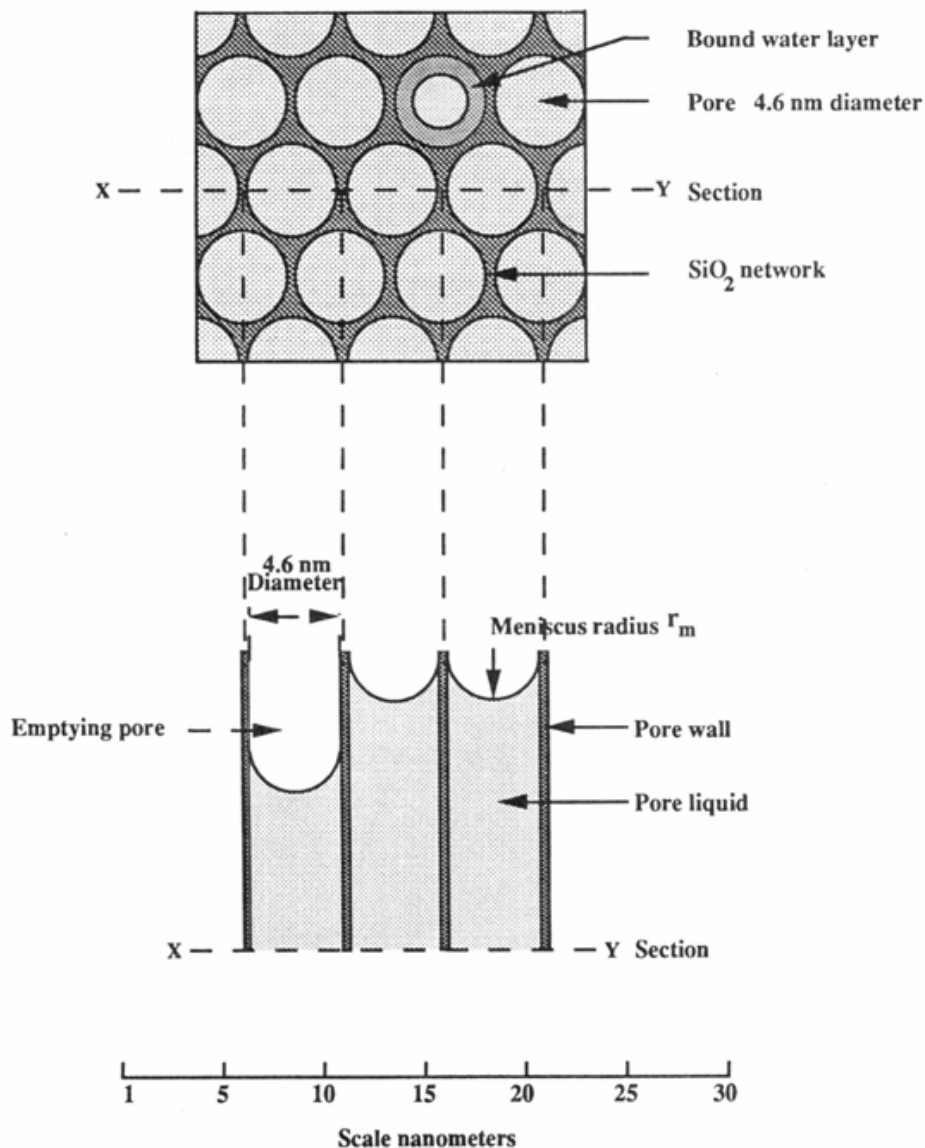
Fig. 5.9. Schematic representation of gel surface at the end of first stage (critical point) (reproduced from ref. 4)

•   When the pores have substantially emptied, surface films along the pores cannot be sustained. This is third stage of drying, which is also called as "second falling rate period". The remaining liquid can escape only by evaporation from within the pores and diffusion of vapor to the surface. During this stage, there are no further dimensional changes but just a

slow progressive loss of weight until equilibrium is reached, determined by the ambient temperature and partial pressure of water.

- The capillary pressure, P, developed in a cylindrical capillary of radius r, partially filled with a liquid of wetting angle α, can be expressed by:

$$\Delta P = \frac{2\gamma}{r} \cos \alpha$$

where γ is the surface tension. When evaporation leads to the formation of menisci, the different radii of the pores cause unequal capillary pressures to generate differential stresses. If the stress difference locally exceeds the strength of the gel network, a crack will result (drying failure). When the gel has had insufficient aging and strength, does not possess the dimensional stability to withstand the increasing compressive stress and leads to cracking in the first stage. Most failure of drying occurs during the early part of second stage, the point at which the gel stops shrinking. This is the point at which the meniscus falls below the surface.

Generally, fractures associated with excessive capillary forces can be eliminated or reduced by one or more of the following proceedings:

- strengthening the gel by reinforcement
- enlarging the pores
- reducing the surface tension of the liquid with surfactants
- making the interior surfaces hydrophobic
- evacuating the solvent by freeze-drying
- Operating under hypercritical conditions.

Xerogel and Aerogel Formation

As a gel is evaporated to dryness either by thermal evaporation or supercritical solvent extraction, the gel structure changes in some cases substantially. During thermal drying or room-temperature evaporation, capillary forces induce stresses on the gel that increases the coordination numbers of the particles and induces collapse of the network. The increase in particle coordination numbers results in the formation of additional linkages that strengthen the structure against further collapse and eventually leads to the formation of a rigid pore structure. The structure of the resulting xerogel can therefore be considered a collapsed, highly distorted form of the original gel network.

The supercritical extraction of solvent from a gel does not induce capillary stresses due to the lack of solvent-vapor interfaces. As a result, the compressive forces exerted on the gel

network are significantly diminished relative to those created during formation of a xerogel. Aerogels consequently retain a stronger resemblance to their original gel network structure compared to xerogels (Fig. 5.10).

GEL PRECURSOR   AEROGEL

Δ
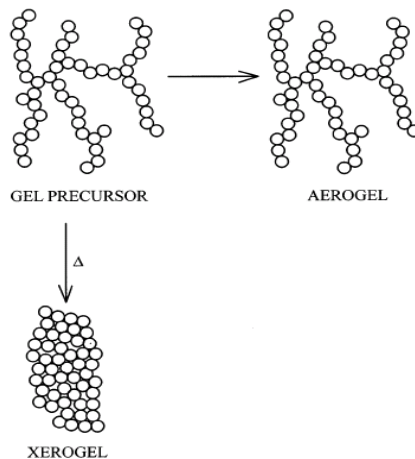
XEROGEL

Fig. 5.10. Structural relationship between a sol-gel precursor, a xerogel, and an aerogel (reproduced from ref. 6)

Densification

Densification is the last treatment process of gels during which the dried gel is heated to convert into a dense ceramic. The sintering of gels, where the pore network is collapsed and organic species are volatilized, is a critical factor in determining the size and morphology of the sol-gel product. For silica gels, the following reactions occur during the densification:

- desorption of physically adsorbed solvent and water from the walls of micropores (100-200 °C)
- decomposition of residual organic groups into $CO_2 + H_2O$ (300- 500 °C)
- collapse of small pores (400-500 °C)
- collapse of larger pores (700-900 °C)
- continued polycondensation (100-700 °C)

If powdered ceramics are desired, no need to take care to prevent fragmentation. Attention must, however, be directed to the removal of organics to avoid undesirable bloating, foaming or blackening. Where as, for monoliths preparation, special care must be taken to ensure complete removal of water, organic groups or decomposition products, prior to micropore collapse to avoid the development of stresses leading to fragmentation for the production of large monoliths of SiO_2.

Sintering and densification phenomena also take place, via typical sintering mechanisms such as evaporation condensation, surface diffusion, and grain boundary and bulk diffusion. The small particle size of the powders lead to high reactivities and enhanced sintering and/or coarsening rates (the principal process involved in densification is often viscous sintering). As illustrated in Fig. 5.11, densification of a gel network occurs between 1000 and 1700 °C depending upon the radii of the pores and the surface area. Fig. 5.11, describes the overall development of a sol-gel process for glass in relative time and temperature scales. This schematic representation summarizes from establishment of a sol condition to formation of a dense material.
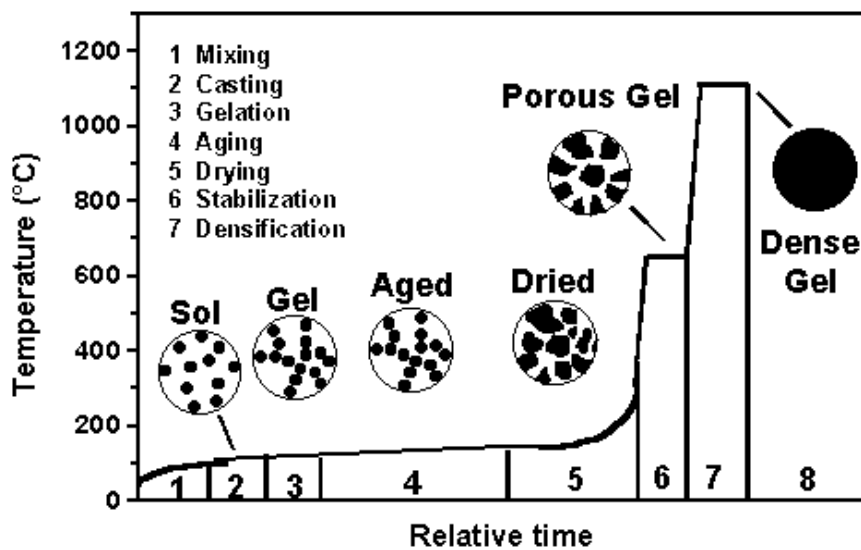
Fig. 5.11. Time vs. Temperature dependence in a sol-gel process
(reproduced from ref. 4)

APPLICATIONS

Monoliths

The physical properties of gel-derived glasses are usually closely similar to those of glasses obtained from the melt. Gel-derived powders are used as batch ingredients for glass melting primarily because of the high degree of chemical homogeneity they offer. This leads to shorter melting times and lower melting temperature as well as compositional uniformity. The key to glass formation is the development of an appropriate heat treatment schedule to remove the residual organic groups and achieve pore collapse without inducing crystallization in the sample. The most attractive feature is the development of novel glass compositions: $CaO\text{-}SiO_2$ or $Na_2O\text{-}ZrO_2\text{-}SiO_2$ with high ZrO_2 content, which is impossible to obtain from the melt, because the cooling rate must

be high to avoid detectable crystallization. Monoliths are defined as bulk gels cast to shape and processed without cracking. Monolithic gels are potentially interesting because complex shapes may be formed at room temperature and consolidated at rather low temperatures with out melting. The principle applications of monoliths are optical ones: fiber optic preforms, lenses and other near-net-shape optical components, graded refractive index glasses and transparent foams (Aerogels) used as Cherenkov detectors and as super insulation.

Fibers

Fibers can be drawn directly from polymer sols by controlling the viscosity of acid catalyzed alkoxide gels. A key to prevent premature gelation is to maintain water at a lower level. High viscosity stabilizes the fibers against spheroidization during the drawing operation. Both silica and titania fibers have been obtained at near room temperature, but without sintering, they remain porous and contain some unreacted alkoxide. The porosity decreases with increasing temperature. Sol-gel method using metal alkoxide as precursor has been applied to the preparation of oxide glass fibers other than SiO_2. Fibers produced by sol-gel processing are an interesting application for the manufacture of optical waveguides (A device that constrains or guides the propagation of electromagnetic radiation along a path defined by the physical construction of the guide is called waveguide). The dispersion-casting technique produces silica fibers with optical loses of about 3.5 dB/km.

Thin films and coatings

Thin films and coatings were the first commercial application of sol-gel processing technology. Films are applied either by dip coating or spin coating techniques, using polymeric alkoxide sols. By controlling the precursor chemistry and deposition conditions, pore size, porosity, surface area, and refractive index of the films can be controlled. Large substrates may be accommodated and it is possible to uniformly coat both sides of planar and axially symmetric substrates such as pipes, tubes, rods and fibers.

Generally, ceramics are more resistant than metals to oxidation, corrosion, erosion and wear. Moreover, they can have good thermal and electrical properties that make them particularly interesting as coating materials. Ceramic coatings are usually deposited on metals for improving their performances in high temperature aggressive environments. Some important applications, include improving resistance against gas, solid, condensed, and molten-phase corrosion, to localized overheating and melting; decreasing fretting and wear; decreasing heat losses and/or reflecting radiations in high temperature systems.

A major development was the formation of multiple transparent layers that produce a gradual change in refractive index from the air interface to that of the substrate. Antireflection coatings are also a vast application of the sol-gel technique, for example, in store front windows, to allow light transmission but reduced glare. Such coatings are also used in solar cells and laser optics. A head up display is a unique application of these coatings: by controlling the reflectance to transmission ratio, the speed of the automobile can be displayed at eye level on the windshield, without distorting the field of view. The driver no longer needs to shift his eyes to the instrument panel.

Electrochromic devices

Active electronic thin films include high temperature superconductors, conductive indium tin oxide (ITO) and vanadium pentoxide, and ferro electric barium and lead titanates, electrochromic tungsten oxide, and titania films used as phtotoanodes. Solid state electrochromic (EC) devices for smart windows, large area displays and automotive rearview mirrors are of considerable technological and commercial interest.
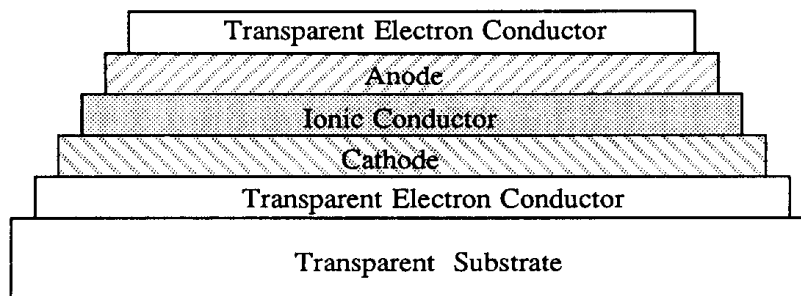
Fig. 5.12. Schematics of an EC window device deposited on one substrate. The electrochromic layer is anode, cathode or both (reproduced from ref .7).

Controlled modulation of solar radiation through smart windows has a large potential in buildings for energy savings and in automobiles to increase occupant comfort while reducing air conditioning requirements. Typically these devices consist of multiple layer stacks that are sequentially vacuum deposited or are laminate constructions. Sol-gel processing offers advantage in depositing films containing multiple cations and controlling the microstructure. These parameters can influence the kinetics, durability, coloring efficiency and charge storage in the electrochromic films (electrodes). A typical structure of a solid state electrochromic window is shown in Fig. 5.12.

    Other applications of sol-gel techniques include

- Synthesis of carbides sulphides and nitrides

- Synthesis of nanocomposites

- Synthesis of powders, grains and spheres

- Catalysis (Mesoporous materials)

- Preparing solid electrolytes

- Absorbing coatings

- Filters for lighting and optical purposes

- Semiconducting coatings

- Protective layers (both chemical and thermal)

- Scratch resistant coating

- Embedding organic molecules (hybrid organic-inorganic materials)

- Flammable gas sensors

- Porous gels and membranes

REFERENCES

1. C. J. Brinker, and G. W. Scherer, Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing, Academic Press Inc., New York, 1989.

2. J. D. Wright and N.A.J.M Sommerdijk, Sol-gel materials chemistry and applications, vol.4, Taylor & Francis Books Ltd., London, 2001.

3. R. D. Gonzalez, T. Lopez and R. Gomez, Sol-Gel preparation of supported metal catalysts. Catalysis Today, 35 (1997) 293.

4. L. C. Klein, (Ed.), Sol-Gel Optics: Processing and Applications, Kluwer Academic Publishers, Boston, 1993.

5. L.L. Hench and J.K. West, The sol-gel process. Chem. Rev., 90 (1990) 33.

6. B. L. Cushing, V.L. Kolesnichenko and C.J. O'Connor, Recent Advances in the Liquid-Phase Syntheses of Inorganic Nanoparticles. Chem. Rev., 104 (2004) 3893.

7. A. Agrawal, J.P. Cronin and R. Zhang, Review of solid state electrochromic coatings produced using sol-gel techniques. Solar Energy Materials and Solar Cells, 31 (1993) 9.

Chapter - 6

TEMPLATE BASED SYNTHESIS

B.Kuppan

INTRODUCTION

To make a jar, a piece of wood of the desired shape is first fabricated, and layer of clay is applied to the wood. Heat treatment of the clay/wood composite at high temperature generates a ceramic jar. During the heat treatment, clay is transformed to a ceramic material and the wood is burned off leaving the empty space in the resulting jar. When this process is scale down to nanometer regime, it is basically the template synthesis process [1].
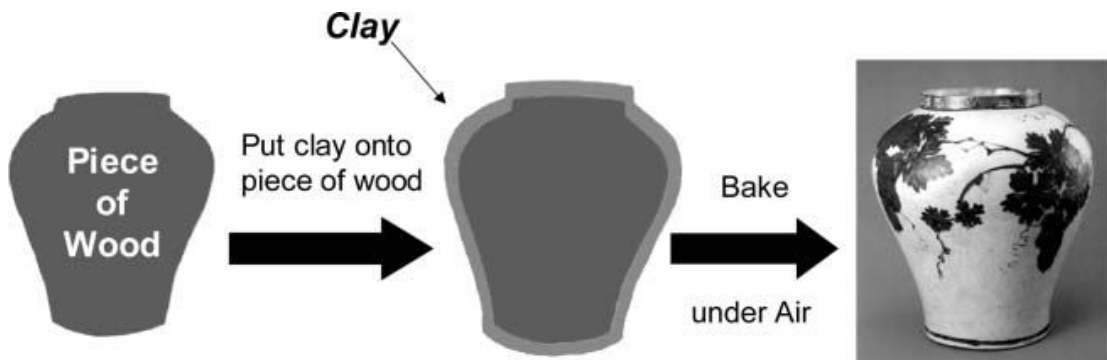
Fig. 6.1. Schematic representation of template synthesis (reproduced from ref. 1)

One class of templates are surfactants that are used to produce mesoporous materials. It is true to say one of the most exciting discoveries in the field of material synthesis over the last 15 years is the formation of mesoporous silicate and alumino silicate molecular sieves with liquid crystal templates. This family materials generally called as M41S family (MCM-41, MCM-48 and MCM-50) [2]. These M41S family materials can be prepared by using cationic surfactants as the templates, and other kind of mesoporous materials also can be prepared by using non-ionic surfactants as the templates. These family materials are called as SBA-n family [3].

The above mentioned mesoporous molecular sieves also can be used as templates to prepare ordered mesoporous carbon by using sucrose as the carbon precursors. These mesoporous silicates, aluminosilicates and mesoporous carbon materials are

more important in the field of catalysis because of its high surface area, narrow pore size distribution and large number of surface functional groups. The surfaces of these materials can also be tuned depending on the applications.

Another kind of template based synthesis is to prepare freestanding, non-oriented and oriented nanowires, nanorods or nanotubes. The fabrication of metal nanowires had potential applications in the microelectronic industry and in particular, for interconnection in electronic circuits. The procedure is based on metal displacement reaction leading to the growth of metal nanowires into the pores. The galvanic displacement reaction for the synthesis of core /sheet nanostructured materials has been investigated in the literature [4].

Nanostructured materials have attracted much interest because of their unique properties. In fact, due to their structure features and size effects, they show physical properties that are different from bulk materials. Many methods have been developed for the fabrication of nanowires. Among these methods template synthesis is considered as quite useful, because it can be used for the preparation of different types of nanostructures. The high order degree of porous structure of anodic alumina membrane (AAM) (consisting in a close packed array of columnar hexagonal cells, each containing a central cylindrical pore normal to the surface), makes it an ideal template for the fabrication of nanostructured materials, suitable for applications in optoelectronics, sensors, magnetic memories and electronic circuits [5].

Synthesis, Mechanism and Pathway

A large number of studies have been carried out to investigate the formation and assembly of mesostructures on the basis of surfactant self-assembly. The initial liquid crystal template mechanism first proposed by Mobil's scientists is essentially always "true" because the pathways basically include almost all possibilities. Two main pathways that is cooperative self assembly and "true" liquid –crystal templating process, seems to be effective in the synthesis of ordered mesostructures.

Surfactants for the formation of templates

The term surfactant is a blend of "surface acting agent" surfactants are usually organic compounds that are amphophilic in nature. Amphophilic means they contain

both hydrophobic groups (tails) and hydrophilic groups (heads). Therefore they are soluble in both organic solvents and water.

Generally a clear homogeneous solution of surfactants in water is required to get ordered mesostructures. Frequently used surfactants can be classified into cationic, anionic and non-ionic surfactants.

Table 6.1. Cationic surfactants

Alkyltrimethyl quaternary ammonium surfactant	$H_3C-(CH_2)_{n-1}-\overset{+}{N}(R_1)(R_2)(R_3)\ [Br^-]$ $R_1, R_2, R_3 = CH_3, C_2H_5, C_3H_7$ $n = 8 - 22$ $H_3C-(CH_2)_{n-1}-\overset{+}{N}(CH_3)(CH_3)-(CH_2)_{m-1}-CH_3\ [Br^-]$ $n = 8 - 22;\ m = 2 - 22$ $H_3C-(CH_2)_{n-1}-\overset{+}{N}(CH_3)(CH_3)-(CH_2)_m-R\ [Br^-]$ $R = -\!\bigcirc,\ -\!\bigcirc\!N, -OH,\ etc$ $n = 8 - 22;\ m = 0 - 3$
Gemini surfactant ($C_{n\text{-}s\text{-}m}$)	$H_3C-(CH_2)_{n-1}-\overset{+}{N}(CH_3)(H_3C)-(CH_2)_s-\overset{+}{N}(CH_3)(CH_3)-(CH_2)_{m-1}-CH_3\ [2Br^-]$ $n = 8 - 22;\ s = 2 - 6;\ m = 1 - 22$
($C_{n\text{-}s\text{-}1}$)	$H_3C-(CH_2)_{n-1}-\overset{+}{N}(CH_3)(H_3C)-(CH_2)_s-\overset{+}{N}(CH_3)(CH_3)-CH_3\ [2Br^-]$ $n = 8 - 22;\ s = 2 - 6$
($18B_{4\text{-}3\text{-}1}$)	$H_3C-(CH_2)_{17}-O-\bigcirc-O-(CH_2)_4-\overset{+}{N}(CH_3)(CH_3)-(CH_2)_3-\overset{+}{N}(CH_3)(CH_3)-CH_3\ [2Br^-]$
Bolaform surfactant (R_n)	$(H_3C)(H_3C)(H_3C)\overset{+}{N}-(CH_2)_n-O-\bigcirc-\bigcirc-O-(CH_2)_n-\overset{+}{N}(CH_3)(CH_3)-CH_3\ [2Br^-]$ $n = 4, 6, 8, 10, 12$
Tri-headgroup cationic surfactant ($C_{m\text{-}s\text{-}p\text{-}1}$)	$H_3C-(CH_2)_m-\overset{+}{N}(CH_3)(H_3C)-(CH_2)_s-\overset{+}{N}(CH_3)(CH_3)-(CH_2)_p-\overset{+}{N}(CH_3)(CH_3)-CH_3\ [3Br^-]$ $m = 14, 16, 18;\ s = 2;\ p = 3$
Tetra-headgroup rigid bolaform surfactant ($C_{n\text{-}m\text{-}m\text{-}n}$)	$(H_3C)(H_3C)(H_3C)\overset{+}{N}-(CH_2)_n-\overset{+}{N}(CH_3)(CH_3)-(CH_2)_m-O-\bigcirc-\bigcirc-O-(CH_2)_m-\overset{+}{N}(CH_3)(H_3C)-(CH_2)_n-\overset{+}{N}(CH_3)(CH_3)-CH_3\ [4Br^-]$ $n = 2, 3, 4;\ m = 8, 10, 12$

Quaternary cationic surfactants, $C_nH_{2n+1}N$ $(CH_3)_3Br$ (n = 8-22), are generally efficient for the synthesis of ordered mesoporous silicate materials. Commercially available CTAB (cetyltrimethylammonium bromide) is often used. Gemini surfactants, multiheadgroup surfactants, and recently reported cationic fluorinated surfactants can also be used as templates to prepare various mesostructures. Frequently used cationic quaternary ammonium surfactants are shown in the table below

First reports of mesoporous silica from Mobil's company, cationic surfactants were used as structure directing agents (SDAs). Cationic surfactants have excellent solubility, have high critical micelle temperature (CMT) values and can be widely used in acidic and basic media. But they are toxic and expensive.

Anionic surfactants include carboxilates, sulphates, sulfonates, and phosphates; recently a kind of lab-made anionic surfactant terminal carboxylic acids is used to template the synthesis of mesoporous silicas with the assistance of aminosilanes or quaternary aminosilanes such as 3-aminoprpoyltrimethoxysilane (APS) N-trimethoxylsilylpropyl-N, N, N-trimethylammonium chloride (TMAPS) as co-structure directing agents (CSDAs).

Anionic surfactants

C_nGluA (M = H   R = C_nH_{2n+1})
C_nGluS (M = Na   R = C_nH_{2n+1})

C_nAlaA (M = H   R = C_nH_{2n+1})
C_nAlaS (M = Na   R = C_nH_{2n+1})

C_nGlyA (M = H   R = C_nH_{2n+1})
C_nGlyS (M = Na   R = C_nH_{2n+1})

$C_nH_{2n+1}AM$

A = COO, OSO_3, SO_3, OPO_3
M = H, Na, K

n = 8 − 18
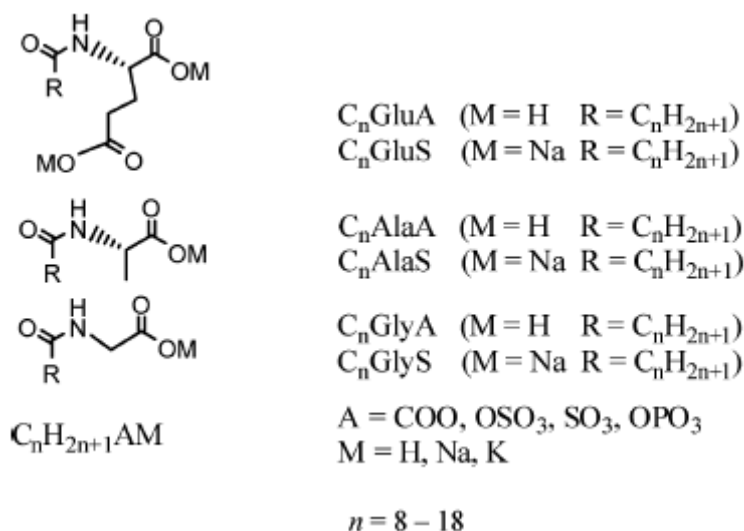
Fig. 6.2.   Representation of anionic surfactants (reproduced from ref. 7)

Table 6.2. Non-ionic surfactants (reproduced from ref. 7)

Non-ionic surfactants are available in a wide variety of different chemical structures. They are widely used in industry because of attractive characteristics like low price, nontoxicity, and biodegradability. In addition the self assembling of non-ionic surfactants products mesophase with different geometries and arrangements. They become more and more popular and powerful in the syntheses of mesoporous solids. The syntheses that largely promote the development of mesoporous materials are simple and reproducible. A family of mesoporous silica materials has been prepared with various mesoporous packing symmetries and well defined pore connectivity.

Cooperative Self-Assembly of Surfactant and Silica Source to Form Mesostructure

This pathway is established on the basis of the interaction between the silicates surfactants to from inorganic-organic mesostructure composites.

Cooperative Self-Assembly Mechanism
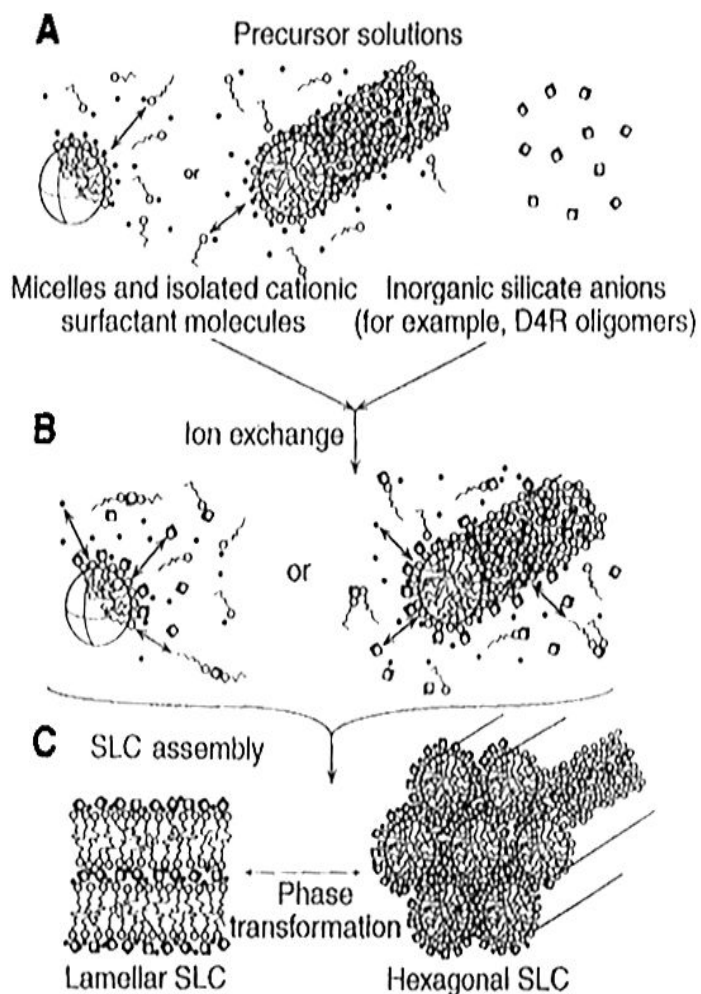
Fig. 6.3. schematic diagram of the co-operative self assembly of silicate-surfactant mesophase. (reproduced from ref. 6)

A layer to hexagonal mechanism (folded sheet mechanism) was postulated by Kuroda and co-workers, according to which the mesostructure is created from a layer kanemite precursors. Silicate polyanions such as silicate oligomers interact with positively charged groups in cationic surfactants driven by Coulomb forces. The silicate species at the interface polymerized and cross-link and further change the

charge density of the inorganic layers. With the proceeding of the reaction, the arrangement of the surfactants and the charge density between inorganic and organic species influence each other. Hence the compositions of the inorganic-organic hybrids differ to some degree. It is the matching of charge density at the surfactants/inorganic species interfaces that govern the assembly process. The final mesosphere is the ordered 3D arrangement with the lowest interface energy. The transformation of the isotropic micellar solutions of CTAB into hexagonal or lamellar phase when mixed with anionic silicate oligomers in highly alkaline solutions were indeed detected through a combination of correlated solution state ^{2}H, ^{13} C, and ^{29}Si nuclear magnetic resonance (NMR) spectroscopy, small angle x-ray scattering (SAXS), and polarized optical microscopic measurements. The mechanism in different surfactant systems has been studied using NMR technique.

This cooperative formation mechanism in non-ionic surfactant system was investigated by *in-situ* techniques. Goldfarb and co-workers investigated the formation mechanism of mesoporous silica SBA-15, which are templated by triblock copolymer P123 ($EO_{20}PO_{20}EO_{20}$)   by using direct imaging and freeze-fracture replication cryo-TEM techniques, *in situ* electron paramagnetic resonance (EPR) spectroscopy, and electron spin-echo envelope modulation (ESEEM) experiments. They found a continuous transformation from speriodial micelles into threadlike micelles. Bundles were then formed with dimension that are similar to those found in the final materials. The elongation of micelles in a consequence of the reduction of polarity and water contact within the micelles due to the adsorption and polymerization of silicate species. Before the hydrothermal treatment, the majority of PEO chains insert into silicate frameworks, which generates micropores after removal of templates. Moreover they found that the extent of the PEO chains located within the silica micropores depended on the hydrothermal aging temperature and Si/P123 molar ratio. The formation dynamics of SBA-15 studied by Flodstrom et al. on the basis of time-resolved *in situ* ^{1}H NMR and TEM investigations. They observed four stages during the cooperative assembly, which are the adsorption of silicates on globular micelles, the association of globular micelles into floes, the precipitation of floes, and the micelle-micelle coalescence. Khodakov et al. proposed a structure with

a hydrophobic PPO core and a PEO –water –silicate corona in the first stage. The cylindrical micelles pack into the domains. At the same time, solvents are replaced by condensed silicate species.

These mechanisms consider the interactions on the surfactants/inorganic species interfaces. Monnier and Huo et al. gave a formula of the free energy in the whole process.

$$\triangle G = \triangle G_{inter} + \triangle G_{wall} + \triangle G_{intra} + \triangle G_{sol}$$

In which $\triangle G_{inter}$ associated with interaction between the inorganic walls and surfactant micelles, $\triangle G_{wall}$ is the structural free energy for the inorganic frameworks, $\triangle G_{intra}$ is the van der Waals force and conformational energy of the surfactant, and $\triangle G_{sol}$ is the chemical potential associated with the species in solution phase.

For surfactant-templating assembly mesostructured silicates, $\triangle G_{sol}$ can be regarded as a constant in a given solution system. Therefore, the key factor is the interaction between surfactant and inorganic species, such as the matching of charge density. The more negative $\triangle G_{inter}$ is, the more easily the assembly process can be proceeded.

Elaborate investigations on mesoporous materials have been focused on understanding and utilizing the inorganic-organic interactions. Table 6.3 lists the main synthesis routes and the corresponding surfactants and classical products.

Stucky and co-workers proposed four general synthetic routes, which are S^+I^-, S^-I^+, $S^+X^-I^+$, and $S^-X^+I^-$ (S^+ = surfactant cations, S^- = surfactant anions, I^+ = inorganic precursors cations, I^- = inorganic precursors anions, X^+ = cationic counter ions, and X^- = anionic counterions). To yield mesoporous materials, it is important to adjust the chemistry of the surfactants headgroups, which can fit the requirement of the inorganic components. Under basic conditions, silicate anions (I^-) match with the surfactant cations (S^+) through Coulomb forces (S^+I^-). The assembly of the polyacid anions and surfactant cations to "salt"-like mesostructures also belongs to S^+I^- interaction. In contrast to this, one of the examples of S^+I^- interaction occurs between cationic keggin ion (Al_{13}^{7+}) and anionic surfactants like dodecyl benzenesulfonate salt.

The organic-inorganic assembly of surfactants and inorganic precursors with the same charge is also possible. However, counter ion is necessary. For example, in the syntheses of mesoporous silicates by the $S^+X^-I^+$ interaction, S^+ and I^- are cationic surfactants and inorganic anionic precursors, and X^- can be halogen ions (Cl^-, Br^-, and I^-), SO_4^{2-}, NO_3^-, etc. In strongly acidic medium, the initial $S^+X^-I^+$ interaction through Coulomb forces or more exactly, double-layer hydrogen bonding interaction, gradually transforms to the $(IX)^-S^+$ one. It was the first time that the mesoporous silica was synthesized under a strongly acidic condition. Here anions affect the structures, regularity, morphologies, thermal stability, and properties of mesoporous silicas. The Hofmeister series of the anions are one of the possible reasons that change the hydrolysis rates of the silicate precursors and the micellar structures. Schematic illustration of the two types of interactions between APS (A) or TMAPS (B) and anionic surfactant headgroups.
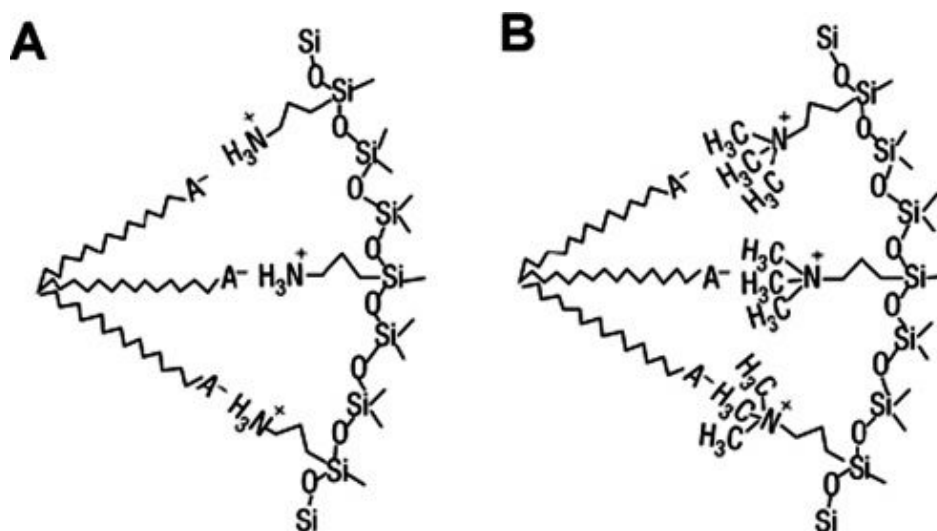
Fig. 6.4. interactions between APS (A) or TMAPS (B) and anionic surfactant headgroups (reproduced from ref. 7)

Compared with those cationic surfactants, the repulsive interaction between anionic surfactants and silicate species fails to organize ordered mesostructures. Concerning the charge matching effect, Che et al. demonstrated a synthetic route to create a family of mesoporous silica structures under basic conditions by employing anionic

surfactants as SDAs APS or TMAPS as CSDAs. This route can be described as an "S^- N^+I^-" pathway, where N^+ are cationic amino groups of organoalkoxysilanes. Fig. 6.4 gives the schematic illustration of interactions between amino groups and anionic surfactant head groups. The negatively charged headgroups of the anionic surfactants interact with the positively charged ammonium sites of APS or TMAPS electrostatic ally through neutralization. The most efficient surfactant is possibly terminal carboxylic acid. The co-condensation of tetraethylorthosillane (TEOS) with APS or TMAPS and assembly with surfactants occur to form the silica framework.

Table 6.3. Synthesis Routes to Mesoporous Materials with the Emphasis on Silicates (reproduced from ref.7)

route	interactions	symbols	conditions	classical products
S^+I^-	electrostatic Coulomb force	S^+, cationic surfactants I^-, anionic silicate species FDU-2, FDU-11	basic	MCM-41, MCM-48 MCM-50, SBA-6 SBA-2, SBA-8 FDU-13
S^-I^+	electrostatic Coulomb Force	S^-, anionic surfactants I^+, Transition metal ions	aqueous	mesoporous alumina
$S^+X^-I^+$	electrostatic Coulomb force, double layer H bond	S^+, cationic surfactants I^+, cationic silicate species X^-, Cl^-, Br^-, I^-, SO_4^-, NO_3^-	acidic	SBA-1, SBA-2 SBA-3
$S^-N^+I^-$	electrostatic Coulomb	S^-, anionic surfactants N^+, cationic amino groups	basic	ASM-n

	Force	I^-, anionic silicate species		
$S^-X^+I^-$	electrostatic Coulomb force, double layer H bond	S^-, anionic phosphate surfactants; I^-, transition metal ions, X^+, Na^+, K^+, $Cr3^+$, Ni^{2+}	basic	W, Mo oxides
S^oI^o	H bond	S^o, nonionic surfactants	neutral	HMS, MSU, disordered
(N^oI^o)		N^o, organic amines; I^o, Silicate species, aluminate species		Worm-like mesoporous silicates
$S^oH^+X^-I^+$	electrostatic Coulomb Force, double, layer H bond	S^o, nonionic surfactants; I^+, silicate species; X^-, Cl^-, Br^-, I^-, SO_4^{2-}, NO_3^{-1}	acidic	SBA-n (n=11, 12, 15, 16) FDU-n (n=1, 5) KIT-5 and KIT-6
$N^o...I^+$	coordination bond	N^o, organic amines; I^+, transition metal	acidic	Nb, Ta oxides
S^+-I^-	covalent bond	S^+, cationic surfactants; I^-, silicate species	basic	mesoporous silica

Liquid Crystal Template Pathway

In this pathway true or semi-liquid crystal mesophases are involved in the surfactant assembly to synthesize ordered mesoporous solids. Attard and co-workers synthesized mesoporous silicas using high concentrations of non-ionic surfactants as

templates. The condensation of inorganic precursors is improved owing to the confined growth around the surfactants and thus ceramic-like frameworks are formed. After the condensation, the organic templates can be removed by calciation, extraction, etc. The inorganic materials "cast" the mesostuructures, pore sizes, and symmetries from the liquid crystal scaffolds. Direct templating of microemulsion liquid-crystal mesophases were used to synthesis mesoporous silicas from butanol-water-copolymer –silica ternary system [6, 7].

Silica/surfactant = 1/0.27

As-synthesized MCM-41
(hexagonal structure)

calcination

MCM-41

Silica/surfactant = 1/0.60

As-synthesized MCM-48
(cubic structure)

calcination

MCM-48
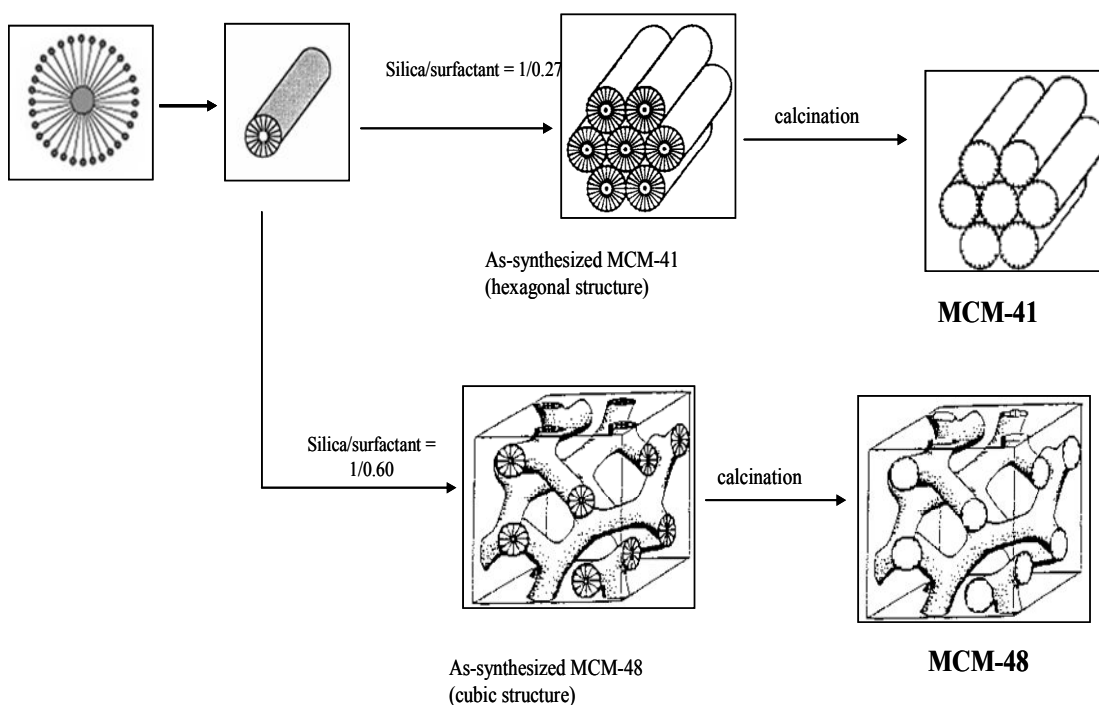
Fig. 6.4. possible mechanism pathways for the formation of M41S family by liquid crystal template method (reproduced from ref. 2).

Evaporation Induced Self Assembling Techniques (EISA)

Evaporation induced self-assembly mechanism

The evaporation induced self assembling technique is one of the best techniques to prepare the nanomaterials. The successful synthesis of mesoporous silica films, the EISA method is engaged to prepare ordered mesoporous polymer and carbon materials. The EISA method is strategy that avoids the cooperative assembling

process between the precursors and the surfactant template. Therefore, the cross-linking and thermopolymerization process of the resols separate from the assembly.
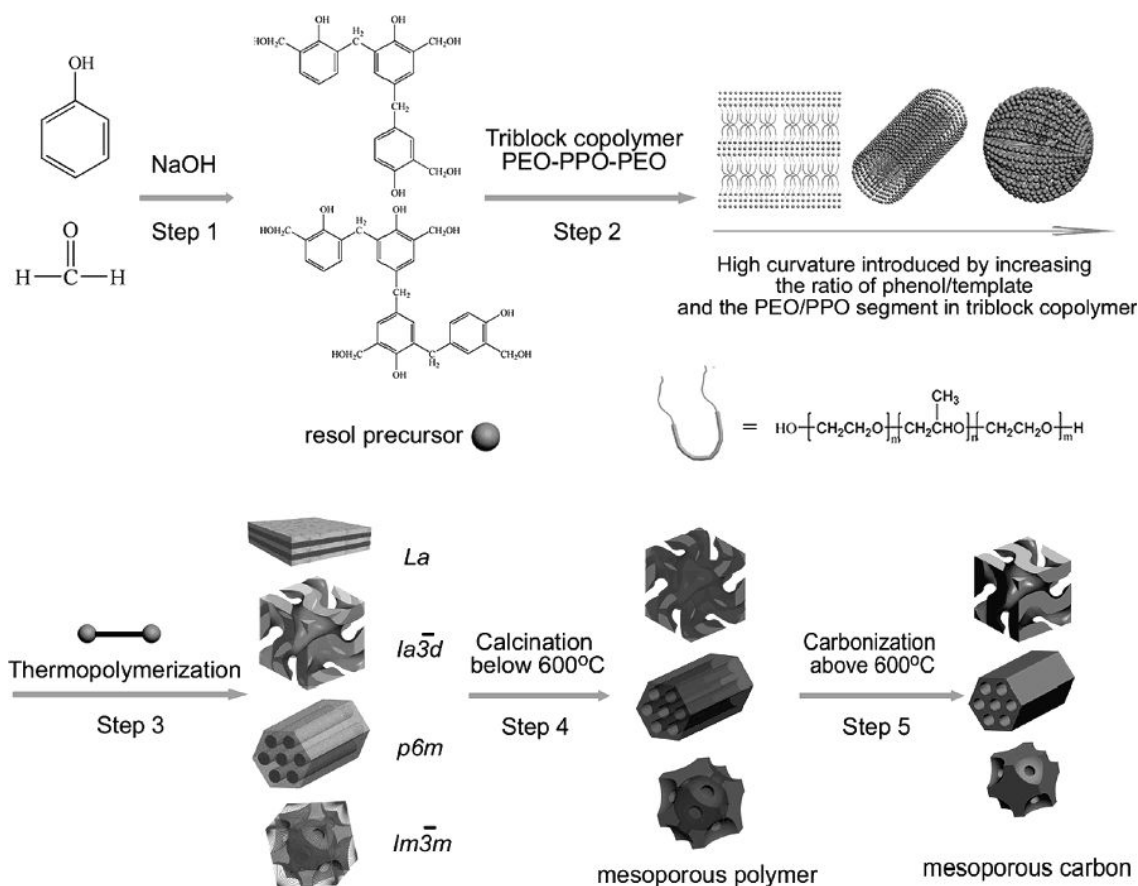
Fig. 6.5. Scheme for the preparation of ordered mesoporous polymer resins and carbon frameworks from the surfactant templating process of EISA. (reproduced from ref. 8)

Compare to hydrothermal synthesis the EISA method is easier and can produce the mesoporous resins and carbon in a wider synthetic range, including pH values, surfactant and phenol/template ratio.

The choice of organic precursors is essential for the EISA of the organic –organic templating process. The polymerization of inorganic precursors should be low enough to form a moldable inorganic-organic framework at the initial assembly stage of inorganic species with organic surfactants. Highly ordered mesostructures can be formed. The inorganic framework is rigid. Therefore, the mesophase can be

solidified, and the surfactant can be easily removed by calcinations or extracted with ethanol.

The synthesis procedure includes five major steps (Fig. 6.5), which are the preparation of resol precursors, the formation of ordered hybrid mesophases by organic-organic self assembly during the solvent evaporation, thermopolymerization of the resols around the templates to solidify the ordered mesophases, the removal of the templates, and carbonization of the resin polymer frameworks to the homologous carbons [8].

Template Synthesis of Metal Nanostructures
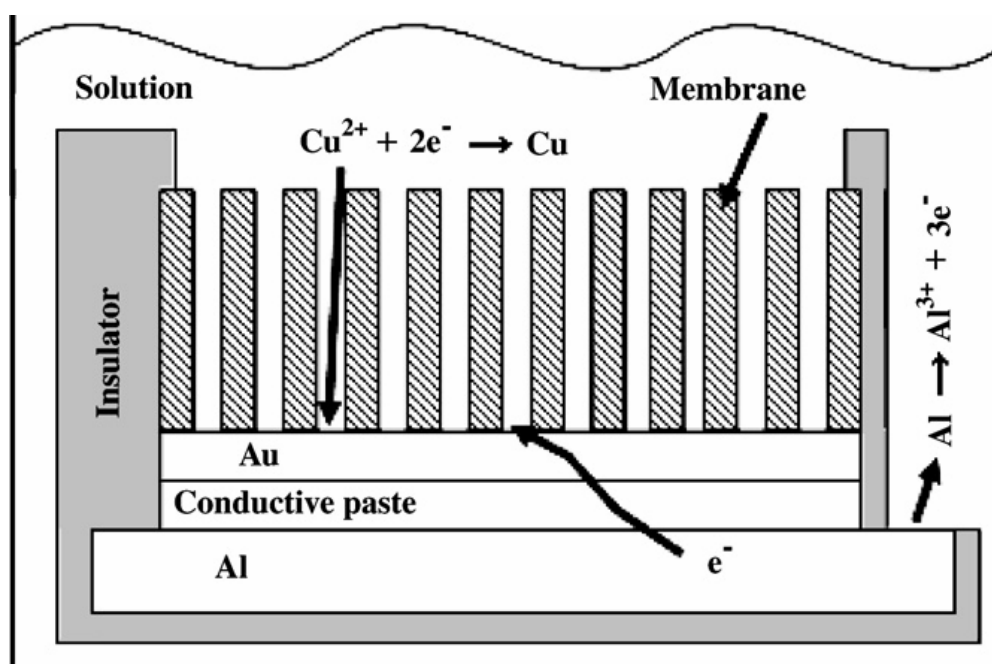
Fig. 6.6. Scheme of the arrangement used for the fabrication of copper nanowires into the AAM template (reproduced from ref. 5)

Copper nanowires are prepared by using aluminium foil as active metal having a thickness of 1.5 mm. In order to deposit copper inside the channels of anodic alumina membrane (AAM), prior to cementation a thin conductive layer of Au was sputtered on one side of the AAM using a conventional sputter coater to make this surface electrically conductive. A portion of AAM was mounted onto the aluminum support by means of a conductive paste and delimited by an insulating film. Since the displacement deposition process needs an electrolytic contact of the active metal

surface, a small area of the aluminum support was exposed to the deposition solution. A scheme of the arrangement used for the fabrication of copper nanowires is reported in Fig. 6.5. This arrangement was placed horizontally in a beaker and covered with 25 ml of a 0.2 M copper sulphate and 0.1 M boric acid solution having pH 3. The experiments were conducted at room temperature. The surface area of the AAM exposed to the deposition solution was of the order of 1 cm^2. A fresh solution was used for each experiment. Experiments were carried out for different times of deposition (from 7 h to 7 days) [5].

Preparation of Carbon Nanotubes
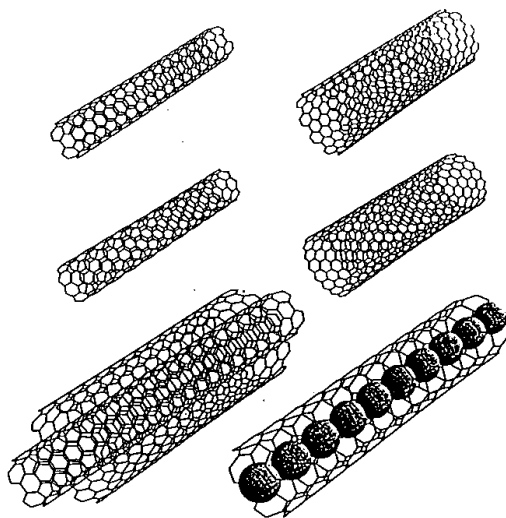
Fig. 6.7. Schematic representation of carbon nanotubes (reproduced from ref. 9)

Alumina membrane is used as template for the preparation of carbon nanotubes; here polyphenyl acetylene is used as a carbon source for the preparation of carbon nanotubes. It contains only carbon-hydrogen bonds. The polyphenyl acetylene/alumina composite was prepared by adding 10 ml of 5% w/w polyphenyl acetylene in dichloromethane to the alumina membrane applying vacuum from the bottom. The entire polymer solution penetrates inside the pores of the membrane was dried in vacuum at 373 K for 10 min. the composite was then polished with fine neutral alumina powder to remove the surface layers and ultrasonicated for 20 min to

remove the residual alumina powder used for polishing. The composite was carbonized by heating in Ar atmosphere at 1173 K for 6 h at heating rate of 10 K/min. This resulted in the deposition of carbon on the channel walls of the membrane. The carbon/alumina composite was then placed in 48 % HF to free the nanotubes. The nanotubes were washed with distilled water to remove HF [9].

Preparation of Porous Solids by Template Method

Ordered mesoporous carbon has been prepared by using mesoporous silica as the template, and this mesoporous silica can be prepared by using CTAB, P123, surfactants as the templates.

   Mesoporous silica SBA-15 is prepared by the following method, P123 non-ionic surfactant was dissolved in 2 M HCl solution, and it was stirred for 1 h then TEOS was added as the silica source, this mixture was stirred until TEOS were completely dissolved. The mixture was placed in oven at 373 K for 48 h. The product was filtered and washed with distilled water and dried at 333 K for 6 h and then SBA-15 was calcined at 823 K for 6 h in air atmosphere.
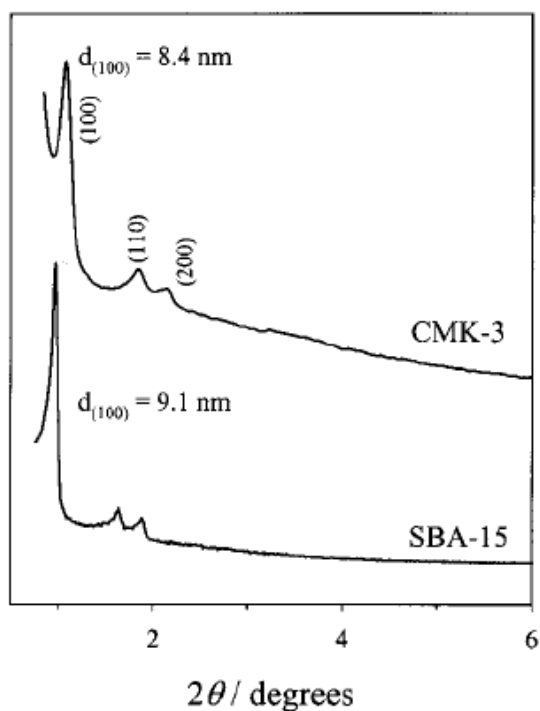
Fig. 6.8. XRD patterns of SBA-15 and CMK-3 (reproduced from ref. 10)

The calcined SBA-15 was impregnated with aqueous solution sucrose containing sulfuric acid, this mixture was heated to 373 k to 433 K for 24 h. then the carbonization was completed by pyrolysis with heating to typically 1173 K under N_2 atmosphere for 6 h at the rate of 5 K/min. the carbon-silica composite obtained was washed with 1 M NaOH solution or 5 Wt % hydrofluoric acid at room temperature, to remove the silica template. The template free carbon product thus obtained was filtered, washed with ethanol and dried at 393 K.

In Fig. 6.9 the low angle XRD conforms the mesoporous structure and to support this mesoporous structure the transition electron microscopy images shows the presence of ordered mesoporous structure [10].
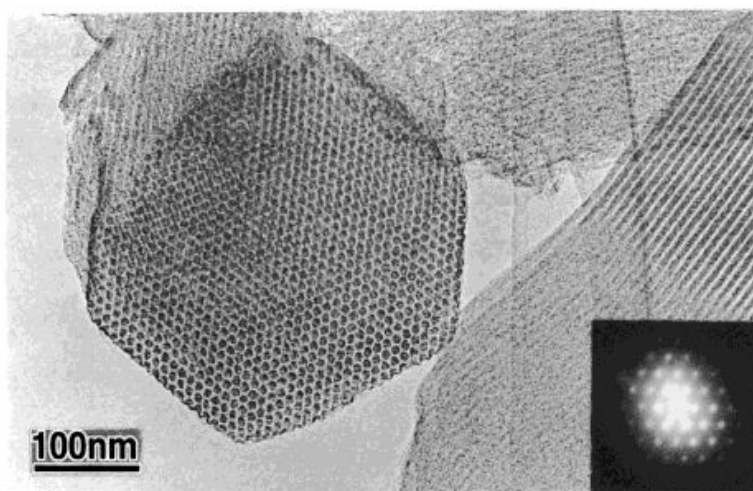
Fig. 6.9 TEM and selected area electron diffraction (SAED) images of CMK-3 (reproduced from ref.10)

SUMMARY

Strategy aimed at the controllable synthesis has been focused on the control of micro, meso and macroscale, including synthetic methods, architecture concepts, and fundamental principles that govern the rational design and synthesis. In this chapter, synthesis mechanisms and the corresponding pathways are first demonstrated for the synthesis of mesoporous silicates from the surfactant-templating approach. Virtually all mesoporous silicates begin with an understanding of the interaction between organic surfactants and inorganic species, as well as among themselves.

Soft templating approach is one of the most general strategies now available for crating nanostructures. The assembly of surfactants and silicates species is normally carried in solutions or the interface to allow the required driving force for the formation of nanostructures. Relying on sol-gel, solution and surface chemistry, there is great potential to explore novel strategies for mesostructures, especially a strategy that can utilize interfacial tension. Items that attract attention also include the control of weak interaction such as the hydrophobic interaction between the assembling components. In view of the fact that surfactant self-assembly can occur with components larger than 1 nm continuous to be challenge and an interest in condensed matter science.

REFERENCES

1. J. Lee, J. Kim, T. Hyeon, *Adv. Mater.*, 18 (2006) 2073.

2. C. T. Kresge, M. E. Leonowicz, W. J. Roth, J. C. Vartuli, J. S. Beck,
   Nature, 359 (1992) 710.

3. D. Zhao, J. Feng, Q. Huo, N. Elosh, G. H. Fredirckson, B. F. Chemlka,
   G. D. Stucky, *Science*, 279 (1998) 548.

4. G. Cao, D. Liu, *Adv. Colloid. Interface. Sci.* 136 (2008) 45

5. R. Inguanta, S. Piazza, C. Sunseri, *Eleectrochem. Commun.,* 10 (2008) 506

6. A. Corma, *Chem. Rev.* 97 (1997) 2373.

7. Y. Wan, D. Zhao, *Chem. Rev.* 107 (2007) 2821.

8. Y. Meng, D. Gu, F. Zhang, Y. Shi, L. Cheng, D. Feng, Z. Wu, Z. Chen,
   Y. Wan, A. Stein, D. Zhao, *Chem. Mater.*, 18 (2006) 4447.

9. M. Sankaran, Ph.D Thesis*, Indian Institute of Technoloyg Madras,* 2007.

10. S. Jun, S. Joo, R. Ryoo, M. Kruk, M. Jaroniec, Z. Liu, T. Ohsuna,
    O. Terasaki, *J. Am.Chem. Soc., 122 (2000)* 712.

Chapter - 7
MICROEMULSION TECHNIQUES

Ch. Venkateswara Rao

The main focus of this chapter is to give brief introduction to the microemulsion systems, formation of microemulsions, how those microemulsions can be used for the preparation of various types of nanoparticles and the dominant factors that influence the nanoparticles preparation in the microemulsion.

INTRODUCTION

In 1943, Hoar and Schulman first reported that oil can be dissolved in bulk water or water in bulk oil with the aid of surfactant to produce a clear homogeneous solution. The oil phases are simple long-chain hydrocarbons and the surfactants are long-chain organic molecules with a hydrophilic head (usually an ionic sulfate or quarternary amine) and lipophilic tail. The generally used oil phases are cyclohexane, decane, heptane and surfactants are cetyltrimethylammonium bromide (CTAB), sodium bis(2-ethylhexyl) sulfosuccinate (AOT).   The clear homogeneous solution is called as microemulsion. According to the nature of the bulk solvent used in the microemulsion, they are designated as water-in-oil or oil-in-water microemulsions. The microemulsion is primarily distinguished from the emulsion not by being composed of smaller droplets but by being subjected to a restrictive condition that it is thermodynamically stable.

MICROEMULSION FORMATION AND NANOPARTICLES PREPARATION

In general, water and oil are not miscible. But the amphiphilic nature of the surfactants such as CTAB makes them miscible. The surfactant molecules form a monolayer at the interface between the oil and water, with the hydrophobic tails of the surfactant molecules dissolved in the oil phase and the hydrophilic head groups in the aqueous phase. It leads to the formation of microemulsion. So the microemulsion is defined as a system of water, oil and surfactant. This system is an optically isotropic and thermodynamically stable. At macroscopic scale, a microemulsion looks like a homogeneous solution but at molecular scale, it appears to be heterogeneous. Even though it is optically isotropic; it cannot be properly described as a solution. The internal structure of the microemulsion at a given temperature is determined by the ratio of its constituents. The structure consists either of nanospherical monosized droplets or a

bicontinuous phase. The different structures of a microemulsion at a given concentration of surfactant are shown in Fig 1. It indicates that

(i)   At high concentration of water, the internal structure of the microemulsion consists of small oil droplets in a continuous water phase (micelles), known as o/w microemulsion.

(ii)   With increased oil concentration, a bicontinuous phase without any defined shape is formed.

(iii) At high oil concentration, the bicontinuous phase is transformed into a structure of small water droplets in a continuous oil phase (reverse micelles), known as a w/o microemulsion.

Depending on the type of surfactant used to form microemulsion, size of the different droplets will be varied from 5-100 nm. It is also evident that the microemulsion system is sensitive to temperature. It can be seen in Fig. 7.1 that the increase in temperature will destroy the oil droplets while the decrease in temperature will destroy the water droplets.
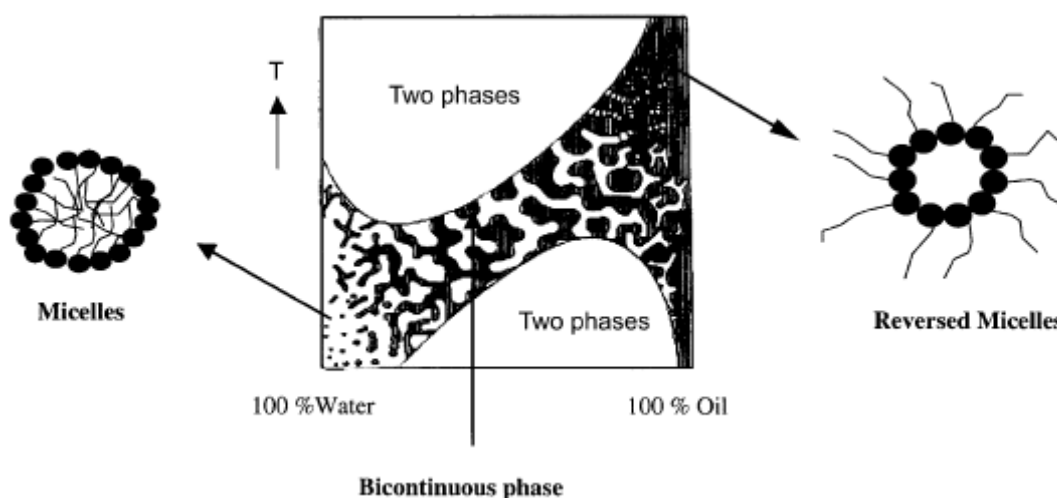
Fig. 7.1 The microscopic structure of a microemulsion at a given concentration of surfactant as function of temperature and water concentration (reproduced from ref. 20).

Significance of Packing Parameter

The shape of micellar aggregates and the formation of microemulsion can be understood from the packing parameter of surfactant molecule used for the microemulsion formation. Packing

parameter is defined as *v/a.l*, where *v* is the volume of hydrocarbon of the surfactant, *a* is the polar head area and *l* is the fully extended chain length of the surfactant. The packing parameter value can be 1, <1 and >1. When the packing parameter value (or ratio *v/a.l*) is greater than 1, the aggregate curvature will be toward the water. This corresponds to a situation where the oil is penetrating the surfactant tails and/or the electrostatic repulsion between the charged head group is low. When the packing parameter value (or ratio *v/a.l*) is less than 1, it corresponds to a situation where the electrostatic repulsion is larger and/or the oil is not penetrating the surfactant tails. It implies that (i) when oil is solubilized in hydrophilic micelles, one can observe the formation of o/w microemulsions for *v/a.l*<1; (ii) when water is solubilized in hydrophobic micelles, one can observe the formation of w/o microemulsions for *v/a.l>1*.; and (iii) When *v/a.l*≈1, lamellar phases or bicontinuous microemulsions are observed.

Based on the experimental results, it is observed that the micelles will be in spherical shape when the packing parameter is less than 1/3. The packing parameters for cylinders and planar bilayers are 0.5 and 1, respectively. In the case of reverse micellar structures, the packing parameter is greater than 2 for cylinders as well as spherical micelles. It was observed that reverse micelles will be in cylinder shape up to *v/a.l*≤2 and spherical shape when *v/a.l*>3.

Oil-in-water (o/w) microemulsions are monodisperse. Water-in-oil (w/o) microemulsion solutions are mostly transparent, isotropic liquid media with nanosized water droplets that are dispersed in the continuous oil phase and stabilized by surfactant molecules at the water/oil interface. These surfactant-covered water pools offer a unique microenvironment for the formation of nanoparticles. They not only act as micro-/nano-reactors for processing reactions but also exhibit the process aggregation of particles because the surfactants could adsorb on the particle surface when the particle size approaches to that of the water pool. As a result, the particles obtained in such a medium are generally uniform in size and shape (i.e., monodisperse).

APPLICATIONS OF MICROEMULSIONS

1. Synthesis of Metal Nanoparticles

Precipitation of metal particles in the Water-in-oil (w/o) microemulsion solutions (reverse micellar system) has been found to be the simple methodology for the preparation of nanoparticles.

The method of nanoparticle preparation consists in mixing of two microemulsions carrying the appropriate reactants (generally metal precursor and reducing agent) in order to obtain the desired particles. It is represented in Scheme 7.1.
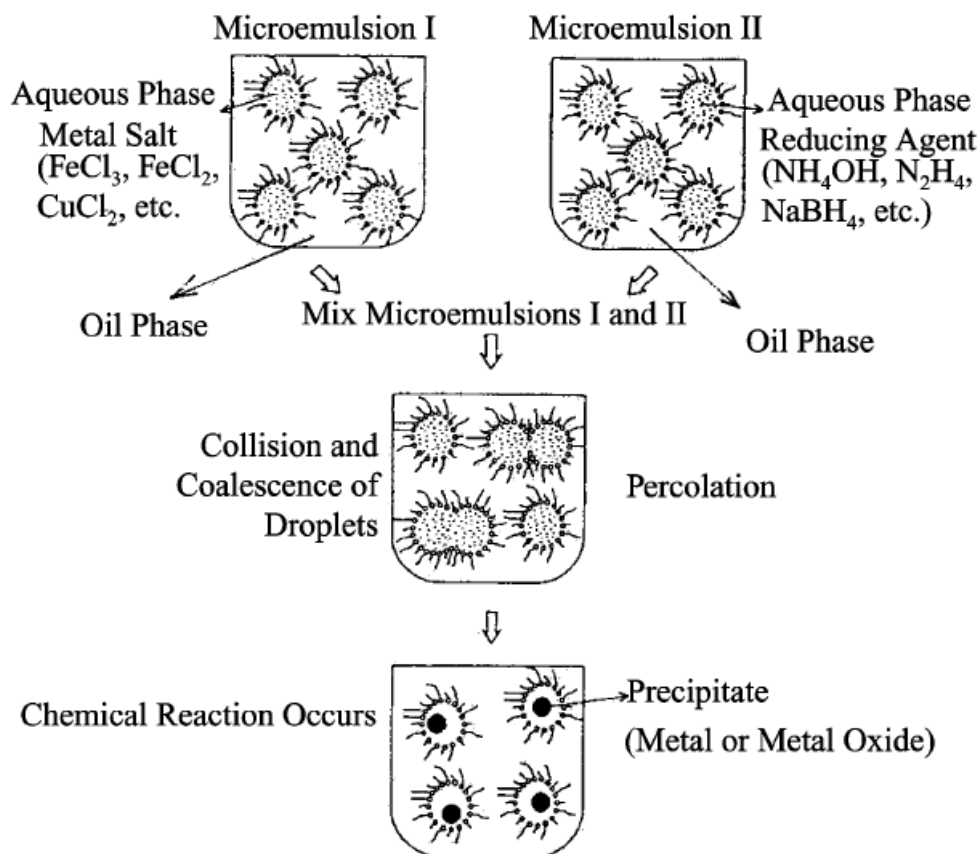
Scheme 7.1. Proposed mechanism for the formation of metal particles by the microemulsion approach (reproduced from ref. 24)

At the beginning of reaction, the attractive van der Waals force and the repulsive osmotic force between reverse micelles lead to collisions of micelles. It results in the interchange of the reactants (in general, metal ions and reducing species) solubilized in two different reverse micelles respectively. As a result, the initial monomeric metal nuclei begin to form and grow. When the exchange of reactants is fast in the water droplets, metal ions reduce and the metal nuclei grow quickly. It remains unchanged when the particle size reaches a certain size. It corresponds to the thermodynamically stabilized species in the presence of microemulsion. Due

to the possible aggregation, the final size of silver particles is generally larger than that of the water cores. Once the particles attain the final size, the surfactant molecules are attached to the surface of particles and stabilize and protect them against further growth. The dynamic exchange of reactants such as metallic salts and reducing agents between droplets via the continuous oil phase is strongly depressed due to the restricted solubility of metal salts in the oil phase. This is a reason why the attractive interactions (percolation) between droplets play a dominant role in the particle nucleation and growth in the water-in-oil (w/o) microemulsion reaction medium.

2. Synthesis of Metal Alloys

Various metal alloys can be prepared in the similar way as described in scheme 1. It consists of mixing the reverse micelle containing two or three metal precursors and another reverse micelle contain reducing species. Example: formation of Pt-Ru (1:1) alloy. In order to prepare the alloy nanoparticles, both Pt^{4+} and Ru^{3+} will be taken in 1:1 atomic ratio to form reverse microemulsion I. Reverse microemulsion II will be prepared by using $NaBH_4$ reducing agent. When both the reverse microemulsions are mixed together, reduction of Pt^{4+} and Ru^{3+} takes place by BH_4^- ions and results in the formation of Pt-Ru (1:1) nanoparticles (Xiong and Manthiram, 2005). In the similar way, Pt-Fe nanoparticles in different ratios (1:1, 1:2 and 1:3) can be prepared (Carpenter *et al.*, 2000). In the same manner, various metal chalcogenides also can be prepared by taking two micelle solutions containing the desired ions prepared separately and then rapidly mixed.

In conventional methods of preparation, the reaction temperature should be high to promote alloy formation. As a result, the formed particles will be large in size. Moreover, the shape of the particle cannot be controlled. Since the reaction takes place inside the micellar cores,

(i) the enormous amount of heat that is generated within the micellar cores during the reduction process is enough to form alloy of desired composition.

and (ii) both size, shape and composition can be controlled.

3. Synthesis of Metal Oxides

The synthesis of oxides from reverse microemulsion relies on the co-precipitation of one or more metal ions. It is almost similar in many respects to the precipitation of oxides from aqueous solutions. But the precipitation occurs within the micellar cores so that particle size as well as shape can be controlled. In a typical process, precipitation of hydroxides is induced by addition of a reverse micelle solution containing dilute NH_4OH to a reverse micelle solution containing aqueous metal ions at the micellar cores. Alternatively, dilute NH_4OH can simply be added

directly to a micelle solution of the metal ions. The precipitation of the metal hydroxides is typically followed by centrifugation and heating in the presence of oxygen to remove water and/or improve crystallinity. In general, it is represented as follows:

$$A^{2+} + 2B^{2+} + OH^- \text{ (excess)} \rightarrow AB_2O_4 + xH_2O\uparrow$$

Where A and B are metals.

In this way, simple metal oxides and multicomponent metal oxides can be prepared. Some of the examples of nanomaterials synthesized in w/o microemulsions are given in Table 7.1.

Table 7.1. Nanomaterials formed in w/o microemulsions

Nanoparticle system	Example	Reference
Metals/Metal alloys	Pt	Rojas *et al.*, 2005
	Pd	Boutonnet *et al.*, 1982
	Ag	Taleb *et al.*, 1997
	Au	Herrera *et al.*, 2005
	Pt-Ru	Xiong and Manthiram, 2005
	Fe-Pt	Carpenter *et al.*, 2002
	Pd-Co-Au	Raghuveer *et al.*, 2006
Metal chalcogenides	ZnS	Khiew *et al.*, 2005
	PbS	Eastoe *et al.*, 1995
	RuSe	Venkateswara Rao and Viswanathan, 2007
Metal oxides	$Pb_2Ru_2O_7$	Raghuveer *et al.*, 2002
	CeO_2	Bumajdad *et al.*, 2004
	$CoFe_2O_4$	Liu *et al.*, 2003
	$LiNi_{0.8}Co_{0.2}O_2$	Lu *et al.*, 2000
Core-shell nanoparticles	Fe_3O_4/SiO_2	Tago *et al.*, 2002
	Fe/Au	Zhou *et al.*, 2000

4. Synthesis of Core-Shell Nanoparticles

Some of the metallic nanoparticles like Fe, Co, Ni are susceptible to rapid oxidation. This problem can be largely circumvented by coating the nanoparticles with gold or other inert metals. The technique for applying gold coatings on metal nanoparticles is reasonably straightforward and simply adds an additional step to the reverse micelle synthesis. In this process, a water-soluble gold salt ($HAuCl_4$) is dissolved and dispersed in a separate reverse micelle solution that is then added to the metal-containing reverse micelle solution that has already been reduced with an excess of BH_4^-. The aqueous $AuCl_4^-$ ions encapsulate the metal particles and are subsequently reduced by forming a metallic gold shell around the metal particles.

$$8AuCl_4^- + 3\,BH_4^- + 9H_2O \rightarrow 8Au + 3B(OH)_3 + 21H^+ + 32Cl^-$$

The preparation of core-shell type structures is not limited to metals as the core or shell materials. Combinations of precipitation, reduction and hydrolysis reactions can be performed sequentially to produce oxides coated with metals, oxides coated with oxides, and so forth.

EFFECTS OF THE PARAMETERS ON THE FORMATION OF NANOPARTICLES IN MICROEMULSION

The main parameters that influence the size of nanoparticle are molar ratio, $W =$ [water]/[surfactant], type of solvent employed, surfactant or co-surfactants used and concentration of reagents. Recent investigations suggest that the particle shape also can be affected by the influence of micellar template, added anions and molecular adsorption. But a general method for controlling nanocrystal shapes through soft chemistry has not yet been found. The major factors that influence the formation of nanoparticles are explained with examples below.

Water-to-Surfactant Ratio, W

The size of the metallic particle will depend on the size of the droplets in the microemulsion. The droplet size will be influenced by the water-to-surfactant ratio, W.

In general, the volume of water in microemulsions is proportional to the cubic radius of the water core. And also the amount of surfactant which is present as a film around the water cores is proportional to the surface area of the micro/nanodroplets. So the molar ratio of water to surfactant (W) has a linear relationship with the radii of the water cores (R_w). It has been observed in AOT microemulsion system that the water-pool radius increases with the water

content. An increase of molar ratio, W at constant concentration of surfactant will increase the average diameter of the droplets. Consequently, the obtained nanoparticles will be large in size.

Table 7.2. Characteristic of silver particles obtained in w/o microemulsion (data taken from ref. 23)

W	Reducing agent	Conc. of reducing agent (M)	Particle size (nm)
2	NaBH$_4$	2.5 x 10^{-4}	-
5	NaBH$_4$	2.5 x 10^{-4}	2.7
7.5	NaBH$_4$	1.0 x 10^{-5}	-
7.5	NaBH$_4$	1.0 x 10^{-4}	4.5
7.5	NaBH$_4$	2.5 x 10^{-4}	5.5
15	NaBH$_4$	1.0 x 10^{-4}	6.0
15	NaBH$_4$	2.5 x 10^{-4}	7.0

For example, by dynamic light scattering technique, it has been confirmed that the water core radius, R_w, is coincident with the equation $R_w(nm) = 0.18W + 1.5$ in a wide range of alkanes. For example in the AOT-water-isooctane microemulsion system, it was found that the linear relationship between R_w and W was $R_w(\text{Å}) = 1.5W$. Thus the linear relationship may be different in various systems. Generally, low water content is favorable to form smaller microemulsion droplets (reverse micelles) which yield fine nanoparticles with a narrow size distribution. On the contrary, high water content is favorable to form bigger microemulsion droplets which are easy to fabricate larger particles. The reason for the behaviour is explained as follows: Actually, at low water content, the water solubilized in the polar core is bound by the surfactant molecules, which increases the boundary strength and decreases the intermicellar exchange rate. As a result, a decrease in water content induces formation of monodisperse nanoparticles with small particle size. However, the bound water would turn into bulk water with an increase in water content, which is benefit for the water pools to exchange their contents by collisions and makes the chemical reaction or co-precipitation between compounds solubilized in two different reverse micelles complete more quickly. Since the nature of bulk water is drastically different from that of bound water, reactants would be rapidly transferred from one water core to another, and thus

the resultant particle size is relatively big and the size distribution becomes relatively wide. The variation of silver and Fe nanoparticles size with W is given in Tables 7.2 and 7.3 respectively.

Table 7.3. Characteristic of iron particles obtained in w/o microemulsion (Data taken from ref. 24)

S. No	[AOT]	W	$[FeCl_2]x10^4$ (mol/dm^3)	$[NaBH_4]x10^3$ (mol/dm^3)	Particle size (nm)
1	0.1	22	7.5	3.5	3.9
2	0.1	22	1.6	0.68	4.1
3	0.05	10	0.93	0.35	2.5
4	0.025	5	48	24	1.9
5	0.025	9	48	24	2.5
6	0.025	13	48	24	3.3
7	0.025	18	48	24	4.3
8	0.025	22	48	24	4.7
9	0.025	26	48	24	5.4
10	0.025	31	48	24	5.8

Solvent Effect

Particle size is affected by solvent type. This was shown initially by Pileni (2003) in a study on silver nanoparticles, in which larger particles were seen (by TEM) to be formed in isooctane than in cyclohexane. This is probably due to the significant difference in intermicellar exchange rate constant between the two solvents - a factor of 10.

The change in growth rate has been explained in the following way:

(i)   Smaller and less bulky solvent molecules with lower molecular volumes such as cyclohexane, can penetrate between surfactant tails and increase the surfactant curvature and rigidity. The increased rigidity at the interface may lead to a slower growth rate.

(ii)   Isooctane, being bulkier with a larger molecular volume, cannot penetrate the surfactant tails so efficiently, thereby leading to a more fluid interface and thus faster growth rates.

Although these ideas provide plausible explanations of the phenomena they remain controversial.

Measurement of the surfactant film rigidities in microemulsions show that the solvent type has only a minor effect. Solvent molecular volume may also explain the observed change in final particle size. It was proposed that a more stable micelle system arises from greater interactions between the solvent and surfactant tails which in turn leads to an enhanced ability to stabilize larger particles. Any increase in rate of intermicellar exchange will result in a higher rate of growth comparable to nucleation, hence is likely to generate systems with lower polydispersity. Effect of solvent on the size of the Ag nanoparticles is given in Table 7.4.

Table 7.4. Effect of solvent on the absorption spectra of silver nanoparticles synthesized in reverse micelles of AOT (data taken from ref. 22)

System	Particle size (nm)
AOT/decane	6.0
AOT/heptane	22.0
AOT/cyclohexane	5.4

Surfactants and co-surfactants

Various studies showed that the choice of surfactant is critical to the size, shape and stability of the particles. The most commonly used surfactant is the anionic AOT, although a variety of common cationic surfactants are also frequently employed, such as CTAB or DDAB (di-n-didodecyldimethylammoniumbromide) and non-ionics Triton X-100, polyoxyethylene (5) nonylphenyl ether (NP-5) or polyoxyethylene (9) nonylphenyl ether (NP-9). For some systems co-surfactants (intermediate chain length alcohols, such as n-butanol or n-hexanol) are also employed.

Among the anionic surfactants that form reverse micelles, the best known are the systems derived from AOT (sodium 1,4-bis-2-ethylhexylsulfosuccinate) in different non-polar media. The reasons are as follows:

(i)   AOT has a well-known V-shaped molecular geometry, giving rise to stable reverse micelles without co-surfactant.

(ii)   AOT has the remarkable ability to solubilize water with values of W (W = $[H_2O]/[AOT]$) as large as 40-60 depending on the surrounding non-polar medium, the solute and the temperature; however the droplet size depends only on the water amount, W. The bulk properties of water (polarity, viscosity, hydrogen bond ability, etc.) either inside the pool (free) or at the interface (bound) change with W.

It is also known that addition of co-surfactant can reduce the surfactant concentration in microemulsion preparation. Normally, low molecular weight alcohols, such as n-butanol can be used for this purpose. Their short hydrophobic chain and terminal hydroxyl group is known to enhance the interaction with surfactant monolayers at the interface, which can influence the curvature of the interface and internal energy. The amphiphilic nature of co-surfactants could also enable them to distribute between the aqueous and oil phase.

In general, it was concluded that the addition of a co-surfactant leads to a higher fluidity of the interfacial film, thus increasing the rate of intermicellar exchange (but also leading to a higher curvature of the droplets), so smaller particles.

Surfactant Concentration

When the amount of water and oil is kept at fixed values, an increase of the amount of surfactant will increase the number of droplets. It means that the number of metal ions per droplet will decrease and consequently the size of the particles. The morphology of reverse micelles is different with the surfactant concentration. At different concentrations, the surfactant molecules can form various molecule aggregations (Fig. 7.2).
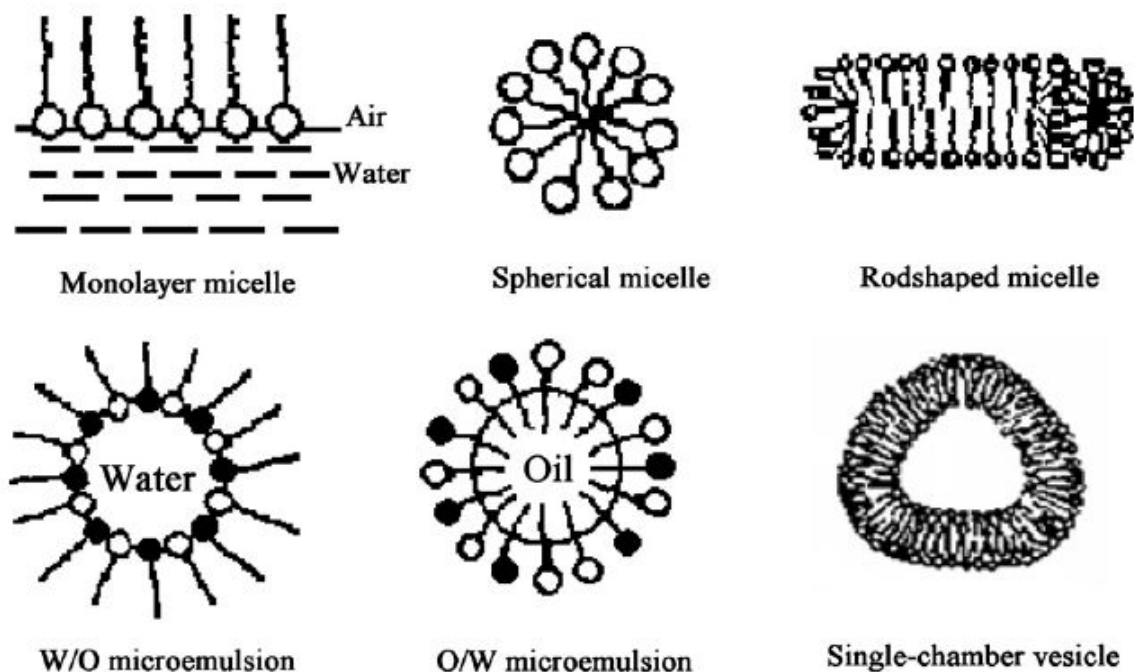
Fig. 7.2. Structures of different micelles (reproduced from ref. 26)

It was found that the change of micelle structures had an energetic barrier. The main points are given as follows:

(i)   At a low surfactant concentration, only spherical micelles appear in solution.

(ii)   When the surfactant concentration in the solution reaches a well-defined saturation value, i.e., second critical micelle concentration (second CMC), the energetic barrier will be overcome and the micelle structure will change from a spherical micelle to other special structure, and then the micelle will be steady again at a new concentration range. For example, if the concentration of surfactant attains to 40–50%, the spherical micelle turns into rod-shaped or column-shaped micelle. Furthermore, the micelle is also able to self-assemble into layer or liquid crystal structure.

The special micelles formed at different concentrations of surfactants can be usually used as effective structure-directing agents to prepare nanoparticles with desired morphologies. Thus, the micelle formed by the surfactant with a proper concentration can offer an appropriate growth condition for nanoparticles.

Nature of the Precipitating Agent (reducing agent)

The main point that should be followed in the selection of suitable reducing agent in the preparation of nanoparticles is it must be stable in an aqueous environment and does not react with the other components of the reverse micelle system. As a general rule, a fast nucleation process will result in the production of small particles.

In most of the cases, water soluble sodium borohydride and hydrazine (usually $N_2H_4.2HCl$ or $N_2H_4.H_2O$) are used as effective reducing agents. Eventhough bubbled H_2 gas results in the reduction of metal particles, the kinetics is not desirable, particularly at room temperature. As it was mentioned earlier, faster exchange between the reactants and fast nucleation process will give smaller particles. So both sodium borohydride ($NaBH_4$) and hydrazine are efficient reducing agents for most of the transition metal salts. The reduction process is in this case completed instantly and is very fast in comparison to pure hydrogen.

When increasing the concentration of hydrazine while the concentration of metal salt is kept constant, a decrease in the particle size is observed. This was shown when Ni particles were prepared in a microemulsion containing cetyltriammonium bromide (CTAB) as surfactant, *n*-hexanol as oil phase, water as aqueous phase and hydrazine as reducing agent at a temperature of 350 K (Capek, 2004). The diameter of the nickel particles decreases when the ratio of the hydrazine to nickel chloride concentrations increases. The diameter of the particles reaches a constant value when this ratio is above 10.

Effect of the Micellar Template

It was claimed that particle shape can be controlled by using micellar templates. A simple surfactant/water/oil system can produce many different self-assembly structures: by changing composition, one can obtain spheres (reverse micelles or micelles), cylinders, interconnected cylinders and planes, termed lamellar phases, which also can re-organise into onion-type structures. Hence in theory many possible nanoparticle structures could be grown inside these different shaped templates. Despite plenty of work, there is still much controversial debate on these aspects.

Influence of ion/molecular adsorption

Anion species added as electrolyte is important for generating different shapes of metal nanocrystals. The initial micellar shape is shown to be largely unaffected by these additives. For example, in the case of copper nanoparticle systems, a large excess of hydrazine favours disk

over spherical particles. In both cases, Pileni *et al*. (2003) postulate that selective adsorption of molecules or ions on to facets of the nanocrystal affects growth in certain directions, explaining the apparent preference for certain shapes.

It was also known that pH affects the shape of nanocrystals, for example, nanostructured NiZn ferrites (Uskokovic *et al*., 2005). When the pH is lower, needle-like nanocrystals are formed, whereas other spheres are observed at higher pH. One possible reason for this is due to an increased number of hydroxyl ions at higher pH which eliminate the sulphate and bromide ions, hampering their ability to promote uniaxial growth.

SUMMARY

The most remarkable features of the microemulsion technique are: (i) particle size and composition can be controlled to a great extent and a narrow particle size distribution can be obtained and (ii) Bimetallic particles can be obtained at room temperature.

A large number of different nano-materials can be synthesised in water-in-oil microemulsions and reverse micelles. Particle growth has shown to be strongly dependent on intermicellar exchange rates. The resultant particle size appears to be dependent on dominant parameters, namely solvent type, surfactant/co-surfactant type, concentration of the reagents and composition via [water]:[surfactant] ratio, W.

However, the generality of the factors that affects the shape of particle remains to be established.

REFERENCES

1. K. Tapas and A. Maitra, *Adv. Colloid Interface Sci*., 59 (1995) 95.
2. J.J. Silber, U.A. Biasuttia, E. Abuinb and E. Lissi, *Adv. Colloid Interface Sci*., 82 (1999) 189.
3. T. Tadros, P. Izquierdo, J. Esquena and C. Solans, *Adv. Colloid Interface Sci*., 108-109 (2004) 303.
4. S. Eriksson, Ulf Nylén, S. Rojas and M. Boutonnet, *Applied Catalysis A: General* 265 (2004) 207.
5. T.P. Hoar and J.H. Schulman, *Nature* 152 (1943) 102.
6. M.-P. Pileni, *Nature* 2 (2003)145.

7. T. Tago, T. Hatsuta, K. Miyajima, M. Kishida, S. Tashiro and K. Wakabayashi, *J. Am. Ceram. Soc.* 85 (2002) 2188.

8. S. Rojas, F.J. Garcıa-Garcıa, S. Jaras, M.V. Martınez-Huerta, J.L. Garcıa Fierro and M. Boutonnet, *Applied Catalysis A: General* 285 (2005) 24.

9. M. Boutonnet, J. Kitzling and P. Stenius, *Colloids. Surf.* 5 (1982) 209.

10. A.P. Herrera, O. Resto, J.G. Briano and C. Rinaldi, *Nanotechnology* 16 (2005) S618.

11. L. Xiong and A. Manthiram, *Solid State Ionics* 176 (2005) 385.

12. V. Raghuveer, P.J. Ferreira, A. Manthiram, *Electrochem. Commun.* 8 (2006) 807.

13. P.S. Khiew, S. Radiman, N.M. Huang, Md Soot Ahmad and K. Nadarajah, *Mater. Lett.* 59 (2005) 989.

14. J. Eastoe and A.R. Cox, *Colloids Surf A Physicochem. Eng. Asp.* 101 (1995) 63.

15. Ch. Venkateswara Rao and B. Viswanathan**,** *J. Phys. Chem. C* 111 (2007) 16538.

16. V. Raghuveer, Keshav, Kumar and B.Viswanathan, *Indian J. Eng. Mater. Sci.* 9 (2002) 137.

17. A. Bumajdad, M.I. Zaki, J. Eastoe and L. Pasupulety, *Langmuir* 20 (2004)11223.

18. S. Xing, Y. Chu, X. Sui and Z. Wu, *J. Mater. Sci.* 40 (2005) 215.

19. E. Carpenter, J.A. Sims, J.A. Wienmann, W.L. Zhou and C.J. O'Connor, *J. Appl. Phys.* 87 (2000) 5615.

20. R. Schomäcker, M.-J. Schwuger and K. Stickdorn, *Chem. Rev.* 95 (1995) 849.

21. V. Uskokovic and M. Drofenik, *Colloids Surf. A Physicochem. Eng. Asp.* 266 (2005)168.

22. R.P. Bagwe and K.C. Khilar, *Langmuir* 16 (2000) 905.

23. C. Petit, P. Lixon and M.P. Pileni, *J. Phys. Chem.* 97 (1993) 12974.

24. I. Capek, *Adv. Colloid Interface Sci.*, 110 (2004) 49.

25. Taleb, C. Petit and M.P. Pileni, *Chem. Mater.* 9 (1997) 950.

26. J.H. Fendler, *Chem. Rev.* 87 (1987) 877.

27. W.L. Zhou, E.E. Carpenter, J. Sims, A. Kumbhar and C.J. O'Connor, *Mater. Res. Soc. Symp. Proc.* 581 (2000) 107.

28. C.-H. Lu and H.-C. Wang, *J. Mater. Chem.* 13 (2003) 428.

29. C. Liu, A.J. Rondinone and Z.J. Zhang, *Pure Appl. Chem.* 72 (2000) 37.

Chapter - 8

SYNTHESIS BY SOLID STATE DECOMPOSITION

S. Navaladian

INTRODUCTION

Synthesis of materials is an important part in materials science and chemistry because the properties of materials vary drastically based on their synthetic method. Even the stability of the material varies based on method by which it is synthesized. By varying synthetic methods, surface area, pore size, crysatallite size, allotropes, morphology, presence of impurities, defects and other oxidation state of the metal can also be varied. Hence, their potential to certain applications vary drastically. For example, in catalysis, catalyst with high surface area is preferred to achieve high conversion. So, synthetic method that yield high surface of the catalyst is adopted. A lot of methods are known in the synthesis of materials of various applications in different fields, still efficient and cost-effective methods are being developed.

DECOMPOSITION METHODS

Decomposition is one of the methods known in the synthesis of various materials. In this method, a solid or liquid is heated to its decomposition temperatures to obtain the solid of interest. For example, sugar can be decomposed in an inert atmosphere to get the carbon material (solid-to-solid). Decomposition of titanium isopropoxide (a liquid) in air atmosphere is used to get the titanium dioxide (TiO_2) (liquid-to-solid). $Ni(CO)_4$, a volatile complex can be decomposed to get Ni metal (vapour-to-solid). In this particular chapter, solid state decomposition is considered.

Solid-State Decomposition

Decomposition of any material occurs due to its instability when the particular conditions are applied. Also, it depends upon the activating source. These activating sources can be thermal, photochemical, microwave and γ-radiation. For example chemical compound which need high temperatures to decompose can be photochemically decomposed with ease at room temperature. Particularly, the decomposition of AgBr to Ag can be achieved by thermal modes only at 1330°C but it can be easily decomposed at room temperature under visible light. As we know, this principle is used in photography. Thus, based on the activating sources, solid-state decomposition can be classified into the following

decomposition methods (1) thermal decomposition, (2) Microwave-assisted and (3) Photochemical decomposition.

Thermal Decomposition Methods

In general, thermal decomposition methods are chosen for synthesis of metal oxides. Decomposable precursors which posses low decomposition temperature are preferred for the synthesis because at high temperatures, sintering is also high. So materials formed will have poor surface area and large crystallite size. Decomposition temperature of any compounds is mainly decided by the redox properties of the compound. In general, salts of the silver with easily utilizable organic moiety can be decomposed at lower temperatures. Various materials such as metal, metal oxides, mixed metal oxides and metals chalogenides have been synthesized using decomposition method.

Synthesis of Metals
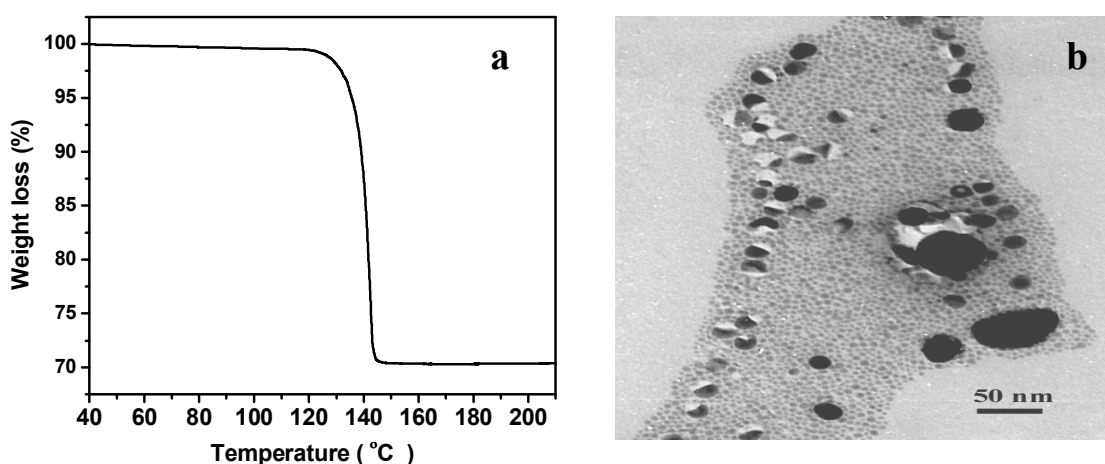
Fig. 8.1. TGA profile of silver oxalate and (b) silver nanoparticles synthesized by decomposition of silver oxalate [1].

Synthesis of metallic silver can be achieved using silver formate, silver oxalate, oleate, maleate and fumarate and their decomposition temperature is 93, 140, 287, 170 and 280 °C respectively (1 and 2). Recently silver dodecanate, myristate and palmitate also have been utilized for the synthesis of silver nanopartices. Decomposition of these silver compounds yield various gaseous products like CO, CO_2 and organic residues. In the case of silver oxalate decomposition to Ag metal and CO_2 are produced. Hence, this is one of the methods known for the production pure CO_2. In the case of silver oxalate

decomposition, reaction was carried out in a water medium under refluxing conditions at under N_2 atmosphere with a capping agent (poly (vinyl alcohol)) (Fig. 8.1). TGA of the silver oxalate, given in Fig. 8.1 (a) shows the sharp decomposition at around 140 °C. The corresponding weight loss is due to the loss of two moles of CO_2. TEM image of Ag nanoparticles synthesized by decomposition of silver oxalate is given in Fig. 8.1(b). The average particle is around 7 nm.

Metal Oxides

Metal oxides can also be synthesized by decomposition of certain precursors like hydroxides, oxalates, hydroxyl carbonates, hydroxyl sulphates and carbonates. In general, the direct calcination of metal salt such as nitrates and sulphates is not carried out to synthesis the metal oxides in order to avoid the impurities and heterogeity of the materials.

Synthesis of Magnesia

The decomposition of magnesium hydroxycarbonate $(Mg_5(CO_3)_4(OH)_2)$ yields magnesium oxide (MgO). In this particular case, the morphology of the precursor is flower like particle of 3 μm. After calcinations at 400 °C, MgO with tube-like morphology is obtained as shown in Fig. 8.2.

$$Mg_5(CO_3)_4(OH)_2 \xrightarrow{\;400^\circ\,C\;} 5\,MgO + 4CO_2 + H_2O$$

(a)   **(b)**
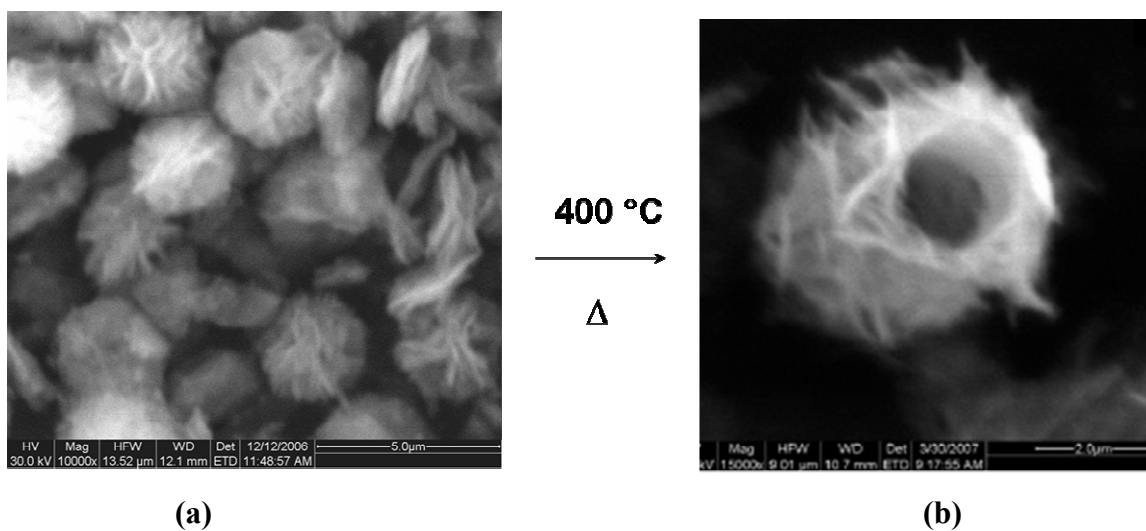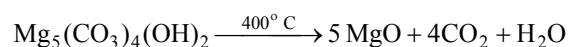
Fig. 8.2 SEM image of (a) magnesium hydroxycarbonate and (a) MgO [3].

Similarly $MgSO_4.5Mg(OH)_2.2H_2O$ also yields the MgO by decomposition, but the complete decomposition needs temperature above 800 °C. In this case, morphology of the particles is strip-like. In general, MgO is synthesized decomposing the $Mg(OH)_2$ in the air. But MgO synthesized in the presence of air shows less surface area than that of MgO synthesized in nitrogen atmosphere. This is due to the high amount of sintering in presence of oxygen.

Synthesis of Matel Oxides from Oxalate Precursors

Due to the low temperature decomposition of metal oxalates, oxalate precursors are most widely used for syntheses of metal oxides. Nickel, copper, iron and zinc oxides can be synthesized directly decomposing their oxalate precursor. Nickel oxalate precursor has yielded nickel oxide with sizes around 9 nm at 450 °C. Fe_2O_3 has been synthesized by thermal decomposition of ferrous oxalate at 415 °C. When copper oxalate has been decomposed in air at 300 °C for 1 h mesoporous CuO microspheres have been obtained (Fig. 8.3). Zinc oxalate has yielded ZnO particles of size around 55 nm. In all these cases, the formation of CO and CO_2 are the by products. Zinc acetate also decomposes and yields the zinc oxide at 600 °C. Stoichiometric barium titanate ($BaTiO_3$) is synthesized by thermal decomposition of bariumtitanyl oxalate at 600 °C.
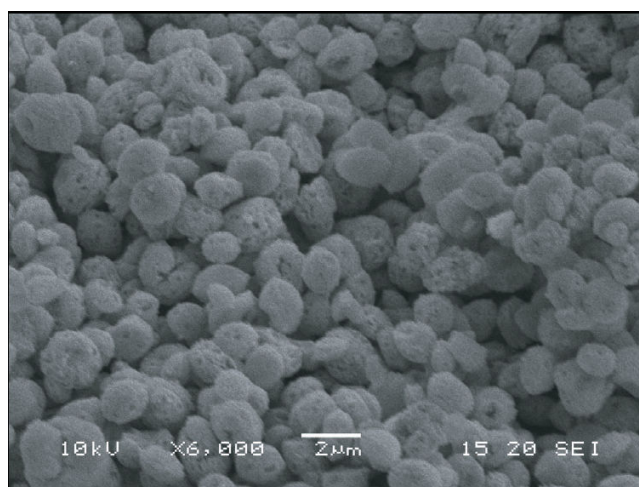
Fig. 8.3. Copper oxide micropshere obtained by the decomposition of copper oxalate [4].

Metal Chalcogenides

Cd(II)complex of thiosemicarbazide and selenosemicarbazide are thermally decomposed to obtain CdS and CdSe. In typical procedure 500 mg of cadmium tetramethylthiourea complex was mixed with 182 mg of thiosemicarbazide ligand, dispersed well in 3 ml tri-n-octylphosphine oxide (TOPO). This precursor mixture was injected into TOPO (5 g) at 300 °C. The resulting orange yellow solution was maintained at 300 °C for about 1 h and then cooled to 70 °C. TEM image of CdS nanorods formed are shown in Fig. 8.4. In this case the thicknesses of the rods formed are 15 nm and aspect ratio is 3-4.
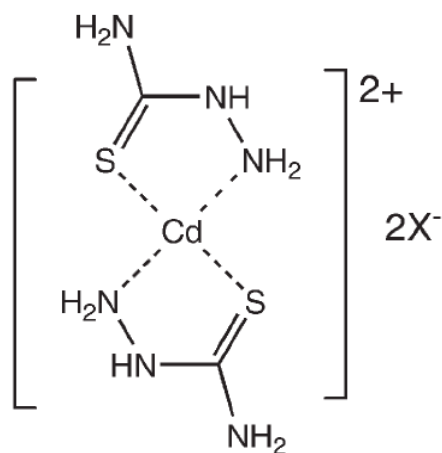
Cadmium thiosemicarbazide
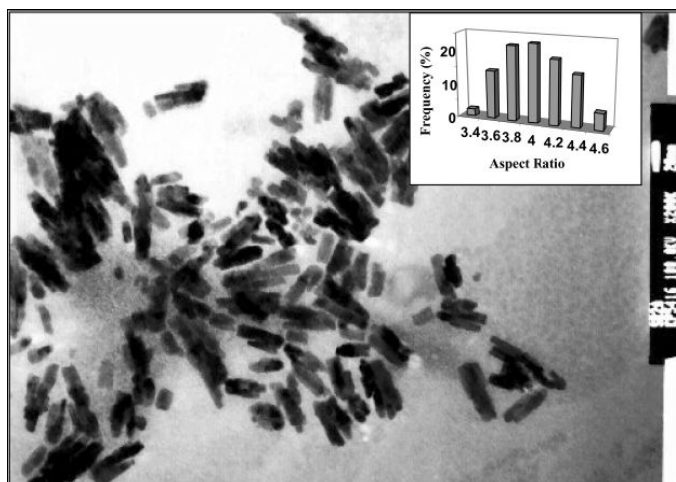
Fig. 8.4. CdS nanorods synthesized by decomposition of cadmium thiosemicarbazide [5]

Microwave-assisted Decomposition

In general, microwave is used to quicken the reactions. The main advantages of microwave assisted processes are: (i) the rate of the reaction is increased by orders of magnitude, (ii) the initial heating process is rapid, and (iii) microwaves induce the generation of localized high temperatures at reaction sites, which enhances the reaction rates. Moreover, microwave-based syntheses are energy efficient. Hence, microwave is used in the synthesis of materials as well as organic compounds.

Synthesis of Metals

Decomposition of silver oxalate has been carried out by using microwave radiation in ethylene glycol and diethylene glycol. Formation of silver nanoparticles has been observed in 60 s in the case of ethylene glycol. In the case of diethyelene glycol, only after 75 s of irradiation, the formation of silver nanoparticles has been observed. Ag nanoparticle formed in ethylene glycol medium is given in Fig. 8.5 (a). Formation of anisotropic nanoparticle is observed in the case of 75 s of microwave irradiation (see for example Fig. 8.5 (a)).
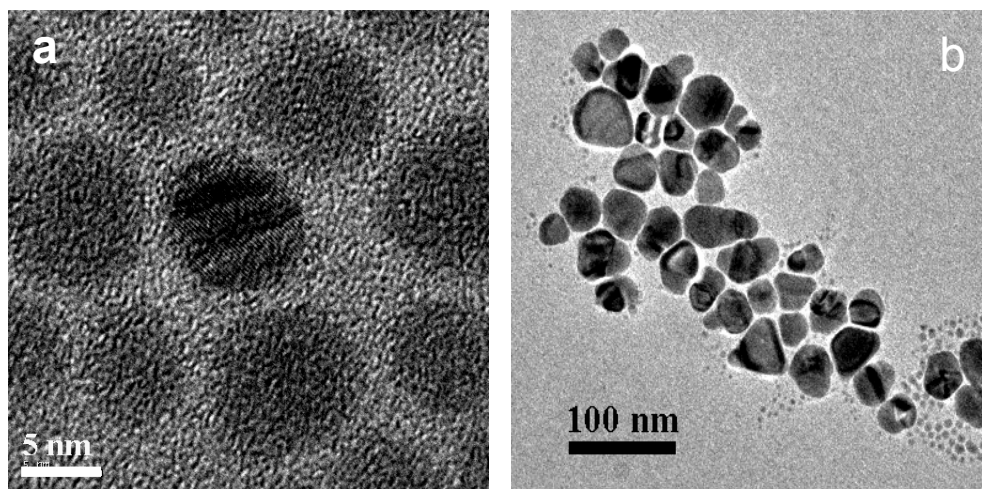
Fig. 8.5. TEM images of Ag nanoparticles formed in (a) 60 s and (b) 75 s of microwave irradiation [6].

Synthesis of Metal Oxides

$CaMoO_4$ has been synthesized at low temperatures by a modified citrate complex method using microwave irradiation. Synthesizing mixed metal oxides at low temperatures is a

tedious process an it needs high temperatures. As a result, the resulting material has poor surface area and larger crystallite size. For this kind of purpose, microwave can be used to effectively bring down the temperature required for the formation of mixed metal oxides. A flow chart for the synthesis of $CaMoO_4$ is given Scheme 8.1. In this case, citric acid makes a complex with the metal ions and due to the presence of the citrate, the formation of the nanoparticles is observed. This method is also known as citric acid combustion method. The corresponding nanoparticles of $CaMoO_4$ formed are shown in Fig. 8.6.

| Citric acid | ▶ | De-ionized Water | ◀ | Calcium Nitrate Ammonium Molybdate |

| Mixing and Stirring | 100 ˚C, 1 h |

| Metal-Citrate Complex | Microwave irradiation |

| Polymerized Complex | gel |

| Precursor |

| Heat Treatment | 300 ~ 700 ˚C , 3 h |

| $CaMoO_4$ powders | Characterization |
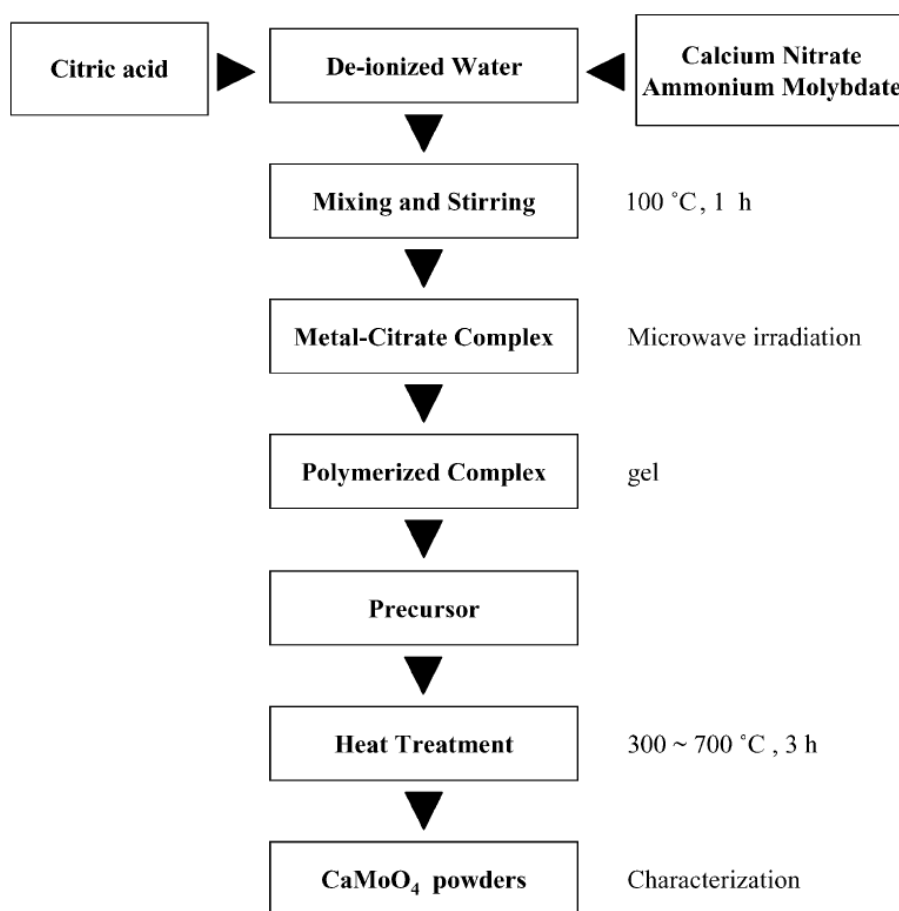
Scheme 8.1. Flow chart of the synthesis of $CaMoO_4$ by microwave assisted route [9]
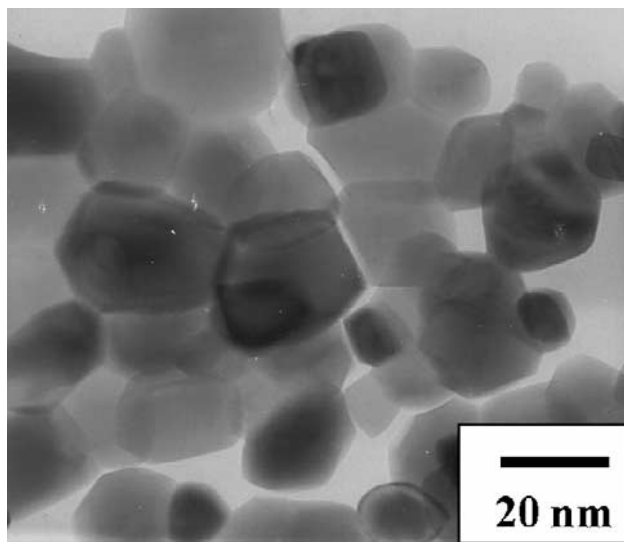
Fig. 8.6. TEM image of CaMoO₄ nanoparticle synthesized at 600 °C for 3 h [9]

Photochemical Decomposition Method

Synthesis of Metals

Silver nanowires have been synthesized using photographic principles. In this case, AgBr is reduced by in presence of a fluorescent light and followed by the development of the film. TEM images AgBr and Ag nanowires formed from this process are shown in Fig 8.7.
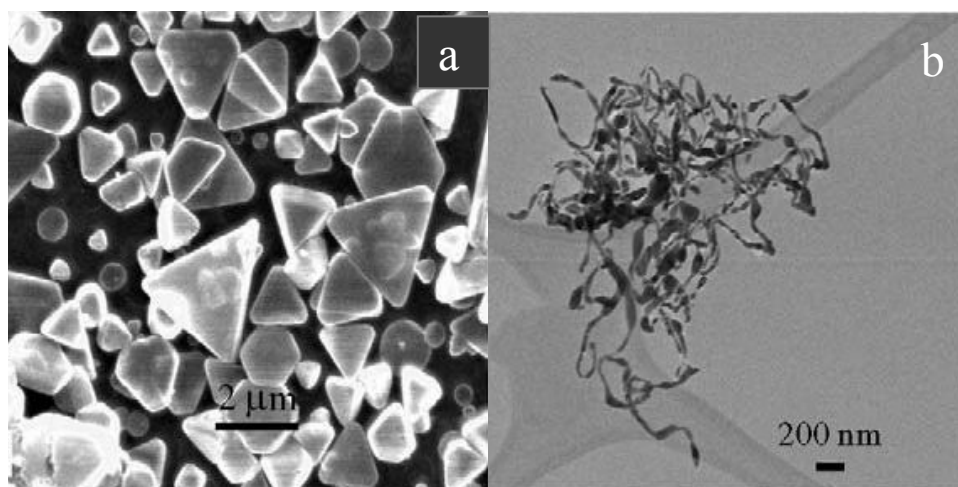
Fig. 8.7. TEM images of (a) AgBr and (b) Ag nanowire [10]

Synthesis of Metal Oxides

Iron oxide Nanoparticles

Nanoparticles of iron oxide have been synthesized by decomposing $Fe(CO)_5$ under ultraviolet light. During the photolysis, decomposition of $Fe(CO)_5$ takes place to form nanoparticles of iron metal and further it turns into iron oxide due to the instability of iron nanoparticles.

Synthesis of EuO nanocrystals

In a quartz vessel, $Eu(NO_3)_3$ (37.5 mM) and urea (112.5 mM) were dissolved in methanol (400 ml) under an N_2 atmosphere, and the solution was irradiated with a 500-W high-pressure mercury arc lamp at 25°C. A yellowish powder precipitated after 30 min. After 24 h of irradiation, the powder was separated by centrifugation and washed with methanol several times.

Synthesis of CdS nanorod
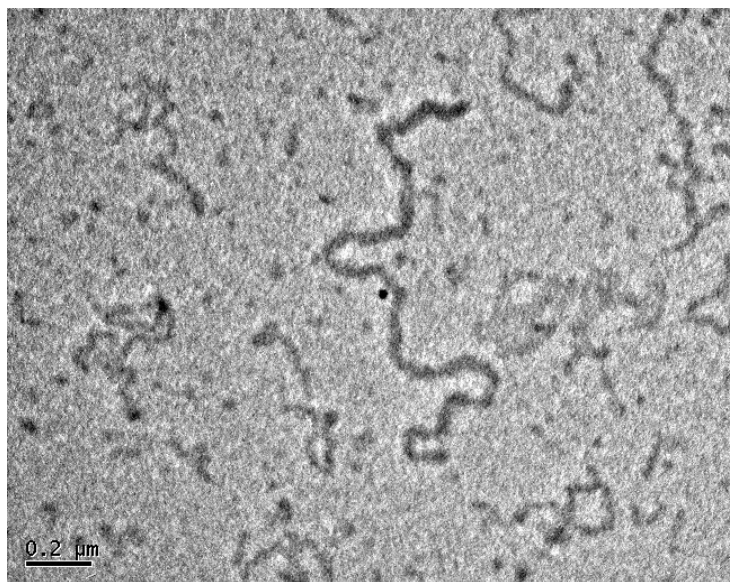
Fig. 8.8. TEM image of CdS nanowires synthesized by photochemical method [11].

CdS nanorods have been synthesized using cadmium salt, DNA base pairs and thioacetamide (TAA). Photo-irradiation was performed by directly placing the cuvette containing the mixture of DNA, Cd salt, and TAA solutions under 260 nm UV light

irradiation for six hours. The initially occurring DNA-Cd^{2+} complex formation was confirmed by a shift in the UV-vis spectrum of the mixed solution compared to the pure DNA. After photo-irradiation the UV-vis spectrum was again recorded showing the formation of CdS nanoparticles. Thioacetamide acts as sulphur source in this reaction. The corresponding CdS nanowires formed are shown in TEM image in Fig. 8.8.

SUMMARY

Solid state decomposition methods are important in the synthesis of the material both in nano size ranges as well as in bulk. In the case of thermal decomposition route, the compound having lower decomposition temperature is preferred. The decomposition temperature of the compound is mainly based on the redox potential of cation and anion of the compound. Microwave-assisted syntheses are more advantageous than conventional heating due to the increased rate of the reaction. Photochemical synthetic methods are also advantageous due to fact that the material is formed at ambient conditions so that the sintering of the materials is reduced.

REFERENCES

1.   S. Navaladian, B. Viswanathan, R. P. Viswanath and T. K. Varadarajan, *Nanoscale Research Letter,* 2 (2007) 44.

2.   I. K. Shim, Y. L. Lee, K. J. Lee, J. Joung, *Materials Chemistry and Physics,* (2008) (in press).

3.   C. M. Janet, B. Viswanathan, R. P. Viswanath and T. K. Varadarajan, *Journal of Physical Chemistry C*, 111 (2007) 10267.

4.   R. N. Nickolov, B. V. Donkova, K. I. Milenova1 and D. R. Mehandjiev, *Adsorption Science & Technology*, 24 (2006) 497.

5.   P. S. Nair, T. Radhakrishnan, N. Revaprasadu, G. A. Kolawole and P. O'Brien,*Chemiacl Communication* (2002) 564.

6.   S. Navaladian, C. M. Janet, B. Viswanathan, R. P. Viswanath and T. K. Varadarajan, Nanotechnology, 19 (2008) 045603.

7.   X. Wang, J. Song, L. Gao, J. Jin, H. Zheng and Z. Zhang, *Nanotechnology* 16 (2005) 37.

8.   Z. Zhou, Q. Sun, Z. Hu, and Y. Deng, *Journal of Physical Chemistry C, 110* (2006) 13387.

9. J. H. Ryu, J.-W. Yoon, C. S. Lim, W.-C. Oh and K. B. Shim, *Journal of Alloys and Compounds,* 39*0* (2005) 245.

10. C. Liewhiran, S. Seraphin, S. Phanichphant, Current Applied Physics, 6 (2006) 499.

11. S. Liu, R. J. Wehmschulte, G. Lian and C. M. Burba, *Journal of Solid State Chemistry,* 179 (2006) 696.

Chapter – 9

NEWER SYNTHETIC STRATERGIES FOR NANOMATERIALS

P. Sangeetha

1. INTRODUCTION

The emerging science in the world today mainly focuses on nanomaterials and its applications. Nano is interrelated to chemistry, physics and biology and it has attracted the attention of all eminent scientists to its side. Nanochemistry can be described as a special discipline of inorganic or solid state chemistry. It focuses on the synthesis of nanoparticulate systems. The nanochemist can be considered to work towards this goal from the atom "up", whereas the nanophysicist tends to operate from the bulk "down". It is schematically represented in Fig. 9.1
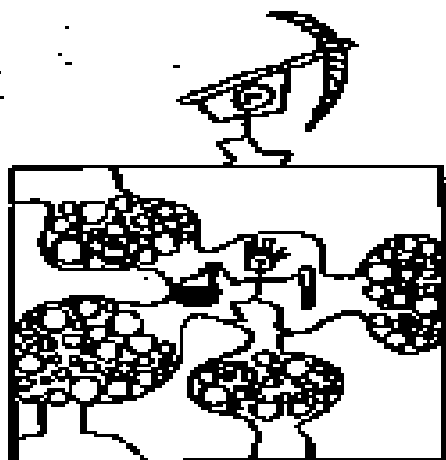
Fig. 9.1 Schematic diagram

1.1 What is Nano?

The term nano is a measurement of size. A nanometre (nm) is a millionth of a millimetre. By way of illustration, a nanometer is about 1/50,000th the width of a human hair, and a sheet of normal office paper is about 100,000 nm thick. A nanomaterial or a nanoparticle is usually considered to be a structure between 0.1 and 100 nm (1/1,000,000 mm). The origin of the prefix "nano" is from the Greek word "nanos"' meaning dwarf. Nanotechnology deals with a scale that is over 10,000 times smaller than a millimetre. It

involves investigating, producing and applying structures that are smaller than 100 nanometres (nm). At the nanoscale, the physical, chemical, and biological properties of materials differ in fundamental and often valuable ways from the properties of individual atoms and molecules or bulk matter. Research and development in nanotechnologies is directed toward understanding and creating improved materials, devices, and systems that exploit these new properties. These properties have been found to be very useful for an increasing number of commercial applications, for example: protective coatings, light-weight materials, self-cleaning clothing, to name but a few. The main classes of nanoscale structures and tunable properties are summarized in Table 9.1 and 9.2.

Table 9.1 Main classes of nanoscale:

Dimension	
3 dimensions < 100nm	Particles, quantum dots, hollow spheres, etc.
2 dimensions < 100nm	Tubes, fibres, wires, platelets, etc.
1 dimension < 100nm	Films, coatings, multilayer, etc.
Phase composition	
Single-phase solids	Crystalline, amorphous particles and layers, etc.
Multi-phase solids	Matrix composites, coated particles, etc.
Multi-phase systems	Colloids, aerogels, Ferro fluids, etc.
Manufacturing process	
Gas phase reaction	Flame synthesis, condensation, CVD, etc.

Liquid phase reaction Sol-gel, precipitation, hydrothermal processing etc.

Mechanical properties   Ball milling, plastic deformation etc.

Table 9.2. Tunable properties by nanoscale surface design and their application potentials

Mechanical properties (e.g., hardness, scratch resistance, tribology).	Wear protection of machinery and equipment, mechanical protection of soft materials (polymers, wood, textiles, etc.)
Wetting properties (e.g. anti-adhesive, hydrophobic, hydrophilic).	Anti-graffiting, anti-fouling, lotus-effect, self cleaning surface for textiles and ceramics, etc.
Thermal and chemical properties (e.g. heat resistance and insulation, corrosion resistance).	Corrosion protection for machinery and equipment, heat resistance for turbines and engines, thermal insulation equipment and building materials etc.
Biological properties (biocompatibility, anti-infective).	Biocompatible implants, medical tools and wound dressings etc.
Electronical and magnetic properties (e.g. magnetoresistance, dielectric)	Ultra-thin dielectrics for field-effect transistors, magneto-resistive sensors and data memory etc.
Optical properties (e.g. anti-reflection, photo and electro-chromatic)	Photo and electro-chromic windows, anti-reflective screens and solar cells etc.

1.2 Nanotechnology:

Nanotechnology is one of the key technologies of the 21st century. Nanotechnology refers broadly to a field of applied science and technology whose unifying theme is the control of matter on the atomic and molecular scale as shown in Fig. 9.2, generally 100 nanometers or smaller, and the fabrication of devices with critical dimensions that lie within this size range.
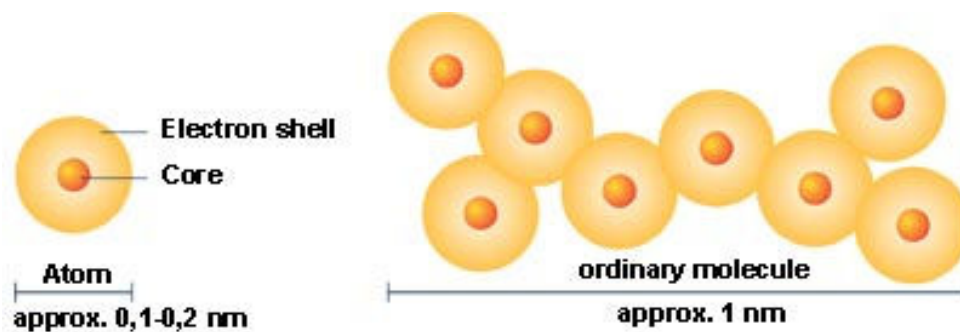
Fig. 9.2. Schematic representation for atom and molecule

1.3 Nanomaterials:

It is the study of how materials behave when their dimensions are reduced to the nanoscale. It can also refer to the materials themselves that are used in nanotechnology. Unique changes occur in the electronic structure and chemical properties of solids when their dimensions are reduced to the nanoscale, including development of discrete electronic structure, quantum confinement, structural strain and distortion, and altered interfacial/surface reactivity. These changes translate into new physical and chemical behavior which is not observed in the 'bulk' form of the material.

Given that processes at the gas/solid and liquid/solid interfaces are largely controlled by local phenomena (e.g., the availability, reactivity and density of surface sites), changes in the local electronic and physical structures of a solid brought about by 'nanostructuring' which should have a tremendous impact on heterogeneous chemistry (catalysis). Examples: Au for selective oxidation, arene and alkene hydrogenation by Ir, Rh, photocatalytic activity of TiO_2 and unique reactivity of oxide nanoparticles.

2. NEWER SYNTHETIC STRATEGIES TO BUILD PROTEIN BASED NANOMATERIALS:

Recent progress in nanotechnology has yielded new device components with unprecedented capabilities. However, the small size of these building blocks makes it difficult to position them into functional assemblies using existing patterning techniques.

(a)   **(b)**
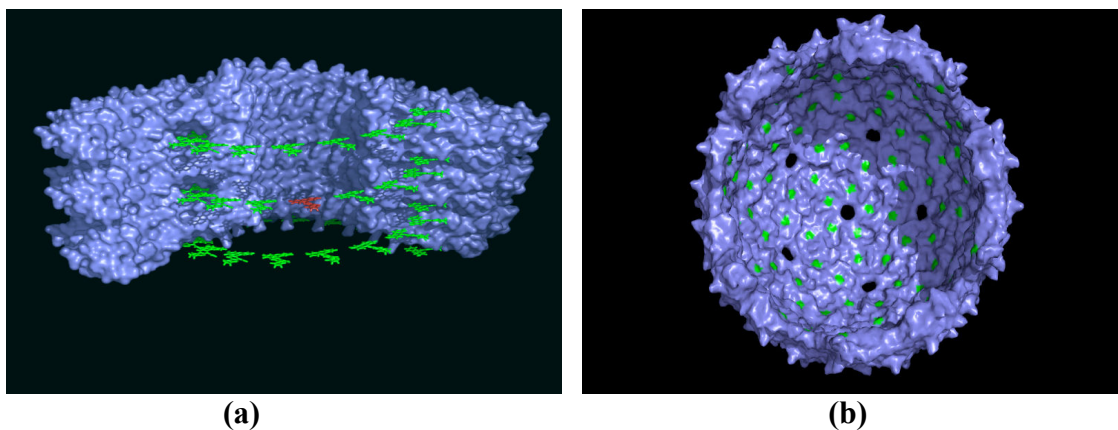
Fig. 9.3 (a) Arrys of chromophores for light harvesting and (b) Spherical carriers for PET imaging applications

3. SYNTHESIS AND CHARACTERIZATION OF INORGANIC NANOMATERIALS

As one solution to this problem, the protein shells of two viruses are converted into scaffolds that can position nanoscale objects with excellent spatial resolution. In one case, this strategy has been used to synthesize arrays of fluorescent molecules, providing efficient mimics of the light harvesting system present in photosynthetic organisms. In a second research area, well-defined core/shell materials have been prepared for applications in diagnostic imaging. The cornerstone of these efforts has been a series of new synthetic reactions that can modify biomolecules (Fig. 9.3) with high site-selectivity and yield. The synthetic route will focus on the development of the methods and the applications of the new materials that have been built through their use.

The study of nanoscale inorganic materials is an exciting and rapidly growing area of research which offers multiple opportunities for innovation and creativity. Our research focuses primarily on the development of new synthetic approaches to nanoparticles with tunable properties. One aspect of our work is synthesis of new precursors as well as the application of established molecular precursors to synthesize nanometer size metal alloy, metal phosphide, metal oxide, and metal chalcogenide materials. Some new wet-chemistry procedures to produce size- and morphology-controlled nanoparticles are:

> Single-source precursors to heterometallic oxide materials
> Single-source precursors to phosphide nanoparticles
> Single-source precursors to metal chalcogenide materials
> Synthesis of nanoalloys from organometallic precursors
> Shape control syntheses of iron and manganese oxides

3.1 Single-Source Precursors to Heterometallic Oxide Materials

The development of efficient photocatalytic systems has been of vital interest since these can contribute to the reduction of pollution and solve some energy-related problems. However the synthesis of environmentally-friendly binary oxides of desired morphology still remains a challenge. In the synthesis described so far, the problems encountered were phase inhomogenities and the inclusion of carbon originating from the ligands. Developing new heterometallic (single-source) precursors to synthesize AMO_3 (A = Li, Na, K, Rb; M = Nb, Ta) and $MBiO_4$ (M=V, Nb, Ta) nanoparticles, which are known as

stable and efficient photocatalysts. The precursors to be synthesized are composed of salicylate and alkoxide complexes that contain the metal elements in the desired ratios. A number of heterometallic complexes were synthesized (Fig. 9.4) and their utility as single-source precursors was tested. Pyrolysis and wet-chemistry routes were successfully used to produce mixed oxide of micron and nano-sized particles.
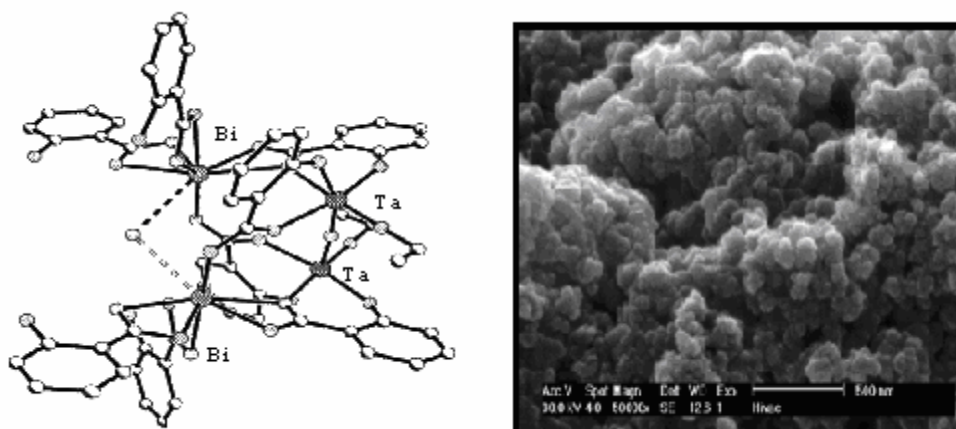
Fig. 9.4 $Bi_2Ta_2(sal)_4(Hsal)_4(OEt)_2$ (left) and SEM image hydrolysis product (right)
(sal = $O_2CC_6H_4O$, Hsal = $O_2CC_6H_4OH$)   [12]

3.2 Single-Source Precursors to Phosphide Nanoparticles

Magnetic materials can be made in a variety of forms including nanoparticles, thin molecular films, and bulk materials.
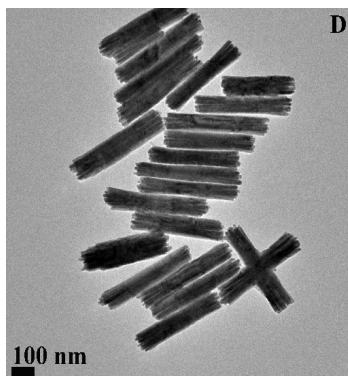
Fig. 9.5. Iron phosphide nanorods [13]

Improving the current technologies that utilize magnetic compounds depends upon the ability to produce pure materials; of concern in the synthesis of these materials is the ability to produce materials with a controlled stoichiometry. While most studies of magnetic nanoparticles have been on magnetic metals, alloys, and oxides, the focus of this research is on binary magnetic materials composed of transition metals and p-block elements.

3.3 Single-Source Precursors to Metal Chalcogenide Materials

The initial research will involve the synthesis of iron phosphide nanomaterials from known heterometallic precursors; there are a few binary phases of iron phosphide that possess magnetic properties (FeP possesses antiferromagnetic behavior, while Fe_3P and Fe_2P exhibit ferromagnetic properties). Fig. 9.5 shows iron phosphide nanorods synthesized, utilizing a heterometallic iron-phosphorus cluster.
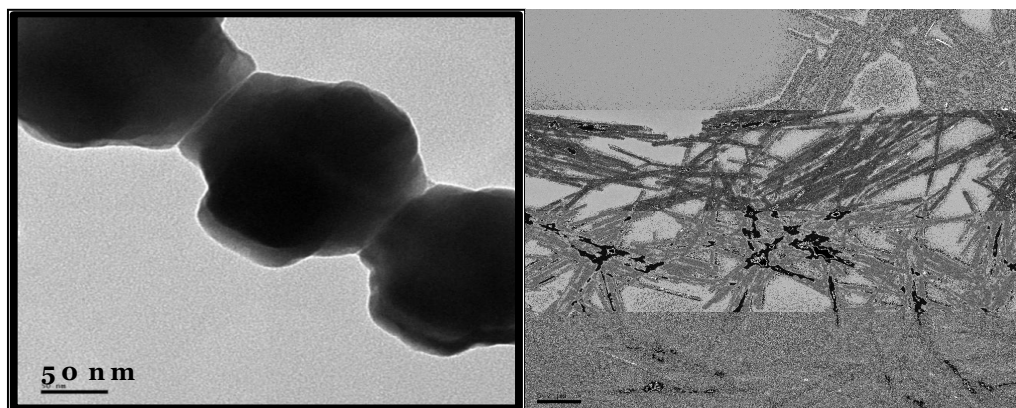
Fig. 9.6. Nanoparticles of PbS and Bi_2S_3 [14]

The design of chalcogenide materials in discrete forms is a major problem for modern solid-state chemists and materials scientists. Many of these chalcogenide materials have potential applications in electronic devices. It is mainly focused on the design, syntheses, and decomposition of new molecular precursors to such chalcogenide materials in forms, such as rods, wires, and more complex shapes that have been unattainable with conventional solid-state methods. Developing the chemistry of metal complexes with chalcogen containing ligands as molecular precursors to a number of metal chalcogenide materials, including Bi_2S_3, Bi_2Se_3, PbS, PbSe, CdS, CdSe (Fig. 9.6). A major emphasis of the synthesis is to control the organization of the materials at the nanoscale and to find

a relationship between the nature of the precursors and the quality of the nanomaterials obtained. To accomplish this, an interdisciplinary approach, with experience in synthetic and materials chemistry, as well as crystallography, will provide a plethora of opportunities to investigate these interesting problems in nanoscience. Various methods are being developed to synthesize, re shape and study the assembly characteristics of chalcogenide metal nanoparticles.

3.4 Synthesis of Nanoalloys from Organometallic Precursors

Another research in the area of nanoscale materials concerns the synthesis of alloy and intermetallic nanoparticles from the corresponding organometallic precursors. The preparation of a series of Bi-Ru, Bi-Pd, and Bi-Pt intermetallic nanocrystals using wet-chemistry procedures has been achieved (Fig. 9.7). These methods are based on the relatively low-temperature reaction between two organometallic precursors in the presence or absence of stabilizing agents. The most advantageous points of these procedures consist in overcoming the need of chemical reducing agents and high temperature decomposition. In addition, regular spherical agglomerates are formed and their size could be tuned by varying temperature and surfactants. The efficiency of this procedure is shown by the ability of the particles to be dried and redispersed, while maintaining their morphology. These nano-alloys have recently attracted attention because of their activity and selectivity toward numerous catalytic reactions such as dehalogenation, oxidation of alcohols and aldehydes, as well as for applications in fuel cells.
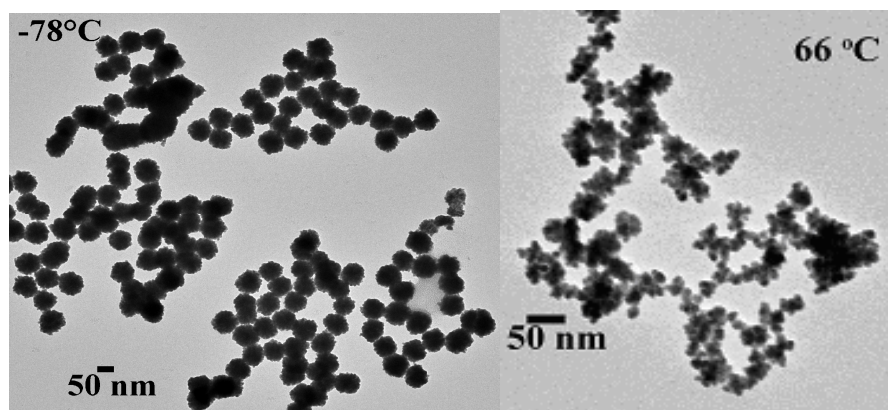
Fig. 9.7 Bi-Pd nanoparticles prepared at two different temperatures [13]

3.5 Shape Control Synthesis of Iron and Manganese oxides

Bulk iron oxides and manganese oxides have many technical applications due to their magnetic and catalytic properties. These properties can be enhanced by tuning particle sizes within the nanometer scale. Magnetic nanoparticles (NPs), for example, have potential applications in information storage, medical imaging, drug delivery, and water remediation. Many applications, such as heterogeneous catalysis, are enhanced by the high surface area that nanoparticles possess. However, enhancement of physical properties is not only limited to size effects. There are a number of publications on nanoparticles with shape-dependent magnetic, electronic, and optical properties. Most of these studies are on NPs such as spheres, rods, wires, belts, and disks, which can be classified as 'traditional' shapes. The synthesis, the physical properties, and the growth mechanisms of 'traditional' shapes, including iron and manganese oxides, have been widely investigated and are well-understood. However, the formation mechanism and physical properties of non-traditional multi-branched NPs such as tetrapods, hexapods, tripods, stars, and dumbbells, are not completely understood and have led to investigations on shape controlled synthesis and to the development of non-traditional growth mechanism.
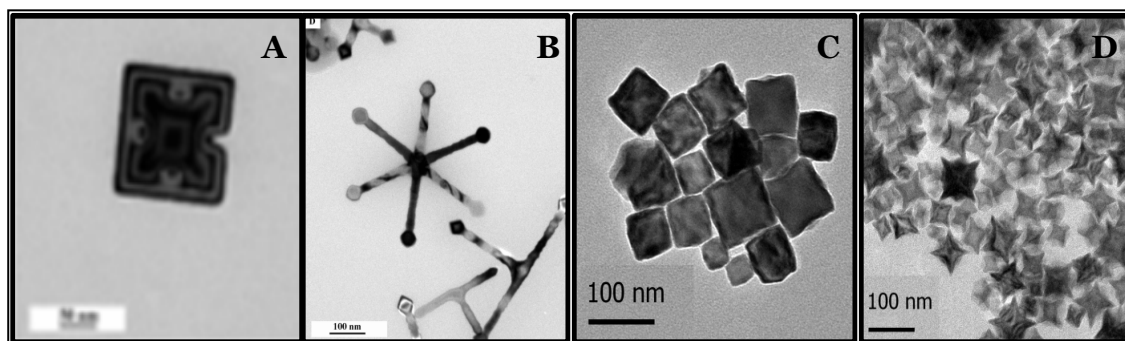
Fig. 9.8. MnO (A and B) and FeO (C andD) NPs [13]

The synthesis of new cross-shaped, hexapod, and concave-faces cubic nanoparticles (NPs) of MnO, FeO, and Fe$_{1-x}$Mn$_x$O have been reported. The main goals of these studies are :

 1. To develop simple and inexpensive synthesis to grow nanoparticles with new shapes.

2. To study the growth mechanisms by observation of the nanoparticle morphologies as a function of the reaction parameters: surfactant ratio, water concentration, time, temperature, and precursor.

Some of the morphologies obtained are shown in Fig. 9.8

A motivation in nanoscience is to try to understand how materials behave when sample sizes are close to atomic dimensions. Fig. 9.8 for example shows a picture of nanofibrils that are 10 to 100 times smaller in diameter than conventional textile fibers. In comparison to a human hair which is ca. 80,000 nm in diameter, the nanofibers are 1,000 times smaller in diameter. When the characteristic length scale of the microstructure is in the 1- 100 nm range, it becomes comparable with the critical length scales of physical phenomena, resulting in the so-called "size and shape effects." This leads to unique properties and the opportunity to use such nanostructured materials in novel applications and devices. Phenomena occurring on this length scale are of interest to physicists, chemists, biologists, electrical and mechanical engineers, and computer scientists, making research in nanotechnology a frontier activity in materials science.
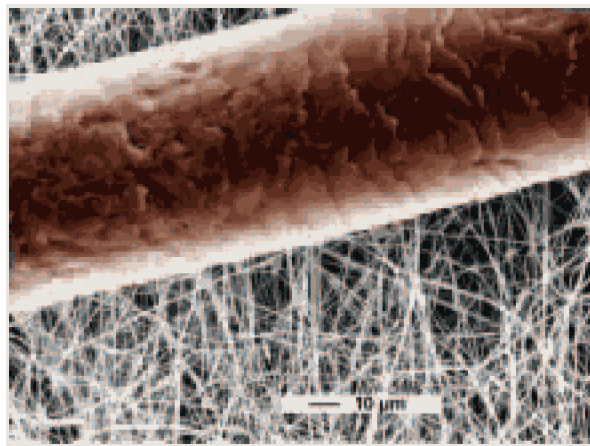
Fig. 9.9 A picture of nanofibrils shown with a human hair for reference [17]

On tracking the nano evolution, it has been stated that no matter what the market outcomes in the near or long term, nanoscience will never be an industry unto itself but a science of many avenues of application, and possibility that could redefine the direction of several industries. This insight allows one to recognize that nanotechnology is not "a

technology" but "a set of technologies," yielding a set of technical breakthroughs that will sweep into many different markets. Within such a framework, the world of nanotechnology may be divided into three broad categories: nanostructured materials, nanotools, and nanodevices.

4. Nanotools

These include fabrication techniques; analysis and metrology instruments; and software for nanotechnology research and development. They are used in lithography, chemical vapor deposition (CVD), 3-D printing, and nanofluidics. Nanofluidics, the study of nanoscale fluid behavior, for example, the study of dynamics of droplets adsorbed onto surfaces under shearing, is mostly used in areas such as medical diagnostics and biosensors.

5. Nanostructured Materials

- Nanocrystalline Materials
- Fullerenes/ Carbon Nanotubes
- Dendrimers (Organic Nanoparticles)
- Polyhedral Silsesquioxanes (Inorganic-Organic Hybrid Nanoparticles)
- Nano-Intermediates
- Nanocomposites

Nanostructured (NsM) materials are materials with a microstructure the characteristic length scale of which is on the order of a few (typically 1-100) nanometers. The microstructure refers to the chemical composition, the arrangement of the atoms, and the size of a solid in one, two, or three dimensions. Effects controlling the properties of nanostructured materials include size effects (where critical length scales of physical phenomena become comparable with the characteristic size of the building blocks of the microstructure), changes of the dimensionality of the system, changes of the atomic structure, and alloying of components (e.g., elements) that are not miscible in the solid and/or the molten state.

The synthesis, characterization and processing of nanostructured materials are part of an emerging and rapidly growing field. Research and developement in this field emphasizes scientific discoveries in the generation of materials with controlled microstructural characteristics, research on their processing into bulk materials with

engineered properties and technological functions, and introduction of new device concepts and manufacturing methods.

Nanostructured materials may be grouped under nanoparticles (the building blocks), nano-intermediates, and nanocomposites. They may be in or far away from thermodynamic equilibrium. For example, nanostructured materials consisting of nanometer-sized crystallites of Au or NaCl with different crystallographic orientations and/or chemical compositions vary greatly from their thermodynamic equilibrium. Nanostructured materials synthesized by supramolecular chemistry yielding nanoassemblies are examples of those in thermodynamic equilibrium. In the subsequent paragraphs, the various classes of nanoparticles that serve as the building blocks of nanomaterials and devices will be discussed. They include nanocrystalline materials such as ceramic, metal and metal oxide nanoparticles; fullerenes, nanotubes and related structures; nanofibers and wires, and precise organic as well as hybrid organic-inorganic nanoarchitechtures such as dendrimers and polyhedral silsesquioxanes, respectively.

5.1 Nanocrystalline Materials

Ceramics, metals, and metal oxide nanoparticles fall in this category. In the last two decades a class of materials with a nanometer-sized microstructure have been synthesized and studied. These materials are assembled from nanometer-sized building blocks, mostly crystallites. The building blocks may differ in their atomic structure, crystallographic orientation, or chemical composition. In cases where the building blocks are crystallites, incoherent or coherent interfaces may be formed between them, depending on the atomic structure, the crystallographic orientation, and the chemical composition of adjacent crystallites. In other words, materials assembled of nanometer-sized building blocks are microstructurally heterogeneous, consisting of the building blocks (e.g. crystallites) and the regions between adjacent building blocks (e.g. grain boundaries). It is this inherently heterogeneous structure on a nanometer scale that is crucial for many of their properties and distinguishes them from glasses, gels that are microstructurally homogeneous.

Grain boundaries make up a major portion of the material at nanoscales, and strongly affect properties and processing. The properties of NsM deviate from those of single crystals (or coarsegrained polycrystals) and glasses with the same average chemical

composition. This deviation results from the reduced size and dimensionality of the nanometer-sized crystallites as well as from the numerous interfaces between adjacent crystallites. An attempt is made to summarize the basic physical concepts and the microstructural features of equilibrium and non-equilibrium NsM. Nanocrystallites of bulk inorganic solids have been shown to exhibit size dependent properties, such as lower melting points, higher energy gaps, and nonthermodynamic structures. In comparison to macro-scale powders, increased ductility has been observed in nanopowders of metal alloys. In addition, quantum effects from boundary values become significant leading to such phenomena as quantum dots lasers.

One of the primary applications of metals in chemistry is their use as heterogeneous catalysts in a variety of reactions. In general, heterogeneous catalyst activity is surface dependent. Due to their vastly increased surface area over macro-scale materials, nanometals and oxides are ultra-high activity catalysts. They are also used as desirable starting materials for a variety of reactions. Nanometals and oxides are also widely used in the formation of nanocomposites. Aside from their synthetic utility, they have many useful and unique magnetic, electric, and optical properties.

5.2 a. Fullerenes:

The discovery of fullerenes in 1985 by Curl, Kroto, and Smalley culminated in their Nobel Prize in 1996. Fullerenes, or Buckminsterfullerenes, are named after Buckminster Fuller the architect and designer of the geodesic dome and are sometimes called bucky balls. The names derive from the basic shape that defines fullerenes; an elongated sphere of carbon atoms formed by interconnecting six-member rings and twelve isolated five-member rings forming hexagonal and pentagonal faces. The first isolated and characterized fullerene, C_{60}, contains 20 hexagonal faces and 12 pentagonal faces just like a soccer ball and possesses perfect icosahedral symmetry.

Fullerene chemistry continues to be an exciting field generating many articles with promising new applications every year. Magnetic nanoparticles (nanomagnetic materials) show great potential for high-density magnetic storage media. Recent work has shown that C_{60} dispersed into ferromagnetic materials such as iron, cobalt, or cobalt iron alloy can form thin films with promising magnetic properties. A number of organometallic-fullerene compounds have recently been synthesized. Of particular note

are a ferrocene-like C_{60} derivative and pair of fullerenes bridged by a rhodium cluster. Some fullerene derivatives even exhibit superconducting character. There has been a report of a fullerene containing, superconducting field-effect device with a T_c as high as 117 K.

5.2 b. Carbon Nanotubes:

Carbon nanotubes (CNTs) are hollow cylinders of carbon atoms. Their appearance is that of rolled tubes of graphite such that their walls are hexagonal carbon rings and are often formed in large bundles. The ends of CNTs are domed structures of six-membered rings capped by a five-membered ring. Generally speaking, there are two types of CNTs: single-walled carbon nanotubes (SWNTs) and multi-walled carbon nanotubes (MWNTs) (Fig.10). As their names imply, SWNTs consist of a single, cylindrical graphene layer, where as MWNTs consist of multiple graphene layers telescoped about one another. Carbon nanotubes (CNTs) were first isolated and characterized by Ijima in 1991. Since then numerous research articles have been published, and new applications for CNTs have been proposed every year. The unique physical and chemical properties of CNTs, such as structural rigidity and flexibility continue to generate considerable interest. Additionally, CNTs are extremely strong, about 100 times stronger (stress resistant) than steel at one-sixth the weight. CNTs can also act as either conductors or semiconductors depending on their chirality, possess an intrinsic superconductivity, are ideal thermal conductors, and can also behave as field emitters.

SWNT (top), MWNT (bottom)
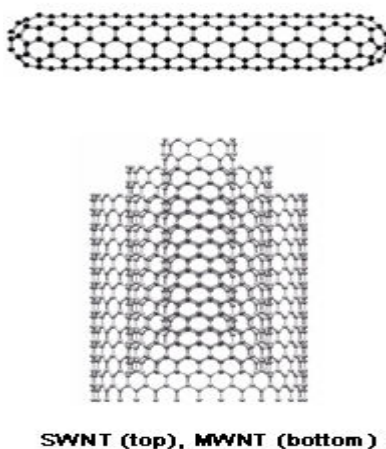
Fig. 9.10. Carbon nanotubes

Currently, the physical properties are still being discovered and disputed. What makes it so difficult is that nanotubes have a very broad range of electonic, thermal, and structural properties that change depending on the different kinds of nanotube (defined by its diameter, length, and chirality, or twist). To make things more interesting, besides having a single cylindrical wall (SWNTs), nanotubes can have multiple walls (MWNTs)--cylinders inside the other cylinders.

(i) Properties of Carbon Nanotubes: With graphene tubes parallel to the filament axis, nanotubes would inherit several important properties of 'intra-plane' graphite. This imparts a very unique combination of properties on this material, namely:

> ➢ High aspect ratio structures with diameters in nanometers, lengths in microns

> ➢ High mechanical strength (tensile strength 60GPa) and modulus (Young's modulus 1TPa)

> ➢ -- High electrical conductivity (10^{-6} ohm m typically), and for well crystallized nanotubes ballistic   transport is observed

> ➢ High thermal conductivity (1750-58 00 W/mK)

> ➢ -- Being covalently bonded, as electrical conductors they do not suffer from electro-migration   or atomic diffusion and thus can carry high current densities (10^7 -10^9 A/cm^2)

> ➢ Single wall nanotubes can be metallic or semi-conducting

> ➢ Chemically inert, not attacked by strong acids or alkali

> ➢ Collectively, nanotubes can exhibit extremely high surface area

(ii) CarbonNnanotubes Developed by Arry Group

Arry has done a lot of research and development work in the carbon nanotubes synthesis and application, and developed a scalable CVD method to produce high purity single-walled carbon nanotubes (SWNTs) and multi-walled carbon nanotubes (MWNTs) with various diameters and narrow diameter distribution. The technology for producing 5kg 20-40 nm MWNTs per day was evaluated as an advanced technology in the world by CAS scientists. They can produce 1.5kg SWCNTs per day and 10kg MWNTs with 8-15nm in diameter per day. The production facilities can be enlarged easily. In Fig.11, the proportion of usage as conceived by Array group is shown.

International Patent of Nanotubes Filings and Issuances

Source: Science 2002
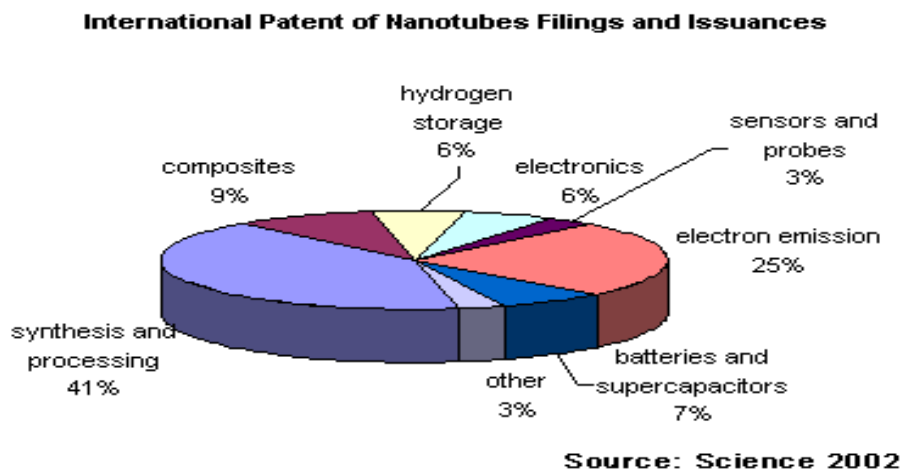
Fig. 9.11. Illustration given by Array group [15]

Nanotechnology develops the basis for increasingly smaller data memories with increasingly larger storage capacity, for highly efficient filters for sewage treatment, for photovoltaic windows, for materials which can be used to build ultra-light engines and body parts in the automobile industry or for artificial joints which are better tolerated by the human body due to organic nano-surfaces. In the future, as nanoscale molecular self-assembly becomes a commercial reality, nanotech will move into conventional manufacturing. While nanotechnology offers opportunities for society, it also involves profound social and environmental risks, not only because it is an enabling technology to the biotech industry, but also because it involves atomic manipulation and will make possible the fusing of the biological world with the mechanical world. There is a critical need to evaluate the social implications of all nanotechnologies; in the meantime, the Arry Group believes that a moratorium should be placed on research involving molecular self-assembly and self-replication.

(iii) Carbon Nanotube-Based Nanodevices

Carbon nanotubes are a hot research area at the moment. The excitement has been fueled by experimental breakthroughs that have led to realistic possibilities of using them commercially. Applications could include field emission-based flat panel displays, novel semiconducting devices, chemical sensors, and ultra-sensitive electromechanical sensors. The utility of carbon nanotubes for molecular electronics or computers, first predicted by theory and simulations, is now being explored through experiments to

fabricate and conceptualize new devices based on simulations. Carbon nanotubes are now the top candidate to replace silicon when current chip features cannot be made any smaller in 10-15 year's time. Calculations show that nanotubes can have metallic or variable semiconducting properties with energy gaps ranging from a few meV to a few tenths of an eV. Experiments probing the density of states confirm these predictions. Conductivity measurements on single nanotubes have shown rectification effects for some nanotubes and ohmic conductance for others. These properties suggest that nanotubes could lead to a new generation of electronic devices. Simulations to investigate the interaction of water molecules with a nanotube tip revealed an atomistic understanding of the interaction, which is critical in designing commercial-quality flat panel displays around carbon nanotubes. Their use as ultra-sensitive electromechanical sensors has also been explored.

5.3 Dendrimers (Organic Nanoparticles)

In recent years, a new structural class of macromolecules, the *dendritic polymers*, has attracted the attention of the scientific community. These nanometer sized, polymeric systems are hyperbranched materials having compact hydrodynamic volumes in solution and high, surface, functional group content. They may be water-soluble but, because of their compact dimensions, they do not have the usual rheological thickening properties that many polymers have in solution. Dendrimers, the most regular members of the class, are synthesized by step-wise convergent or divergent methods to give distinct stages or generations. Dendrimers are defined by their three components: a central core, an interior dendritic structure (the branches), and an exterior surface (the end groups). Over 50 compositionally different families of these nanoscale macromolecules, with over 200 end-group modifications, have been reported.They are characterized by nearly spherical structures, nanometer sizes, large numbers of reactive end group functionalities, shielded interior voids, and low systemic toxicity. This unique combination of properties makes them ideal candidates for nanotechnology applications in both biological and materials sciences. The state of reports in the current literature has been directed toward their applications in a broad range of fields, including materials engineering, industrial, pharmaceutical, and biomedical applications. Specifically, nanoscale catalysts, novel lithographic materials, rheology modifiers, and targeted drug

delivery systems, MRI contrast agents, and bioadhesives represent some of the potential applications.

5.4 Polyhedral Silsesquioxanes (Inorganic-Organic Hybrid Nanoparticles)

Hybrid inorganic-organic composites are an emerging class of new materials that hold significant promise. Materials are being designed with the good physical properties of ceramics and the excellent choice of functional group chemical reactivity associated with organic chemistry. New silicon-containing organic polymers, in general, and polysilsesquioxanes, in particular, have generated a great deal of interest because of their potential replacement for and compatibility with currently employed, silicon-based inorganics in the electronics, photonics, and other materials technologies. Hydrolytic condensation of trifunctional silanes yields network polymers or polyhedral clusters. Hence they are known by the "not quite on the tip of the tongue" name silsesquioxanes. Each silicon atom is bound to an average of one and a half (sesqui) oxygen atoms and to one hydrocarbon group. Typical functional groups that may be hydrolyzed or condensed include alkoxy- or chlorosilanes, silanols, and silanolates. Synthetic methodologies that combine pH control of hydrolysis/condensation kinetics, surfactant-mediated polymer growth, and molecular templating mechanisms have been employed to control molecular scale regularity as well as external morphology in the resulting inorganic/organic hybrids (from transparent nanocomposites, to mesoporous networks, to highly porous and periodic organosilica crystallites) all of which have the silsesquioxane stoichiometry. These inorganic-organic hybrids offer a unique set of physical, chemical, and size dependent properties that could not be realized from just ceramics or organic polymers alone. Silsesquioxanes are therefore depicted as bridging the property space between these two component classes of materials. Many of these silsesquioxane hybrid materials also exhibit an enhancement in properties such as solubility, thermal and thermomechanical stability, mechanical toughness, optical transparency, gas permeability, dielectric constant, and fire retardancy, to name just a few.

5.5 Nano-Intermediates

Nanostructured films, dispersions, high surface area materials, and supramolecular assemblies are the high utility intermediates to many products with improved properties such as solar cells and batteries, sensors, catalysts, coatings, and drug delivery systems.

They have been fabricated using various techniques. Nanoparticles are obvious building blocks of nanosystems but, require special techniques such as self-assembly to properly align the nanoparticles. Recent developments have lead to air resistant, room temperature systems for nanotemplates with features as small as 67 nm. More traditionally, electron-beam systems are used to fabricate devices down to 40 nm.

5.6 Nanocomposites

Nanocomposites are materials with a nanoscale structure that improve the macroscopic properties of products. Typically, nanocomposites are clay, polymer or carbon, or a combination of these materials with nanoparticle building blocks. Nanocomposites, materials with nanoscale separation of phases can generally be divided into two types: multilayer structures and inorganic/organic composites. Multilayer structures are typically formed by gas phase deposition or from the self-assembly of monolayers. Inorganic/organic composites can be formed by sol-gel techniques, bridging between clusters (as in silsequioxanes), or by coating nanoparticles, in polymer layers for example. Nanocomposites can greatly enhance the properties of materials. For example, ppm level impurities can result in the formation of nanoscale aluminide secondary phases in aluminum alloys, increasing their strength and corrosion resistance. Magnetic multilayered materials are one of the most important aspects of nanocomposites as they have led to significant advances in storage media.

5.6 a. Polymer-Clay Nanocomposites

The large industrial demand for polymers has lead to an equally large interest in polymer composites to enhance their properties. Clay-polymer nanocomposites are among the most successful nanotechnological materials today. This is because they can simultaneously improve material properties without significant tradeoffs. Recent efforts have focused upon polymer-layered silica nanocomposites and other polymer/clay composites. These materials have improved mechanical properties without the large loading require by traditional particulate fillers. Increased mechanical stability in polymer-clay nanocomposites also contributes to an increased heat deflection temperature. These composites have a large reduction gas and liquid permeability and solvent uptake. Traditional polymer composites often have a marked reduction in optical clarity; however, nanoparticles cause little scattering in the optical spectrum and very

little UV scattering.Although flame retardant additives to polymers typically reduce their mechanical properties, polymer-clay nanocomposites have enhanced barrier and mechanical properties and are less flammable. Compression-injection molding, melt-intercalation, and coextrusion of the polymer with ceramic nanopowders can form nanocomposites. Often no solvent or mechanical shear is needed to promote intercalation.

6. Novel Materials at the Nanoscale —Functional Nanomaterials

Morphology-controlled functional nanomaterials have unique chemical, mechanical, electrical, optical, magnetic or biological properties that are distinctly different form their macroscopic analogs and provide new diverse opportunities for promising nanotechnologies.
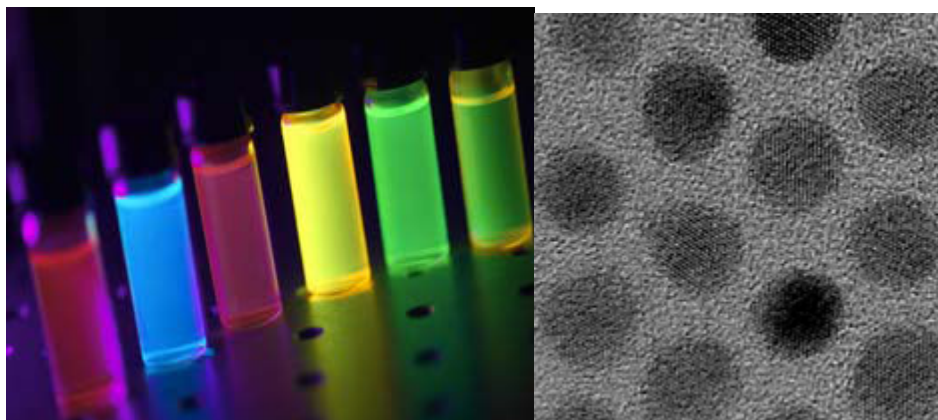
Fig. 9.12 Quantum dots: Colour tuning [2]

6.1 Nanomaterials Size and Composition-Tunable Quantum DotsConducting

Development of a scalable synthetic strategy is necessary to address the quantum dots' colour-tuning and stability issues. Alloyed ZnCdS/Se nanocrystals have unique composition-tunable optical properties including:-High luminescence/stability -Increased narrow luminescence spectral-width. These size and composition-tunable quantum dots have applications in the optoelectronic and biomedical sectors. (Fig 9.12)

7. ZnO/TiO₂ Nanorods or Nanoarrays and Silica-Coated Metal Nanocrystals
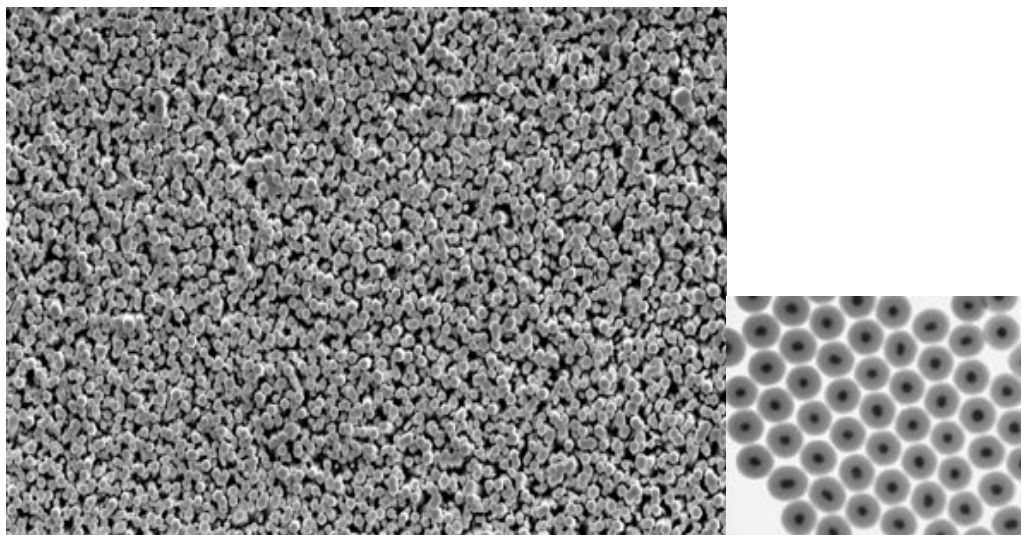
Fig. 9.13. Nanoarrays of ZnO/TiO$_2$ [16]

Researchers have focused on large-scale growth of well-aligned ZnO nanorods on selected substrates. Their applications are short-wavelength optoelectronic devices, solar energy conversion, transparent conducting coating materials and sensors. Researchers try to find other functional nanomaterials with diverse morphologies such as titania nanorods and silica coated nano crystals.(Fig. 9.13)

8. Polyhedral Oligomeric Silsesquioxanes (POSS)
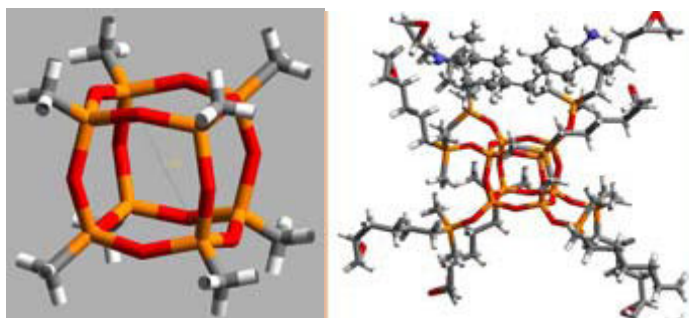
Fig. 9.14. POSS Material

Unique nanostructured material, hybrid inorganic and organic compositions at nanoscale, development and characterization of POSS-modified epoxy and POSS (Fig. 9.14) containing high performance polymers were synthesized to enhance its thermal and mechanical properties.

Advantages:

1. Numerous potential applications such as microelectronics, photonics, aerospace, and coatings.

2. POSS materials are found to be compatible with mostly all thermoplastics and thermosets.

3. POSS materials possess size controllable, processable and tunable properties.

8.a Conducting Polymer Nanofibers via Electrospinning :

The major work in this area is to develop a novel methodology for synthesising conducting polymers with high molecular weight and excellent solubility. It is also necessary to fabricate conducting polymer nanofibers via electrospinning process. Investigating size/quantum confinement effect on the optical, electrochemical and conducting properties of the nanofibers and finally to explore the possible applications of the conducting polymer nanofibers as OLED semissive layer, sensors and molecular electronics.

CONCLUSION:

The impact of understanding self-organizing behavior, and of finding ways to further direct assembly to make exotic nanoscale properties useful at the macroscale, clearly will be enormous. There are general rules of controlled synthesis and directed assembly to be discovered, and the systematic application of these will result in the addition of many different nanostructured materials. Each and every success in the synthesis of nanomaterials will make available a new subset of engineering materials, and it is well known from centuries of experience that the discovery and development of new synthetic stratergies for nanomaterials always have been the source of new technology.

REFERENCES:

1. A.P. Alivisatos, Science, 271 (1996) 993.

2. A. P. Alivisatos, J.Phys.Chem., 31 (1996) 13226.

3. A. Henglein., Chem. Rev., 89 (1989) 1861.

4. M. B. Mohamed, C. Burda, and M. A. El-Sayed, Nanolett, 1 (2001) 589.

5. J. H. Fendler, Chem. Mater, 8 (1996) 1616.

6. H. Gleiter, Acta Mater. 48 (2000) 1.

7. C. R. Henry, Surf. Sci. Rep. 31 (1998) 231

8. K.J. Shea, D.A. Loy, Chem. Mater.13 (2001) 3306.

9. K.Strawhecker, E. Manias, Chem. Mater.12 (2000) 2943.

10.E.P. Giannelis Adv. Polym. Sci. 138 (1998) 107.

11. B. C. Gates, Chem. Rev., 95 (1995) 511.

12. Thurston et al. Inorg. Chem. 42(6), (2003), 2014.

13. www.ruf.rice.edu

14. Quld-Ely et al Chimie 8 (2005) 1906.

15.www.patentstorm.us

16. www.mrs.org

17. http://en.wikipedia.org/

CHAPTER - 10

THE ROLE OF SYNTHESIS IN MATERIALS TECHNOLOGY

And he said unto them, it is not for you to know the *times* or the seasons, which the Father hath put in his own power.

The Holy Bible (The Acts 1:7)

My *times* are in thy hand.

The Holy Bible (Psalm 1:15)

To every thing there is a season, and a *time* to every purpose under the heaven:
A time to be born, and a *time* to die; a *time* to plant, and a *time* to pluck that which is planted;
A *time* to kill, and a *time* to heal; a *time* to breakdown, and a *time* to build up;
A *time* to weep, and a *time* to laugh; a *time* to mourn, and a *time* to dance;
A *time* to cast away stones, and a *time* to gather stones together; a *time* to embrace, and a *time* to refrain from embracing;
A *time* to get, and a time to lost; a *time* to keep, and a *time* to cast away;
A *time* to rend, and a *time* to sew; a *time* to keep silence, and a *time* to speak;
A *time* to love, and a *time* to hate; a *time* of war, and a *time* of peace.

The Holy Bible (Ecclesiastes 3:1-8)

Noah's Ark – The Technological Marvel

13. And God said unto Noah, The end of all flesh is come before me; for the earth is filled with violence through them; and, behold I will destroy them with the earth.

14. Make thee an ark of gopher wood; rooms shalt thou make in the ark, and shalt pitch it within and without with pitch.

15. And this is the fashion which thou shalt make it of: The length of the ark shall be three hundred cubits, the breadth of it fifty cubits, and the height of it thirty cubits.

16. A window shalt thou make to the ark, and in a cubit shalt thou finish it above; and the door of the ark shalt thou set in the side thereof; with lover, second, and third stories shalt thou make it.

Genesis 6: 13-16, **The Holy Bible**

What is new in Materials Technology?

The Living Cell is the All Time Marvel of Almighty God, The Creator. The Living Cell can apparently handle enormous number of unimaginable, uncomprehendable and difficult problems (functions) with ease and spontaneity.   The Living Cell performs multiple functions (reproduction, growth, defense, protein synthesis, transport of nutrients, information storage, site directed information transfer, communication, energy conversion and energy storage, sensing) simultaneously. All vital functions for the sustenance of life takes place in the living cells. Thus the Living Cells are self-replicating, self-containing and self-maintaining.   One of the goals of Materials Technology is to design and synthesize the material with artificial intelligence that replicate Living Cell in all aspects.

An inquisitive mind now poses the following questions:

What is the Living Cell? What does a Cell mean? Where does the term 'Cell' originate from? How can the Living Cell be multifunctional and versatile? How cells form complex organisms? What is the structure of the Cell? What are the dimensions of the Living Cell? What are the constituents of the Cell? Can the Living Cells be mimicked? Can such mimics of the Living Cells act as molecular machines and revolutionize Materials Technology? The queries are recurring.

The Cell is the basis of life. The Cell is the smallest unit of all living organisms whether it be unicellular (eg., bacteria) or multicellular (eg., human beings). Human beings have an estimate of 100 trillion (10^{14}) cells. A typical cell is of 10 μm size and 1 nanogram mass [1].

Robert Hooke is the originator of the term "Cell" and has been derived from the latin word 'Cellula' meaning 'a small room'. It is worth knowing few good things about Robert Hooke which are depicted in the next few lines.

Robert Hooke (18th July, 1635 - 3rd March 1703)

Robert Hooke was a remarkably industrious scientist and philosopher. He was an active, restless, indefatigable genius even almost to the last days of his life. One of the important contributions of Robert Hooke to Biology is his book "Micrographia" published in 1665 [Fig. 10.1 (a)]. Robert Hooke coined the term "Cells". This has originated from his microscopical observation of thin slices of cork (tissue of light soft bark of Mediterranean

tree). He coined the word 'Cell' to the pores separated by walls because the observation reminded him of the cell of a monastery (small rooms where monks lived in) [Fig. 10.1 (b)]. He has recorded his study of the plant tissue in "Observation XVIII" of the Micrographia as follows [2]:

"I could exceedingly, plainly perceive it to be all perforated and porous, much like a honey-comb, but that the pores, or cells, …….. were indeed the first microscopical pores I ever saw, and perhaps, that were ever seen, for I had not met with any Writer or Person, that had made any mention of them before this …."

Truly, history owes to this industrious scientist and philosopher.
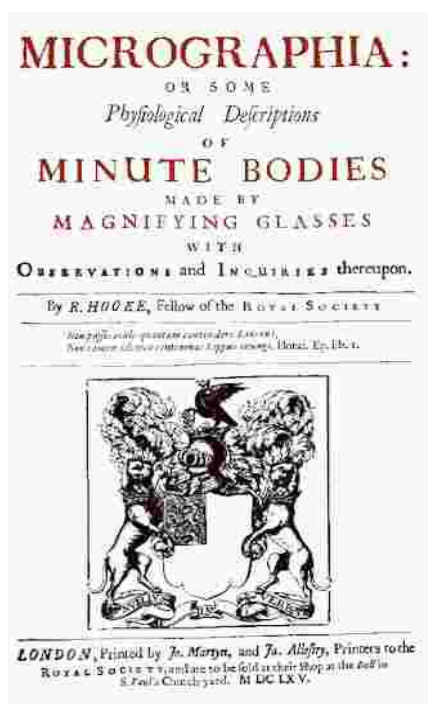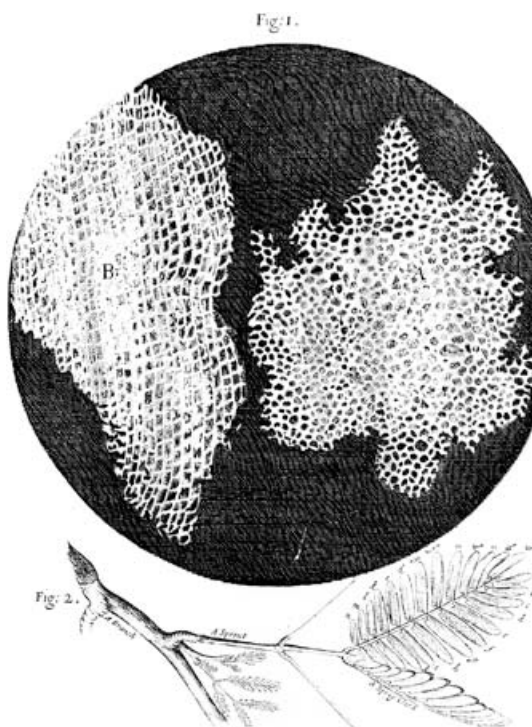
(a)   (b)

Fig. 10.1. (a) Title page of Micrographia (1665) [3], (b) Robert Hooke's drawings of the cellular structure of cork (plant tissue) and a spring of sensitive plant from Micrographia [4].

Living cells are divided into two types, namely, the Procaryotic Cells and the Eucaryotic Cells. Procaryotic cells possess simple structure (eg. Bacteria cell) [5]. Cells

without a nucleus were grouped together as "Prokaryotes'. We human beings, and most of the animals and plants, belongs to the life form enjoying cell nucleus and are collectively called Eukaryotes [6]. Eucaryotic cell (they carry their DNA wrapped in a cell nucleus) possesses complex structure as represented in Fig. 10.2. The cells are surrounded by a double layer membrane. In many cases the cells are further shielded by a cell wall. As a result chemical processes taking place in a cell would not easily get disturbed by the surrounding environment.
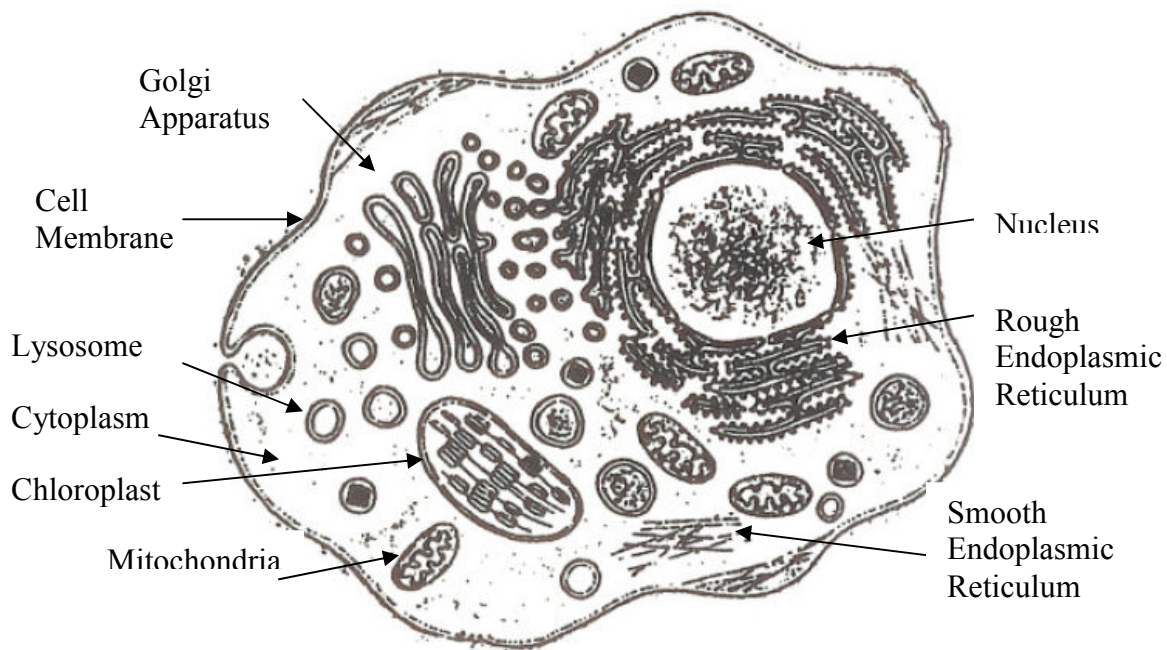
Fig. 10.2. Schematic representation of a eukaryotic cell and its compartments [6]

The cell possesses secluded areas for specific functions. The major organelles (specialized subunit with in a cell that has a specific function to perform) and cellular structure include the nucleus, ribosomes, mitochondria, golgi apparatus, cytoplasm, rough endoplasmic reticulum and smooth endoplasmic reticulum. As houses are divided into living room, dining room, kitchen and bed room, living cells too are compartmentalized as shown in Fig. 10.2. Each compartment has a specific set of functional tasks. For instance, the nucleus contains most of the DNA which is the carrier of genetic information in all the cellular life forms. The mitochondria are the power houses of the

cells. These are the sites where cellular respiration and a consequent release of chemical energy from food takes place. Ribosomes are the protein synthesizing machines of the cell. Ribosomes are the cells protein factory.

Can we imagine a data storage device of micrometer (10^{-6} m) size but can squeez the data equivalent of five high-density floppy disks (5 x 1.44 MB = 7.2 MB) ?

Yes, such a data device is existing in Nature. The chromosome, a very long stretch of DNA wound up in a complicated way, which determines the genetic identity of every living organism on this plant is an example of such data storing device.

Can we imagine a motor that is running on and on and on but only of size measuring a few hundredths of a thousandth of a millimeter?

For your surprise the motor is already in existence. It is a system mainly consisting of the proteins actin and myosin. The system serves to power our muscles. Actin is a soluble protein found in muscle cells. It is the main component of the thin filaments.   Myosin is the motor protein that generates the force and movement in contraction of muscles. Myosin is the oxygen – storage protein of the muscle. When Myosin carries an oxygen molecule, the oxygen molecule is deeply burried within the structure of the protein. Because of the weak interations present the protein is capable of rearranging its structure to be able to take up oxygen or to set it free by way of rearranging itself so that a tunnel is opened between the oxygen binding site and the rest of the world. For such rapid rearrangments to take place weak interactions should be present with in the protein structure as well as with the substrate. The following are some of the weak interactions found in biological systems (The Cell).

i. Hydrogen bonding: Hydrogen atom is normally bound to just one atom of oxygen or nitrogen. In Hydrogen bonding the Hydrogen atom starts interacting with a second atom. Hydrogen bonding is responsible for the extremely high boiling point in spite of its modest molecular weight. If hydrogen bonding did not exist, water would be a gas at ambient temperatures.

ii. Salt bridges: This is because of the electrostatic attraction between parts of molecules having opposite electrical charges.

iii. Van der Waals forces: These forces exist between the negatively-charged cloud of electrons of one atom and the positively-charged nucleus of the other.

iv. The Hydrophobic interaction: The tendency of oily, water-avoiding molecular surfaces to stick together and shut out any water molecules.

Thus the first lesson one need to learn is that the key to generate materials that replicate living cells or biological systems lies in designing synthetic strategies based on weak interations between the reacting systems as represented pictorially in Fig. 10.3..
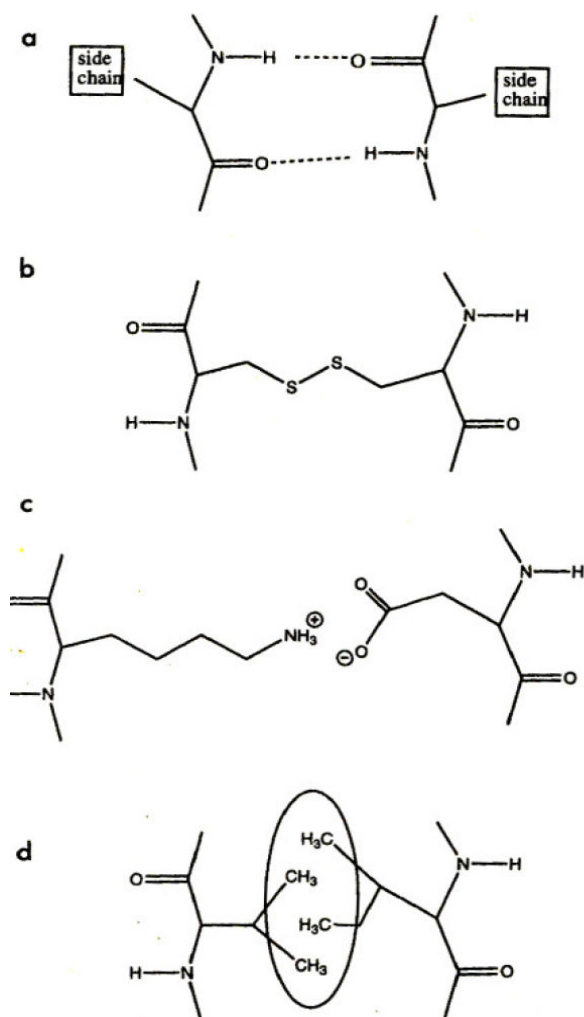
Fig. 10.3. Interactions that stabilize the local structures in proteins: (a) Hydrogen bonds (secondary structure), (b) disulfide bridges (tertiary or even Intermolecular, (c) salt bridges, (d) hydrophobic interaction. The oval shape symbolizes the hydrophobic area from which water is excluded [6].

Can we imagine a catalyst capable of converting the inert nitrogen gas from the air into nitrogen fertilizer at room temperature and atmospheric pressure?

The enzyme nitrogenase present in nodule bacteria that live in symbiosis with certain plants and provide them with freshly made nitrogen fertilizer produced from air and water. There is no technical catalyst producing ammonia from elemental hydrogen and nitrogen at ambient temperature and pressure as the nitrogenase of nodule bacteria. Thus it is the dream not yet realized by the scientists all over the world.

Can we dream of the synthesis of natural products with 100 % enantiomeric excess (ee)?

In organic chemistry, particularly in the synthesis of natural products, one of the major issues of concern even today is to synthesize exclusively one of the two mirror-imaged structures of chiral compounds. Literally, synthetic chemists are battling for every single digit enhancement in the value of ee beyond the statistically 50%. Interestingly enzymes can distinguish the mirror images with 100% reliability. Can we synthesize catalysts (nonnatural) which are on a par with natural enzymes in their performance? This is yet another challenge facing materials technology today.

Other important challenges ahead in Materials Technology are achieving computer technology that matches with human brain, achieving telecommunications technology that matches with nervous system of human body. The only means of realizing such breakthroughs in materials technology is through the evolving synthetic strategies in Chemistry.

Some Benefits from Materials Technology

Audio tapes, audio tape players, audio tape recorders, calculators, cameras, compact disks (CD's), CD players, Barcode, Colour Printers, Computers, Digital video disk (DVD), Electronic commerce, Electronic data interchange, E-mail, Internet, Fax machines, Laboratory equipment, Laser printers, Laser pointers, Liquid crystal display, LCD, Mailing services, Measuring instruments, Modem, Network/cable television, Periodicals, News papers, Over head projectors, Photocopy machines, Play ground equipment, Radio, Refrigerators, Slide Projectors, Scanner, Search Engines, Switching technology, Telephones, Transparencies, Type writers, Video cameras, Vedio conferencing are all some of the marvels of Materials Technology [7].

Materials Technology Vs Material's Technology

Materials technology is a science and a knowledge area that describes properties, functions and applications of different materials [8]. Materials technology is dependent on Material's technology, i.e. the way materials are architectured or build or constructed or fabricated or synthesized. To gain knowledge of Materials technology one should understand the role of synthesis in generating the materials. New materials, improved production techniques, and miniaturization are the three essential ingredients that have tremendous potential to trigger major technological revolutions.

Role of Synthesis

Materials synthesis is so vital that the early history of man kind (from the stone age to the iron age) is classified based on the materials that started new eras. So far the classification of eras is associated with or based on materials that have revolutionized the respective eras. But the role of synthesis has now become so crucial in materials technology that the production methods are going to be used as milestones of development rather than the material itself. Initially materials that are either simply found or gathered from nature (wood, bones, stones) served mankind. Progress has been made from such naturally existing materials to the use of metals retrieved from ores using fire. Metals were found to be more versatile in their use rather than naturally occurring materials.

Currently, metals, glass and other materials are being replaced by polymers. This age which we live can be truly regarded as polymer age because the survival of mankind becomes questionable with out polymers (substances that are chemically assembled from smaller molecules). Again polymers are more versatile than metals and naturally occurring materials like wood or stone. Milestones in the use of materials during the last 10, 000 years have been illustrated in Fig. 10. 4.

But still we have not our destination in technological advancement. Even though polymers have the potential to cater to many of our needs they can not fulfill all the demands we have for advanced materials. The problems associated with polymers are: valuable resources and energy are used up in the production of polymers. Also they are neither biodegradable like wood nor recyclable like iron.

10,000
years
ago

c. 4000 BC
Meteorite iron
used in the
Middle East

c. 1800 BC
End of neolithicum,
bronze age begins

c. 1500 BC
Smelting of iron from
ore; use of wrought
iron in Middle East

1,000
years
ago

14th cent.
Cast iron
in Europe

1000 BC
Iron Age begins
in Greece

400 BC
Cast iron
used in China

AD c. 0
Spread of iron
technique reaches
Scandinavia

100
years
ago

1929/30
Synthetic rubber
commercially available

1939
Introduction
of nylon

18th cent.
Industrial revolution
makes iron the most
common material in
technical applications

1,000
years
ago

1960
Teflon
coatings

100
years
ago

1990
Mass
production of
fullerenes

Fig. 10.4. Time line illustrating the use of materials during the past 10, 000 years [6].

Even though polymers have revolutionized the way we live, in comparison to biological materials they are far inferior as they in no way contain any significant amount of information, also they cannot store energy, or they cannot act in an intelligent way. Thus the focus of the evolving synthetic strategies has been to produce materials mimicking biological materials. Such materials should be functional and adaptive on a molecular scale.

Like our fore fathers and ancestors we may be of the opinion that our present technology is modern, advanced, accomplished and ultimate. Also we may tend to believe that only incremental improvements can be brought about in the present day technology. Major technological breakthroughs are believed to be hardly possible. But this is not true. There is large room for the change to betterment as change happens to be the law of life. The enormous scope and potential for such a major advancement can be noticed if we compare our present day synthetic strategies or production methodologies with the synthetic strategies adopted by molecular machinery in living cells. So long almost all the available synthetic strategies handled bulk amounts (countless atoms or molecules) which yielded materials whose properties can only be controlled with in a limit. But the properties of materials obtained by adopting such synthetic strategies dealing with bulk amounts are not adaptive or intelligent. Even though the tools and machinery that one currently uses to carry out simple processes automatically they can no way go down below macroscopic or at the most microscopic levels. In sharp contrast, in the living cells, the structures of inorganic building materials are controlled at the molecular level guiding the precipitation of the mineral from solution for instance. Incidentally, the most complex machines of the cell are not bigger than 25 – 50 nm. Thus there is ample scope and also the way is long to meet the materials technology mimicking the Living Cell. At the moment The Time of reaching the destination is not clear.

Information technology, Nanotechnology and Biotechnology are regarded as the three eyes of the new millennium. New synthetic strategies can open access to new materials. Materials are transformed into useful products by working on them with hands and tools. Production technology underwent a drastic change. From millennia useful products are made manually. Now most of them are made by machines. Except those processes where decision-making is involved all others are being carried out by machines. As a

consequence length scale is no longer limited to such parts that human workers could grasp with their hands. Thus miniaturization of production has paved the way for the miniaturization of the products.

INFORMATION TECHNOLOGY:

The Beginning of Information Technology – The Age of the Printed Book:

Now this very second you are reading this book. It means you are getting benefited by the revolution of book publishing technology that has started in 15th century. Johannes Gutenberg (1397 – 1468) conceived the idea of printing books with movable type. He developed his idea into a working technology. It is no easy job to achieve uniform dimensions of letters. Such sufficiently uniform dimensions of letter type facilitates a flat printing surface. Hence smooth lines are obtained. Through years of persistent hard work Johannes Gutenberg could overcome this problem by making the type from metal. He could cast all of them in the same mold, which could be combined with different letter shapes and adjusted in its width. This development is a result of several years of hard work. To achieve this objective he has to borrow considerable amounts of money. He could not have given the world the printing technology if he were not to be knowledgeable in metallurgy. His major success involves producing 160-170 copies of the 42-line Bible shown in Fig. 10.5. The name 42-line Bible refers to the number of lines of print on each page. This work of Johannes Gutenberg is of iconic status as this marked the beginning of 'Gutenberg Revolution' and 'the Age of the Printed Book'. The printing of 42-line Bible by Gutenberg is a remarkable development in the history of mankind as this has broken the information monopoly. The new technology has put an end to the Dark Ages. It has brought about the reformation, the enlightenment and the rise of modern science. Interestingly, with in a span of 50 years after the production of Bible with printing technology developed by Johannes Gutenberg, more books were produced than in the 1000 years before. The technology Johannes Gutenberg developed lasted for more than 500 years. Later on this printing technology of Gutenberg was replaced by light reprography. This is followed by the new information revolution brought about with the invention of personal computers.

Fig. 10. 5. (a) A copy of the 42-line Holy Bible, the major work of Johannes Gutenberg [9].

Advent of Computers and Internet – Information Explosion:

Advent of computers and widespread growth of availability and use in internet has brought about revolution in the field of information technology. Since this development has only taken place over the past two decades we are fortunate enough to witness the progress. But how could this happen? What is the driving force for such a drastic explosion in information technology? Literally with computers and internet the whole world is at our finger tips. The marvelous progress can be attributed to the new synthetic strategies that facilitated miniaturization of electronic elements and circuits. Miniaturization means not alone saving space or materials but miniaturization of electronic circuits made them cost effective, efficient and faster. 1000 fold enhancement is memory capabilities and calculation speeds have been achieved with in a short span of 10 years i.e., from early 1980's to 1990's. The number of transistors in typical microchip kept on increasing exponentially from 1971. For every 18 months the number of transistors on a microchip doubled. In 1971 the microchip contained only 2300 transistors when Intel launched the world's first microchip. Nearly a hundred fold increase in the number of transistors has been achieved by 1985 with the creation of Intel 386 processor with 2, 75, 000 transistors. And today the Tukwila contained 2 billions transistors. Very recently, i.e., on 14th April 2008, Intel, the microchip leader, unveiled

two drastically different processors. They succeeded in creating the worlds smallest microchip (computer processor) namely the atom chip as well as the worlds biggest chip namely the Tukwila. The size of the atom chip is of a baby's finger nail. The chip packs 47 million transistors. But consumes only over a half of a watt of power. The atom chip can power hand held internet devices namely the mobile internet devices, small hand held computers that will help in emailing, letter writing and calculations. On the contrary the Tukwila, the new Intel chip possessing the highest number of transistors ever put on the slab of silicon with 2 billion transistors can do the work of four computers. This world's biggest microchip consumes 130-170 watts of power. This will help scientists to build gaint 'number crunchers' far more powerful than the Tata-CRL 'Eka' super computer built in India (the Tata-CRL 'Eka', computer is the world's forth-fastest computing machine). With the help of such super computers fuelled by microchips with 2 billion transistors complete genetic simulation of a human cell can be achieved with in a span of a decade or even lesser time period. This facilitates doctors to precisely simulate an unhealthy cell in a human. Thus exact medication can be possible. With the advent of nanotechnology unimaginable advancements in the field of information technology are anticipated.

NANOTECHNOLOGY:

The word Nanotechnology was used for the first time by Taniguchi at the University of Tokyo, Japan, in 1974. He was then referring to need of electronics industry to engineer materials at nanometer scale [10].

On 29th of December, 1959, Richard P. Feynman took the shiny example of the living cell to drive home his point that individual atoms can be arranged in the way we want them to be. With this ultimate degree of miniaturization all the information contained in all the books in the world can be stored in the grain of a sand. Living cell is not only capable of storing enormous amount of information in a very small volume but also equipped with the hard ware to read out the information and retrieve the same when needed and put the same into action. In an analogous way Richard P. Feynman professed that it should be possible to write the entire Encyclopaedia Britannica onto the point of a needle. In those days when computers were huge machines the wiring of which filled the

whole room completely, he is genius enough and fore sighted to profess that computers of the future should be made of wires that would only be 10 or 100 atoms in diameter.

Role of Synthesis in Nanotechnology:

Carbon materials are very important for Nanotechnology to flourish. Carbon materials are vital, versatile, amazing and unique. Carbon exists in different allotropic forms, namely, graphite, diamond, fullerene, and nanotube. Graphite with its two dimentional hexagonal array of carbon atoms and diamond with its three dimensional structure are well known. Fullerene and nanotubes are newly discovered allotropic forms of carbon.

Synthetic Strategy that lead to the formation of Fullerenes:

A dream team of five scientists namely Kroto, Heath, O'Brien, Curl and Smally in Rice Quantum Institute, Texas were trying to understand how long-chain carbon molecules (cyclopolyynes) are formed in interstellar space. To find an answer, they started vapourizing graphite, the grand old allotrope of carbon, by irradiating with laser. This experiment has lead to the serendipitous discovery of C_{60} molecule, named as Buckminsterfullerene. The structure of C_{60} molecule consisted of 32 faces, 12 of which are pentagonal and the remaining 20 are hexagonal. The structure of C60 is analogous to common foot ball shown in Fig. 10. 6. (a) The experimental set up containing the vapourization chamber is shown in Fig. 10. 6. (b). Later on many studies have been carried out on the properties and applications of fullerens and fullerene derivatives. Not oniy that, fullerene research paved path for the discovery of multiwalled carbon nanotubes by Ijima. Simply the synthetic methodology adopted has changed the course and destination of carbon science and technology.

Carbon species from the surface of a solid graphite disk are vapourized using a pulsed laser source in the presence of He environment. Nd:YAG laser producing pulse energies of ~ 30 mJ is used. In a typical experiment the pulsed valve is opened. Vapourization laser is fired onto the rotating graphite disk. Carbon species start vaporizing into the helium stream, cooled and partially equilibrated in the expansion. As a result molecular beam is formed which travels into the ionization region. The clusters were ionized by a laser pulse and the products were analysed by mass spectrometer. During the process graphite disk is rotated slowly to produce a smooth vaporization surface. The vaporization laser beam is focused through the nozzle to strike the graphite. The species

in the vaporized graphite plasma are cooled and clustered by the thermalizing collisions of He carrier gas.   Also the carrier gas provides necessary wind to carry the cluster through the remaining of the nozzle.   The cluster filled gas expands freely at the nozzle and form a supersonic beam which is probed by mass spectrometer [11].   Kroto, Smalley and Curl were awarded nobel prize for Chemistry in 1996 for their discovery of Fullerenes in 1985.
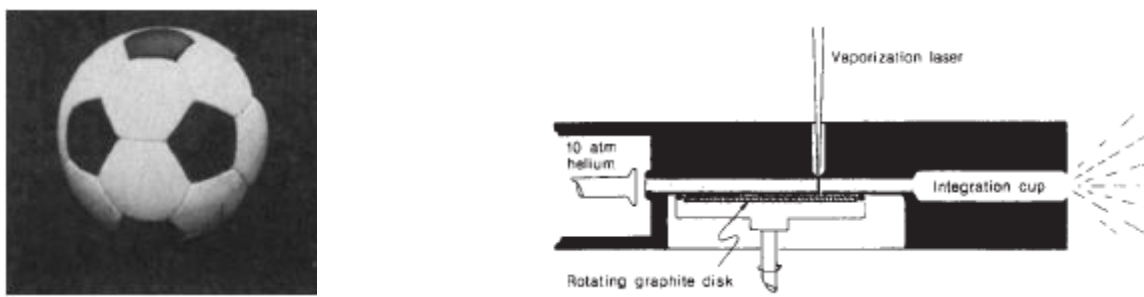
Fig. 10.6. (a) A football (the C60 molecule is supposed to have the structure formed when each vertex on the seams of such a ball is replaced by carbon atm, (b) Schematic diagram of the pulsed supersonic nozzle used to generate carbon cluster beams

Even though Fullerens were discovered in 1985, it is not until 1991 when Kratschmer and Huffman evolved a synthetic strategy based on arc discharge for the mass production of fullerenes that fullerene research grew rapidly and in one way this is a foundation stone for the future discovery of nanotubes by Ijima in 1991.   Hence synthetic strategies play a pivotal role in the birth as well as destination of any new technology.

With the ways being available for the mass production of Fullerenes, derivatives of fullerenes could be synthesized.   Endohedral compounds, exohedral compounds and heterofullerenes are the three classes of fullerene derivative [12].

Fullerene derivatives with atleast one atom or ion located inside the 7 Å cage of fullerene are called endohedral fullerenes.   Endohedral compounds are more polar compared to the parent fullerene making the separation of fullerenes easier.   Electronic properties of fullerenes can be tuned by forming endohedral derivatives.   Endohedral compounds find utility in the fabrication of solar cells, linear optical units and in photo conductors.   Some of the ways of synthesizing endohedral derivatives are by heating the fullerene directly with the guest gas under pressure; evaporating fullerene in presence of

metals or metal oxide to be hosted by using laser source or by generating an arc. Endohedral compounds with noble gases, alkali metals and lanthanides are well known. Recently $N@C_{60}$ has also been synthesized. $La@C_{82}$ could be synthesized by evaporating graphite impregnated with La_2O_3 using a laser. $Rg@C_{60}$ (Rg-rare gas), $Li@C_{60}$ have also been synthesized [13].

Exohedral compounds: By reacting C_{60} with $CrO_2(NO_3)_2$ a compound $C_{60}Cr_2N_6O_{21}$ was obtained. In this compound 50% Cr species are in Cr^{3+} and the other 50% were found to be in Cr^{6+} state. Such exohedral compounds are useful for catalytic and medicinal applications.

Intercalation Compounds: Alkalimetal intercalated fullerene compounds were found to be super conductors. For instance, K_3C_{60} has a transition temperature of 19.8 K and Cs_3C_{60} exhibited a transition temperatures upto 40 K. Compounds like $(NH_3)_6Na_3C_{60}$ $(NH_3)_8Na_2C_{60}$ showed improvements in transition temperatures. Ba_6C_{60} and Sm_3C_{60} have also been found to be superconductors.

Carbon Nanotubes

Synthesis of carbon nanotubes with desired properties in large quantities is a challenge ahead. The second problem in the successful utilization of CNT's for a variety of Technologies is to remove the impurities present such as the catalyst nanoparticles (Fe, Co, Ni-Y and few others), amorphous carbon and fullerenes. The third hurdle is to develop synthetic strategies that exclusively give either SWNT's or MWNT's as currently there is no path available to separate them. Making them soluble is also a note worthy problem.

Carbon nanotubes are a key component of nanotechnology. Carbon nanotubes (multiwalled tubes) were discovered by the Japanese scientist Iijima in 1991. Carbon nanotubes were obtained as a by-product during fullerene synthesis. Discoovery of carbon tubes has supplemented the fullerene research to a major extent. Multiwalled carbon nanotubes should be distinguished from single walled carbon nanotubes. The difference between them is pictorically represented in Fig. 10. 7. Single walled carbons nanotubes contain one single cylinder whose wall is made up of hexagonal carbon structure. Multiwalled carbon nanotube contains concentric cylinders (one inside the other) with each cylindrical wall being made of a graphene sheet.
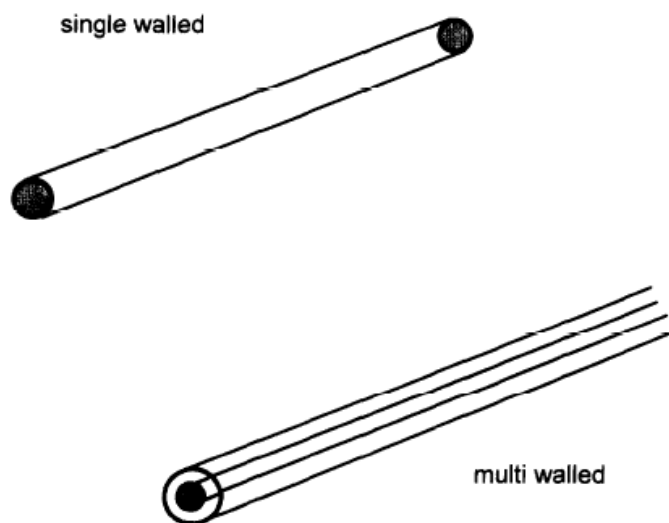
Fig. 10.7. Schematic representation of single walled and multiwalled carbon nanotubes [12]

The discovery of single walled carbon nanotubes (SWCNT's) is incidental. A series of failed attempts to synthesize MWCNT's (multiwalled carbon nanotube's) filled with transition metals resulted in the formation of single walled carbon nanotubes. The credit of the discovery of single walled carbon nanotubes should be given to two research groups who worked independently, namely Iijima and Ichihashi, NEC (Nippon Electric Company), Japan as well as Bethune et al., from IBM, California [14].

Nanotubes of carbon are not soluble. As a result separation and purification are a problem. This has hindered the large scale production of carbon naotubes partially. Fortunately these tubes are less susceptible to combustion. So heating in oxygen can brun the impurities (other forms of carbon namely amorphous carbon) and can yield pure CNT's [13].

Single walled carbon nanotubes can be envisaged or conceptualized or understood as seamless (continuous and uniform through out) cylinders rolled up from graphene sheet as represented in Fig. 10. 8. A graphene sheet is a monolayer of sp^2 bonded carbon atoms.
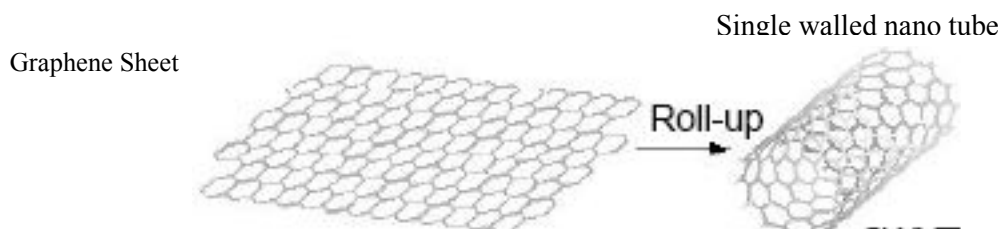
Fig. 10.8. Hexagonal net work of carbon atoms rolled upto make a seamless cylinder [15].

Depending on the way in which the graphene sheet is rolled up there can be three types of carbon nanotubes, namely, zigzag, armchair and chiral. In zigzag tubes some of the C-C bonds lie parallel to the tube axis. The name zigzag comes from the fact that the edge of the tube possesses zigzag structure (⌒⌄⌒). In armchair tube some of the C-C bonds lie perpendicular to the tube axis. The name armchair comes from the very shape of the edge of the tube which looks like arm chair (⌐⌐⌐).   Intermediate orientations of the graphene sheet result in 'chiral' carbon nanotubes.   Thus the classification of nanotubes into zigzag or arm chair is based on the appearance of the rim of the tube formed. The formation of the three types of nanotubes by changing the way of rolling the graphene sheet is represented schematically in Fig. 10.9

    Cabon nanotubes have several potential applications. This is because of their unique properties. Due to the high mechanical stability carbon nanotubes are now being used in carbon-carbon composites. As carbon nanotubes are capable of emitting electrons from the tube ends they are used for flat screen applications. Carbon nanotues serve as host materials for Li or H_2 and can be exploited in energy storage applications.
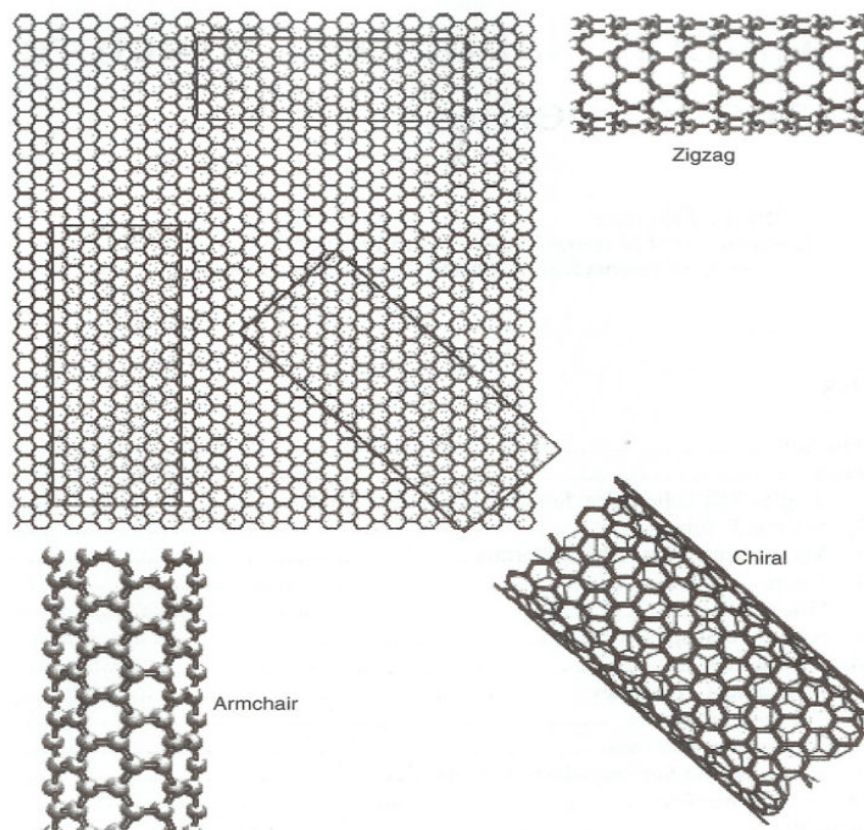
Fig. 10. 9. Schematic representation of the relation between nanotube and graphene [16].

Evolution in Synthetic Strategies

Some of the ways of synthesizing nanotubes include:

1. Arch-discharge or vaporization process (in the presence of transition metal catalyst)

2. Laser-evaporation of graphite (Laser furnace process)

3. Chemical Vapour Deposition, CVD (Catalytic Pyrolysis of hydrocarbons) or Catalytic Chemical Vapour Deposition (CCVD)

4. Template Carbonization Method

The fine details of the synthetic strategies are given in the next few pages.

1. The Arc-Discharge Process:

Carbon nanotubes were first introduced to the world by using this synthetic methodology. As stated earlier carbon nanotubes occurred as a by-product during the synthesis of fullerenes. Kratschmer and coworkers have used the same arc discharge method in 1990 for the mass production of fullerene. The method they have employed comprises of

evaporating the graphitic anode. The two electrodes were made to contact with each other by applying an ac voltage in an inert gas atmosphere. This results in the generation of an arc that evaporates the anodic graphite. Thus fullerenes were generated in bulk amounts.
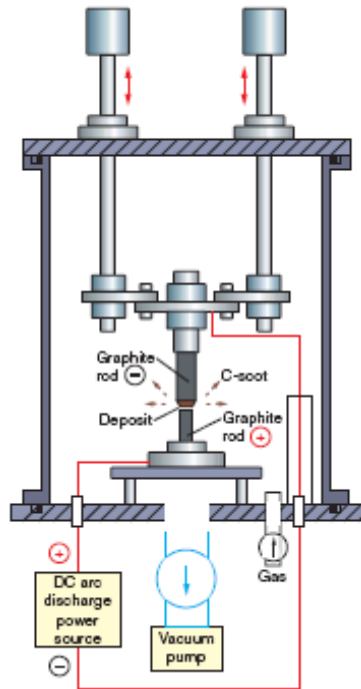
Fig. 10. 10. Schematic representation of the apparatus used for the synthesis of CNT's [17]

The arc-discharge apparatus used for the production of carbon nanotubes is shown in Fig. 10.10. The chamber is first made free from atmospheric air by evacuating the reaction chamber with a vacuum pump. Ambient gas (He or Ar or CH$_4$) is introduced into the chamber. A dc (direct current) arc voltage is applied between the two graphite electrodes (rods of carbon). The anodic graphite evaporates. Fullerenes in the form of sooth are deposited in the chamber. In addition to fullerenes, the great treasure, CNT's were also found to be deposited on to the cathode from the evaporating anode. These CNT's were found to be made of coaxial (concentric) graphene sheets and are termed as multiwalled carbon nanotubes. These results are obtained when pure graphite rods free from any

metal impurities are used as anode and cathode. By using this arc discharge method and by employing He environment large scale synthesis of MWCNT's could be achieved.

If the synthetic condition is slightly changed by using metal catalyst (Fe or Co) containing graphite rod as anode instead of pure graphite rod, single walled carbon nanotubes could be obtained instead of multiwalled carbon nanotubes. In either cases the cathode is only pure cathode. Experiments have been carried out by changing the atmosphere with in the reaction chamber. Among He, Ar and CH_4, CH_4 gas was found to be the best as it resulted in the formation of highly crystalline nanotubes with few coexisting nanoparticles which are not wanted. The major and essential distinguishing feature in the synthesis of fullerens and CNTs is that, fullerene cannot be produced when reaction chamber contains hydrogen containing gases (CH_4 or even H_2). At the same time presence of environment of H_2 facilitates the formation of CNT. During the process of arc evaporation in CH_4, thermal decomposition of methane takes place leading to the insitu generation of H_2 as indicated in the following equation.

$$CH_4 \longrightarrow C_2H_2 + 3\,H_2$$
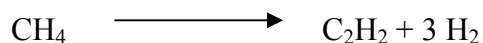
In presence of CH_4, the evaporation of graphitic anode thus takes place in pure hydrogen gas environment. Thus hydrogen arc discharge is effective in the generation of highly crystalline carbon nanotubes (multiwalled). As hydrogen arc results in high temperature and resultant high activity, production of MWCNT's in hydrogen atmosphere (CH_4 environment) is more effective than either He or Ar atmosphere. Not only that, the unwanted carbon nanoparticles (amorphous carbon) which are ubiquitous and unavoidable can be minimized by using hydrogen arc process

SWNT's were synthesized in the year 1993, just two years after the discovery of MWNT's in the year 1991. SWNT's were synthesized by the arc discharge process using a graphite anode but with metal catalyst (either Fe or Co or metal alloys in some cases like Ni-Y). In sharp contrast to the synthesis of MWCNT's, SWNT's were not found on the carbon deposit on cathode but were obtained from the soot in the gas phase.

Xinluo Zhao and coworkers has succeeded in synthesiszing highly crystalline SWCNT's with a clean surface in large quantities by employing arc discharge process. The SWNT's were obtained with 70 at.% purity.
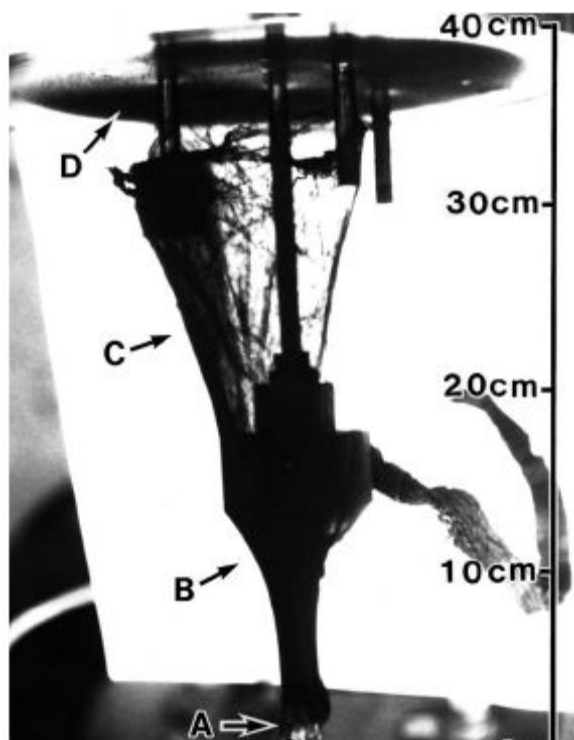
Fig. 10.11. Arc – discharge chamber with a web of SWNT's [18] (Arrow A shows the starting point of the SWNT web; arrow B shows the black thick region of SWNT's; arrow C shows the half-transparent thin region of SWNT's growth; arrow D points towards the roof of the arc discharge chamber where the thin film of SWNT's is located. This film can be peeled of into large slices)

The carbon electrode employed comprises of 1 at% Fe catalyst. Inert atmosphere is maintained in the reaction chamber by H_2-Ar mixture. The catalyst Fe nanoparticles present in the product CNT's could be completely eliminated by heating the product in air at 693 K and also by the subsequent acid treatment with HCl.

The two graphite electrodes were held vertically one over the other with the anode at the lower end and the cathode at the upper end separated by 2 mm distance. The electrode assembly was held in the centre of the vacuum chamber. The anode is the carbon containing Fe catalyst and the cathode is pure carbon. Inert atmosphere is maintained in the reaction chamber by passing H_2-Ar mixture. The synthesis time was roughly 3 mm. This has resulted in the formation of macroscopic web of SWNT's as

shown in Fig. 10.11. The length of the SWNT's is nearly 30 cm. H_2-Ar gas mixture played a crucial role in the synthesis of SWNT's.
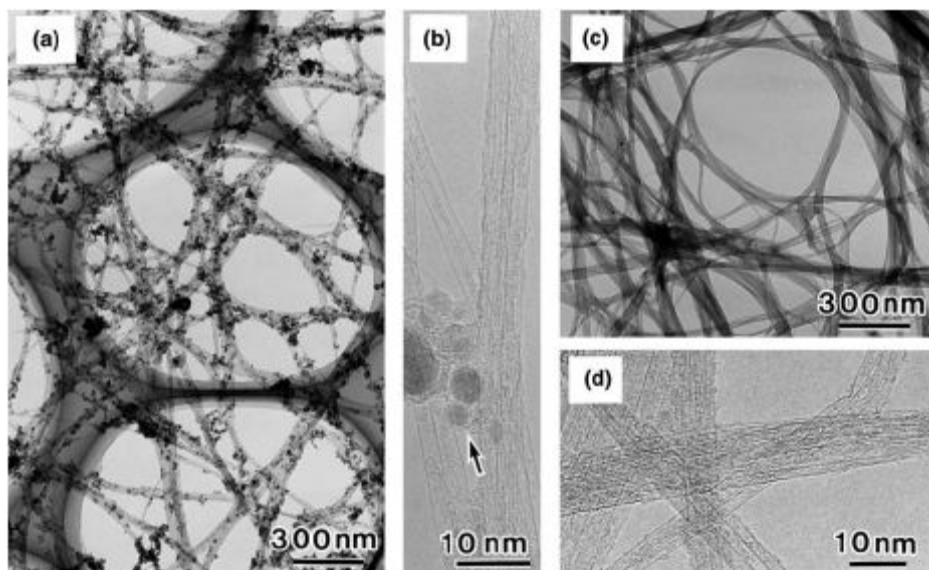
Fig. 10.12. TEM images of (a) as grown CNT's (low magnification, iron particles are seen along with tubes), (b) as grown CNT's (high magnification, iron particles are seen along with the graphene layers) (c) purified CNT's (low magnification, only CTN's and no Fe particles) (d) purified CNT's (high magnification, only graphene folded sheets and no Fe particles) [18].

TEM images of as-grown and purified SWNT's are shown in Fig. 10.12. Both the low magnification and high magnification images are shown. It is clear from the TEM images that after heat treatment and the subsequent acid treatment with HCl the particulate impurities (catalyst as well as amorphous carbon) were completely removed yielding clean and pure SWNT's.

2. Laser Furnace Process

The energy density of lasers is higher compared to any other vaporizing device. So lasers are appropriate means to vaporize materials like carbon with high boiling temperature [17].

Typical laser furnace experimental set up is shown in Fig. 10.13. The essential components are a furnace, a quartz tube provided with a window at one end and a trap for

CNT's provided with a water circulation at the other end, flow system for inert gas (Ar), laser source and the carbon target.
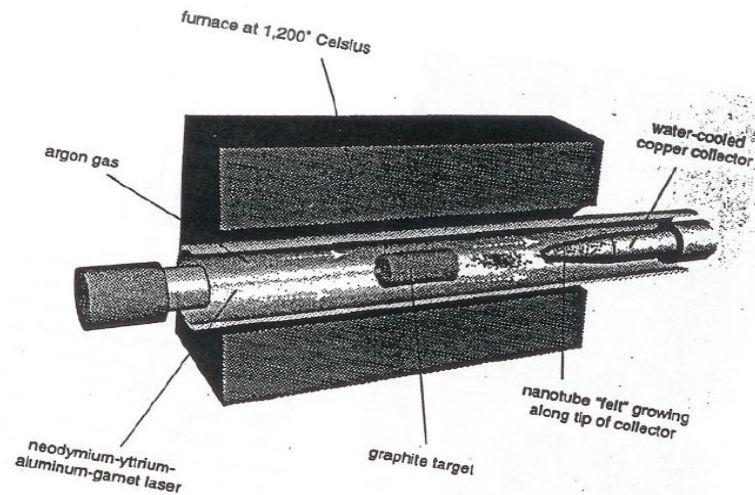
Fig. 10.13. Laser-furnace (vaporization) apparatus [19]

The carbon target used is a composite of carbon doped with catalytic Co-Ni alloy. The carbon composite (Co-Ni/graphite) is placed at the centre of the quartz tube having window at one end through which the laser beam penetrates into the quartz tube. The laser source used is Nd:YAG (Neodymium : Yttrium-aluminium-garnet) and this can produce a temperature of 1200 ºC in the furnace. CO_2 can also be used. A laser beam from the afore mentioned source is introduced into the quartz tube through the window and is focused on to the carbon composite.   Ar gas is circulated through out the furnace. The carbon composite is vapourized when the laser beam hit the target and forms SWNT's. The SWNT's produced are carried to the other end of the quartz tube provided with a trap (with water circulation facility) where the SWNT's are collected.

   It is important to note that the surface of the carbon composite should be kept as fresh as possible for the process of vaporization to be homogeneous. Since there is no way the target can be moved, the focus of the laser onto the target should be changed from time to time. Laser furnace synthesis is an efficient route to synthesize bundles of single-walled carbon nanotubes with a narrow diameter distribution.

3. Chemical Vapour Deposition

In this method of synthesis a hydrocarbon (acetylene, ethylene, benzene or methane) is thermally decomposed in the presence of a transition metal catalyst (Fe, Co or Ni) or catalyst support (alumina, silica or zeolite serve as useful supports for transition metals) The process of synthesis can be carried out even at relatively lower temperatures (600-1200 °C) than those which are normally encountered in either arc discharge process or laser – vaporization processes. But we have to forgo the quality of the nanotubes obtained interms of crystallinity when the synthesis temperatures are lower. Since this synthetic methodology can be employed at relatively lower temperatures and ambient pressure, CVD is simple and also forms a viable means of producing large amounts of nanotubes. Hydrocarbons in either liquid (benzene, alcohols) or solid (camphor, napthelene) or gaseous (CH_4 or C_2H_2) can be virtually employed as carbon precursors.
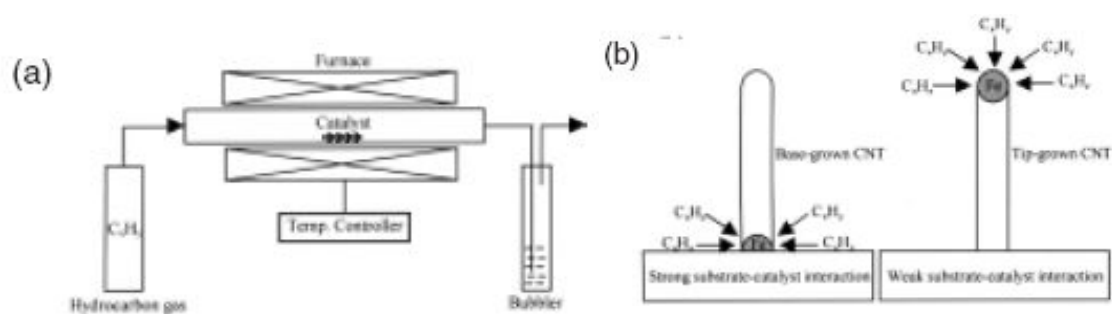
Fig. 10.14. Experimental set up for Chemical Vapour Deposition Synthesis, (b) probable models of CNT growth [17]

The experimental set up used for a CVD or CCVD (catalytic chemical vapour deposition) synthesis is shown in Fig. 10.14 (a) and the possible ways in which the nanostructures grow on catalyst particles is represented pictorially in Fig. 10.14 (b).

In a typical process of CVD, the catalyst is placed in the middle of a quartz tube. The quartz tube with the catalyst is placed in a furnace capable of generating and sustaining temperatures between (600-1200 °C). The hydrocarbon vapour is allowed to pass through the quartz tube containing catalyst material present at sufficiently high

temperature. The hydrocarbon gets decomposed. CNT's start growing on the catalyst particles. The temperature of the furnace is then cooled to room temperature. The CNT's are collected. If the carbon precursors were to be in liquid form as in the case of either benzene or alcohols then an inert gas like Ar is bubbled through the flask containing the liquid hydrocarbon. The liquid hydrocarbon in the flask is heated simultaneously so that vapours of the hydrocarbon are generated. The vapours of the hydrocarbon are thus carried by the inert gas through the catalyst particles located in the hot zone of the furnace. If the carbon precursors were to be in solid state like those of naphthalene or camphor, the hydrocarbon vapours in such cases are generated by placing them in another furnace kept at a lower temperature prior to the main furnace where the deposition of carbon takes place over the catalyst particles. Analogous to the carbon precursors the catalyst materials can also be in either solid or liquid or gaseous state. In the high temperature zone the hydrocarbon vapour gets decomposed. A variety of carbon species are formed. Such carbon species are capable of dissolving in the metal nanoparticles of the catalyst. Once a catalyst particle is supersaturated, carbon species starts precipitating out. Initially, fullerene dome like structure will petrude out of the catalyst particle which extends into carbon cylinders. The position and direction of growth of carbon from the metal nanoparticle depends on the interaction between the metal particle and the support .If the interaction beween the metal particle and the support is strong, the particle is literally immovable. The decomposed carbon species will be adsorbed into the particle initially from all the direction where the catalyst particle surface is exposed to the carbon species. Once a level of super saturation of the particle with carbon species is reached no more carbon species are adsorbed in to the metal particle. Now carbon has to precipitate out from the metal particle. Since the particle is strongly held by the support, the only direction in which the carbon can precipitate out is from the tip. The process of dissolution now takes place from the sides of the particle near the base and the excess carbon is precipitated at the mouth or tip of the particle. Since the grown process starts at the sides of the base this is known as base grown carbon. On the contrary, if there were to exist weak interaction between the catalyst particle and the support, the particle can now be easily lifted vertically up above the support surface the movement when the particle gets supersaturated with carbon that is

being absorbed from the tip. Since the growth of the tube is now originating at the tip of the metal particle the mechanism is regarded at tip grown CNT process. Depending on the size of catalyst particle, we get either SWNT's or MWNT's.

4. Template Carbonization Method:

The structure directing material (template) used for preparing nanotubes in this method is the porous aluminium plate. Channels are created in the aluminium plate by the process of anodic oxidation in the presence of sulphuric acid. Carbon is deposited pyrolytically onto the channels in aluminium oxide film at 800 ºC in inert atmosphere.
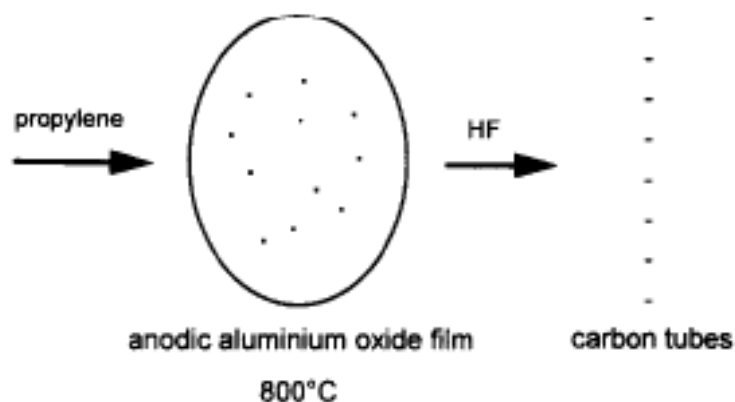
Fig. 10.15. Synthesis of carbon nanotubes by template carbonization method [12]

After the process of carbon deposition and subsequent carbonization the aluminium oxide template is removed by treatment with HF (hydrofluoric acid) solution. (Note: HF should be handled with utmost care. Proper hand gloves should be used while handling HF. It is so hazardous that through skin it can damage even the bones). This resulted in uniform monodisperse carbon nanotubes with uniform length, diameter and thickness. As the temperature of the carbonization is not high (800 ºC only), the tubes contained structural imperfections.   Typical synthetic steps involved in a template assisted synthesis are pictorially represented in Fig. 10.15.

Can a carbon source as common as kerosene be used for the synthesis of nanoforms of carbon materials?

Kerosene is used as a fuel for cooking and lightening. It is a residue of the petroleum refinery. Kerosene contains a mixture of various short and long chain aromatic and aliphatic hydrocarbons. Sharon and coworkers have used kerosene as precursor for preparing various nanoforms of carbon. The method of synthesis comprises of pyrolysis of kerosene at 1000 ºC. The experimental arrangement comprises of a quartz tube held horizontally in a furnace. Kerosene is placed in a round bottom flask and heated thermostatically at 90 ºC. The vapours of kerosene along with Ar gas were allowed to pass through the quartz tube held in a furnace. Stainless steal plates in rectangular shape were placed in the center of the quartz tube. The stainless steal plate serves as a substrate for the deposition of various forms of carbon materials. Straight, stiff and long fibers, flexible, thin hair like threads, soft wool like clusters of carbon, uniform nanotubes, bitter-gourd-like rough fibers, earth worm-like nanofibers and carbon thin film deposits were found around and on the stainless steal substrate. SEM (scanning electron microscope) images of the various nanoforms of carbon synthesized are shown in Fig. 10.16. It is to be noted that the substrate stainless steal is a complex catalyst of different compositions which govern the growth and orientation of the nanostructures. Important questions one should now consider are: How a single carbon precursor under given conditions of synthesis yields different nanostructures simultaneously? What factors are responsible for control of size and shape of the nanostructures? Can each of the different carbon nano structures be separated? How does the synthetic strategy adopted dictates the ultimate materials technology? Or in other words, what impact does this synthetic strategy have on the ultimate materials technology? The ultimate materials technology is a function of material structure as well as material property which are controlled by the specific synthetic strategy employed. For instance, as in the present case, the fibers obtained were found to be conducting and such conducting fibers are useful in biosensors, ion-activated molecular switches and for the fabrication of microelectrodes for medicinal applications. Composite fibers can be obtained from hair-like and wool-like fibers. The bitter gourd like fibers with extremely irregular outer surface yields large specific surface area values and will be useful for catalytic applications. The electrodes

fabricated from the thin film carbon synthesized was found to be a substitutes to an expensive RuO_2 coated titanium sheet which is used as anode against a mercuric cathode for the electrolysis of brine solution. The electrochemical potential range of the electrode fabricated from carbon thin film material was found to be -1.24 to 1.67 V Vs SCE (standard calomel electrode) indicating that water will not be electrolysed by using the electrodes (both anode and cathode) fabricated by this carbon material.   The electrodes fabricated from thin film carbon could electrolyze 30 % NaCl solution at 300 $mAcm^{-2}$ for more than 110 h continuously with out any deterioration [21]. Thus the electrodes fabricated from the carbon obtained by kerosene pyrolysis are useful for Chloro-alkali industry offering a solution for toxicity problem by eliminating the hazardous mercury contamination [20].

| (a) | (b) | (c) |
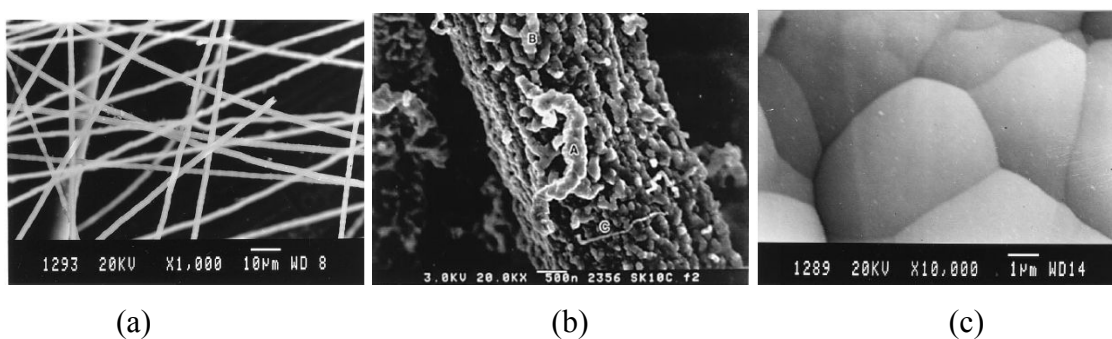
Fig. 10.16. SEM (scanning electron microscope) images of (a) hair like fibers, (b) bitter – gourd - like rough fibers and (c) carbon thin film grown on a stainless steel substrate

Carbon Nanotubes as STM and AFM Tips:

Gerd Binnig and Heinrich Rohrer at the IBM (International Business Machines Corporation) research laboratories in Zurich in the late 1970's developed a method of structural analysis namely the STM, scanning tunneling microscopy. Few details on the principle of operation of STM are worth knowing. Electron is not only a particle but also a wave. In our daily life walking through a brick wall is not possible [7]. Imagine a nanometer scale equivalent of a brick wall. Let this be an energy barrier that an electron following prequantum physics would not be able to overcome. But quantum mechanics tells us that there is still a certain probability that the electron is found on the other side of the wall since electron is not only a particle but also a wave. In this case the electron

behaves more like a wave and this effect is called tunneling which forms the basis of STM analysis. The empty space between the surface to be studied and the probe is regarded as the barrier or the wall through which an electron normally but occasionally will not passes. The tip of the probe should be one atom wide. The next layer can contain more atoms. The probability of tunneling decreases by a factor of ten for each 0.1 nm of additional distance. So the second layer has no virtual significance. The one atom tip is suspended above the object just a few atomic radii. This distance is readjusted using the measured tunneling current. From the distance between the STM tip and the surface to be probed and the measured tunneling current one can feel the structure of the surface. The peaks and troughs of the surface can be felt at atomic scales with out ever touching it. It has now become possible to control the placement of the tip with sufficient accuracy establishing STM as a standard method of analysis in materials science.

A variation of the theme of electron tunneling found as in the case of STM was presented in 1986 by Binnig, C. F. Quate and C. Gerber which was latter called as Atomic Force Microscopy (AFM). In this technique the probe will actually touch the surface. The vertical movement of the tip of the probe will be controlled by the repulsive force measured when the surface is touched. By 1990's individual biomolecules such as the double-stranded DNA could be pictured which made the researchers elated. Thus both STM and AFM techniques are in principle suitable for "feeling" the fine structure of a surface atom by atom.

The performance of STM and AFM instruments has been limited by the quality of the tip which acts as a probe that either exchanges electron with the surface as in the case of STM or touches the surface as in the case of AFM. The virtual characteristics a tip should possess to be used as probe are: such tips should end in a single atom; possess a well defined geometry, should be conductive and chemically inert. So far the tool that worked as a good probe tip is obtained by simply cutting a metal wire with an ordinary pair of scissors. Is it not surprising? Even though the afore mentioned material possessed no such virtual attributes as mentioned previously for an ideal probe, the material derived by cutting through a metal wire with a pair of scissors worked very well. The diameter of such a tip is of a few hundred nanometers indicating that the outer most

layer contains thousands of atoms. Interestingly, alternative methods like etching the wire tips or some other improvements in shaping the metal wire only failed to function. Tremendous improvements have been brought about in the advancement of utility of STM and AFM techniques for probing the surface structure when carbon nanotubes (CNT's) were used for the first time as AFM tips by the researchers from the laboratory of Nobel Laureate Richard Smalley. A single carbon nanotube of 10 nm wide and 100 nm to 1 μm long capped with fullerene – like hemisphere is glued as molecular antenna onto a conventional probe. The conventional probe was coated initially with a suitable glue and then dipped into a bundle of nanotubes. In most cases, this effort culminated into the gluing of just one tube onto the tip.

The new probe onto which carbon nanotube is glued fulfilled the ideal conditions the STM or AFM tip should satisfy. The probe with CNT tips has a well-defined and well-known molecular structure, is conductive, chemically inert and also very thin. Use of carbon nanotubes as AFM tips provided additional advantages by being stable to withstand the forces applied to the tip and also being elastic enough to avoid unwanted collisions with the surface. More over, now-a-days, reliable and reproducible synthetic strategies are at disposal for making such new probes (carbon nanotubes).

Role of Synthesis in Leather Technology:

Transformation of animal hides and skins into attractive, aesthetic and useful artifacts has been one of the oldest technologies of mankind. When wet the animal skins are susceptible to bacterial attack and putrefy. On the contrary drying makes the skin inflexible and useless for clothing and other applications. Such problems can be over come by the use of bactericide during soaking . This forms a good solution for the short term preservation of skins and hides. Addition of bactericide prevent the bacterial attack on hide and skin. Addition of bactericide convert the putrescible biological materials into a stable material resistant to microbial activities with enhanced resistance to wet and dry heat. The bactericide kill the growth of microorganism there by preventing the damage to skin and hide.

Mercury compounds as well as a mixture of sulfite and acetic acid were extensively used as bactericides. Even though the afore mentioned materials are effective they are damageable and harmful to the environment. So they are no longer used for protecting

the hides and skins from bacterial attack. Instead, bronopol which is a highly active antimicrobial chemical compound has been the ubiquitous choice to leather industry to prevent bacteria attacking the skins and hides. Bronopol is 2-bromo-2-nitro propane – 1, 3 – diol.   Bronopol was invented by The Boots Company PLC, Nottingham, England in the early 1960's. It was used as a preservative for pharmaceuticals for the first time [21]. Earlier reports on the synthetic path ways of bronopol include reaction of bromo-nitro-methyl-cyclohexanol with aliphatic aldehyde. The main drawbacks associated with this method of synthesis are the use of cyclohexanol which is expensive and also the use of hazardous sodium ethoxide. Lakshimi Muthusubramanian and Rajat B Mitra [22] have succeeded in deloping a simple but cleaner synthetic strategy that helped Leather manufacturing technology.

$$CH_3NO_2 + 2CH_2O + NaOH \longrightarrow HOH_2C - \overset{\overset{\displaystyle Na}{|}}{\underset{\underset{\displaystyle NO_2}{|}}{C}} - CH_2OH$$

(Nitro-   (Formal-   (Sodium-
methane)   dehyde)   hydroxide)
(Sodium salt of 2-nitropropane-1,3 diol)

$$HOH_2C - \overset{\overset{\displaystyle Na}{|}}{\underset{\underset{\displaystyle NO_2}{|}}{C}} - CH_2OH + Br_2 \longrightarrow HOH_2C - \overset{\overset{\displaystyle Br}{|}}{\underset{\underset{\displaystyle NO_2}{|}}{C}} - CH_2OH$$

(Bromine)
(2-Bromo-2-nitropropane-1,3 diol)
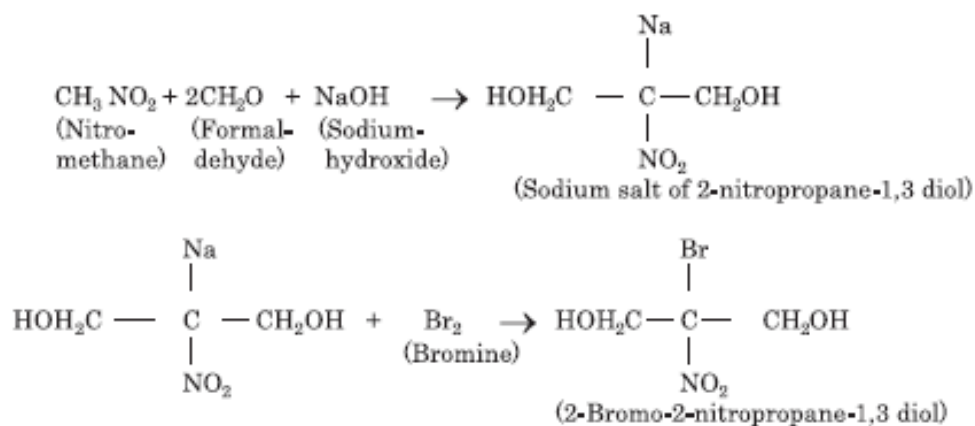
Scheme 10.1. Synthetic strategy for Bronopol

This method of synthesis of bronopol includes reaction of formaldehyde with nitro alkane in the presence of sodium hydroxide (in MeOH) which on bromination yielded bronopol as represented in Scheme 10.1.   The advantages of this method include complete replacement of hazardous and expensive hydroxide and methanol which are inexpensive and readily available. Currently scale up studies are being carried out for the production of bronopol using this environmentally benign synthetic strategy.

CONCLUSION:

The living cells are versatile in its design and function. They provide all necessary inspiration to design and synthesize new materials with specific functions that bring

about revolutions in Technology and also give birth to Advanced Technologies. Understanding and imitation of natural machinery of the living cells holds great rewards. But such endeavours are not free from barriers and obstacles. For instance, molecular level details of the working of ribosomes (their function of protein synthesis) is unclear even today and remains one of the hardest problems in biology. Therefore our knowledge and understanding of the processes going on in a living cell and also the mechanochemical functions of various cell components is limited. Any improvements in such an understanding facilitate imitation and mimicking of the synthetic strategies involved in life process (a unique network of chemical reactions). This knowledge will in turn bring about drastic changes and advancements in Materials Technology.

REFERENCES:

1. http://en.wikipedia.org/wiki/cell_(biology)

2. http://www.ucmp.berkeley.edu/history/hooke.html

3. http://www.roberthooke.org.uk/

4.http://images.google.co.in/imgres?imgurl=http://cache.eb.com/eb/image%3Fid%3D99768%26rendTypeId%3D4&imgrefurl=http://www.britannica.com/ebc/art-99713/Robert-Hookes-drawings-of-the-cellular-structure-of-cork

and&h=450&w=339&sz=44&hl=en&start=1&um=1&tbnid=8NZeLWw7jw9MzM:&tbnh=127&tbnw=96&prev=/images%3Fq%3DRobert%2BHooke%2Bcell%26um%3D1%26hl%3Den%26sa%3DN

5. http://www.cellsalive.com/cells/3dcell.htm

6. Travels to the nanoworld Miniature Machinery in Nature and Technology, Michael Gross, Perseus Publishing, Cambridge, Massachusetts, 1999.

7. North Central Regional Eductional Laboratory, 1-800-356-2735, 1997-99.

8. http://www.sp.se/en/areas/material/Sidor/default.aspx

9. http://en.wikipedia.org/wiki/Gutenberg_Bible

10. Warren H. Hunt, Jr. JOM, October 2004, 13.

11. H. W. Kroto, J. R. Heath, S. C. O'Brien, R. F. Curl and R. E. Smalley, Nature 318 (1985) 162

12. P. Scharff, Carbon 36 (1998) 481

13. T. Pradeep, Current Science, 72 (1997) 124

14. Marc Monthionx, Vladimir L. Kuznetsov, Carbon 44 (2006) 1621

15. Purushottam Chakraborty, Everyman's Science, Vol. XXXIX, No. 4, October-November' 04

16. Nanotube and Nanofibers, Yury Gogotsi (Ed.,) Taylor & Francis, 2006

17. Yoshinori Ando, Xinluo Zhao, Toshiki Sugai, and Mukul Kumar, Materials Today, October 2004, 22-29

18. Xinluo Zhao, Sakae Inone, Makoto Jinno, Tomoko Suzuki, Yoshinori Ando, Chemical Physics Letters, 373 (2003) 266

19. R. Saito, G. Dresselhaus and M. S. Dresselhaus, Physical Properties of Carbon Nanotubes, Imperial College Press, 1998

20. Mukul Kumar, P. D. Kichambare, Maheshwar Sharon, Yoshinori Ando and Xinluo Zhao, Materials Research Bulletin 34 (1999) 791

21. http://en.wikipedia.org/wiki/Bronopol

22. Lakshmi Muthusubramanian, Rajat B Mitra, Journal of cleaner production, 14 (2006) 536

Chapter - 11

ELECTROCHEMICAL SYNTHESIS

M Helen

INTRODUCTION

Electrochemistry is a branch of science which deals with electrical energy and chemical change. Spontaneous chemical reactions liberate electrons and they are taken place in *Galvanic or Voltaic Cells*. These cells are exploited in batteries and fuel cells to produce electric power. On the other hand *Electrolytic Cells* are nonspontaneous where electrical energy is required to carry out chemical transformations. For an example in the process called water electrolysis electrical energy is supplied to split water in producing hydrogen and oxygen. Electrolysis is exploited in electroplating, chlorine gas production and in refining metals.   *Electrochemical synthesis* is the production of chemical products or materials using electricity as the driving or controlling factor.   Electrochemical synthesis is achieved by passing an electric current between two electrodes separated by an electrolyte.   That is, the synthesis takes place at the electrode-electrolyte interface.   This method has significant potential for improving availability of specialty products and for improving environmental compatibility in several industrial sectors by destroying or converting unwanted byproducts into useful products.   Much progress has been made in the last few decades in advancing the basic understanding and industrial applications of electrochemical processes, but many aspects of electrochemical synthesis are still inadequately understood or explored.

FEATURES OF ELECTROCHEMICAL SYNTHESIS

The features that distinguish electrosynthesis from other synthetic methods are:

- ➢ The experiments are simple to perform and the instruments required are inexpensive and readily available.

- ➢ Electrochemical synthesis takes place at the electrode-electrolyte interface which has a very high potential gradient of 10^5 V cm^{-1}.   Under these conditions, the reactions often lead to products which cannot be obtained in a conventional chemical synthesis.

- ➢ An electrochemical synthesis is a redox reaction. By fine-tuning the applied cell potential, the oxidizing or reducing power can be continuously varied. This

> ➤ possibility of continuous variation is not available in conventional chemical synthesis.

> ➤ The product is normally deposited on the electrode in the form of a thin film or a coating.

> ➤ The film composition can be controlled by varying the bath composition.

> ➤ Electrochemical synthesis is a low-temperature process limited by the boiling point of the electrolyte.

> ➤ Reaction taking place can be controlled kinetically by controlling the current passed through the cell, while it can be thermodynamically controlled by choosing the applied potential.

In summary, electrochemical synthesis is a 'green' route to produce to fabricate high-purity materials without any additives.

ELECTROCHEMICAL SYNTHESIS: DESIGNING

Any electrochemical reaction depends on the proper choice of a number of reaction parameters such as:

    (1) Choice of an electrode

    (2) Choice of an electrolyte

    (3) Choice of temperature, pH, concentration, and composition of the electrolyte solution

    (4) Choice of the cell design - divided or undivided

    (5) Mode of electrolysis - potentiostatic or galvanostatic (constant potential or constant current)

In a typical electrosynthesis, the reactant, which is dissolved in the electrolyte is deposited as a solid product.   When a metallic salt is dissolved in water it dissociates to form positively charged ions. The solution that contains these charged ions is referred to as an electrolyte or a plating solution. By passing electric current through this electrolyte, one can reduce the metal ions to form solid metal. This process is referred to *electroplating* or *electrochemical deposition*.   In Fig. 11.1 electroplating is explained by taking silver as the anode, fork as the cathode (fork to be plated with silver) and aqueous solution of silver nitrate as an electrolyte. Both anode and cathode are connected to the external battery.   When the external power is on silver metal at the anode is oxidized to

silver ions and moves towards cathode. At the cathode silver ions is reduced to silver and deposits on the fork. This results in thin covering of silver on the cathode (fork).
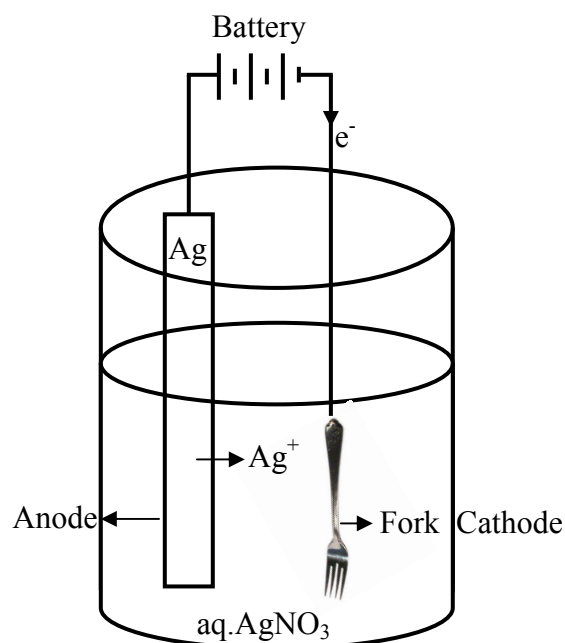
Fig. 11.1 Representation of silver electroplating

Two parameters determine the course of the reaction i) the deposition current and (ii) the cell potential.   Of the two, any one of them can be controlled as a function of time during the reaction.

In a galvanostatic synthesis (Fig. 11.2), a constant current is applied through the electrolytic cell leading to deposits with good adhesion and a controlled morphology. However the cell potential drifts as the activity (concentration) of the reactant is decreased.   The drift in the cell potential may lead to a multiplicity of products.

A potentiostatic synthesis is carried out with a three-electrode electrolytic cell (Fig. 11.3). The synthesis is carried out by polarizing the electrode to a desired potential with respect to a reference electrode.   The cell current usually decays rapidly as the reaction proceeds, both due to low rates of diffusion of the reactant molecules from the bulk to the electrode surface as well as due to decrease in the activity of the reactant.   The reaction yields a pure single-phase product selected for by the applied potential.
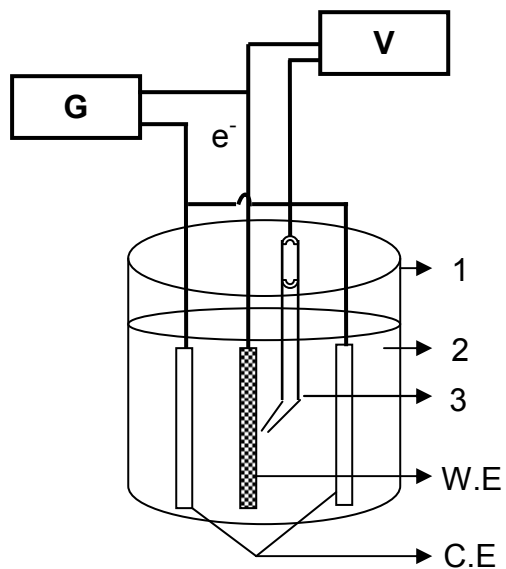
Fig. 11.2.   Galvanostatic Synthesis,
G, galvanostat; V, voltmeter; WE, working electrode; CE, counter electrode;1,
electrochemical cell; 2, electrolyte; 3, Lugin capillary
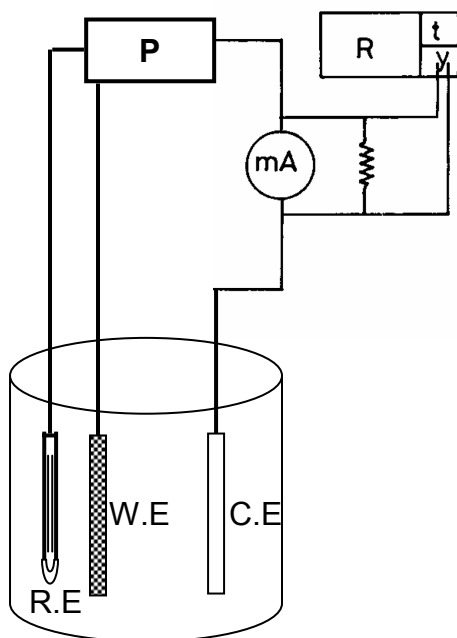
Fig. 11.3.   P, potentiostat; R, recorder; RE, reference electrode; WE, working electrode;
CE, counter electrode

VARIOUS TECHNIQUES FOR ELECTROCHEMICAL SYNTHESIS

Various techniques are employed in electrosynthesis. A list a few of them and the nature of products obtained from each are given in Table 11.1.

Table 11.1. Summary of the Electrosynthetic Techniques

Technique	Product	Application
Anodic oxidation	Coatings/films/powders/ conducting polymers	Synthesis of compounds with high oxidation state, corrosion control, electrochromism
Cathodic reduction	Coatings/films/powders	Synthesis of electrode materials for energy systems, fabrication of hydroxide films/coatings
Electrolysis of fused salts, water	Single crystals, pure metals and gases	Crystal growth at moderate temperature, pure gas production
Electromigration of reactant species	Polycrystalline powders/ single crystals/carbon	Electrode materials for batteries and electrochromism
Alternate voltage/current synthesis	Layer-by-layer films/coatings	Synthesis of composites/solid solutions
Electrospraying	Micro or nanoparticles	Biomedical applications
Electrospinning	Micro or nanofibres	Drug delivery, tissue engineering, sensors

During anodic oxidation a metal ion in a lower oxidation state or a monomer like pyrrole or aniline is oxidized to a higher oxidation state or polymer anodically.   The anodic oxidation technique is especially suited for the synthesis of compounds with metal ions in unusual high oxidation states. In Table 11.2, important anodic syntheses are listed.

Table 11.2. Oxides and Polymers Synthesized by Anodic Oxidation

Compound	Application
Al_2O_3	Template, molecular filters
$CoO_2.nH_2O$	Electrochromic devices, lithium ion batteries, supercapacitors, and the protection film of cathodes in molten carbonate fuel cells
FeO and MnO_2	Electrode material
Ta_2O_5	Protective coating for chemical equipment,

	electronic and sensor devices
$NiO(OH)$, Co_2O_3	Alkaline water electrolysis
PbO_2	Battery, Organic degradation
$Fe_{3-x}Li_xO_4$	Magnetic devices, electrode material
WO_3 with Co, Cr, Fe, Mo, Ni, Ru, and Zn	Electrochromic devices
RuO_2	Supercapacitor
TiO_2	Photocatalyst, humidity sensor
V_2O_5 nanofibers	Battery material, active materials in electrochromic and chemochromic devices
Polypyrrole, polyaniline, polythiophenes, polyacetylenes, polyindole	Sensors, Electroluminescence, Protective coating, FET, Organic semiconductors, batterries

In cathodic reduction electric current is passed through a metal salt solution and hence the metal is deposited at the cathode.   This principle is widely used to obtain metal coatings. But depending upon the deposition potential, choice of the anion and the pH of the solution various other reactions take place at the cathode. Switzer in 1987 introduced this technique for the first time as a synthetic route to obtain oriented ceramic films as well as polycrystalline powders.   Polycrystalline CeO_2 powder was synthesized from a cerous nitrate solution. Various oxide materials are synthesised by using electrogeneration of base by cathodic reduction and their typical applications are listed in Table 11.3.

During electrolysis of fused salts, a low-melting salt containing the transition metal oxide, is melted and electrolyzed at elevated temperatures using an inert Pt electrode or a reactive metal electrode such as Fe, Co, or Ni depending on the desired product.   During water electrolysis pure oxygen and hydrogen is collected at the anode and cathode respectively.

Synthesis by electromigration, is based on kinetic control over the reaction by electrochemistry.   This technique involves intercalation or deintercalation of a guest ion in a host lattice by applying an electric potential between the electrodes.

During pulsed electrolysis, the working electrode is alternately polarized anodically for a length of time, *t1*(called the on-time) and then cathodically for time, *t2* (called the off-time).   Voltage as well as current pulses were used to obtain oxide films in the Pb-Tl

system using a stainless steel electrode and a mixed Pb-(II)-Tl(I) bath.   At low current densities, the films were Tl-rich while at high current densities the films were Pb-rich. Cathodic deposition of the precursor film for the YBaCuO system has been carried out from a mixed metal nitrate bath containing KCN as well as a complexing agent.   The superconductive films obtained from a cyanide bath show a $Tc \sim 92$ K which is greater than all other reported values for this class of superconductors, obtained by electrochemical techniques.   High intensity pulsed electric fields is an interesting alternative to traditional techniques like thermal pasteurization in preservation of liquid foods such as fruit juices or milk.   Conventional preservation methods such as heat treatment often fail to produce microbiologically stable food at the desired quality level. High intensity pulsed electric fields processing can deliver safe and shelf-stable products with high nutritional value.   Pulsed electrodeposition is an effective method to prepare nano materials of different morphologies.

Table 3. Oxides Synthesized by Electrogeneration of Base by Cathodic Reduction (reproduced from [1])

Compound	Application
CeO_2	Gas sensor, fuel cells
$La_{1-x}M_xCrO_3$ (M = Ca, Sr or Ba)	Electronic conductor
ZrO_2	Ionic conductor
$BaTiO_3$	Dielectric components
$LaFeO_3$	Oxide coating
Al_2O_3, Cr_2O_3, $Ln_2Cr_3O_{12}.7H_2O$	Corrosion-protective coating
PbO_2	Electrode material
$Mo_{1-x}M_xO_3$ (M = Co, Cr, Ni, W or Zn)	Optical light modulators
TiO_2	Photocatalyst
Nd_2CuO_4	Superconductor
ZnO	Optical and electronic devices
$LaMnO_3$	Giant magnetoresistance (GMR)
WO_3	Electrochromic devices

MICRO- AND NANOPARTICLE PRODUCTION BY ELECTROSPRAYING

Electrospraying is a process of liquid atomisation by electrical forces. It is a dynamic process of droplet generation and simultaneously charging by means of an electric field. Droplets spraying out of a capillary nozzle, produced by electrospraying are highly charged. Charged droplets are self dispersing in space, resulting in the absence of droplet coagulation. The deposition efficiency of a charged spray on an object is higher than for an un-charged spray. This feature can be advantageous in thin-film formation or in surface coating. Generation of the droplet and its size can be controlled by controlling the flow rate of the liquid and the voltage at the nozzle. Nearly monodisperse size distribution is achievable. The size of the electrospray droplets can range from micrometers to nanometers.
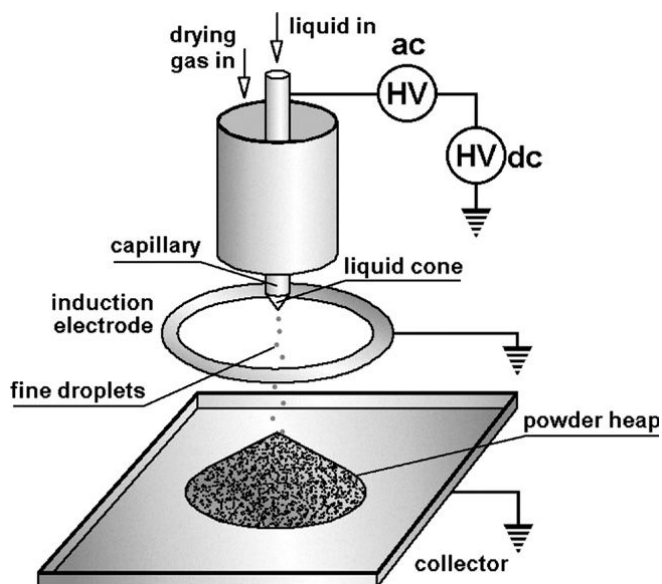
Fig. 11.4. Schematic for production of particles of uniform size by electrospraying
(reproduced from [2])

Electrospraying technique is a single-step, low-energy, and low-cost material processing technology, which can deliver products of unique properties. Electrospraying is exploited in many industrial processes such as painting, fine powder production, or micro- and nanothin film deposition. It is also employed in microfluidic devices and nanotechnology. Spraying solutions or suspensions allows production of particles,

ranging from micro to nanometer size.   Production of particles of uniform size can be accomplished by using pulsed or ac superimposed on dc bias voltage for liquid jet excitation.   By tuning the frequency of ac voltage, uniform size of droplets are formed by disintegrating the liquid jet. Various parameters can control the droplet size they are the bias and ac voltage magnitudes, ac voltage frequency, and volume flow rate of the liquid.   Uniform droplets can be achieved when ac and dc voltages are adjusted such that the droplets are formed and detached at the voltage peaks.   A schematic diagram of a system for harmonic spraying is shown in Fig. 11.4.

Electrospraying is exploited for the generation of micro/nanospheres for biomedical applications since the process has an advantage of not making use of any external dispersion/emulsion phase which often involves ingredients that are undesirable for biomedical   applications.   Chitosan   micro/nanospheres   were   synthesized   by electrospraying with acetic acid solution is exploited for drug delivery applications. This technique is also used to prepare polycaprolactone (PCL) polymer particles with a different microstructure by the evaporation of solvents during the electrospraying process.

MICRO- AND NANOFIBRES PRODUCTION BY ELECTROSPINNING

Electrospinning is a process in which a high voltage electric field is applied to a melt or polymer solution in order to attain charge repulsion on the liquid surface. This overcomes surface tension there by a thin liquid jet is ejected. Narrow jet diameter is attained due to the electrostatic repulsion caused between the charges on the liquid surface and the collector that has a different electric field. Solid or polymer fibres ranging from 10 μm to 10 nm is attainable. As shown in Fig. 9.5, a typical electrospinning setup consists of a syringe with a capillary nozzle through which the liquid to be electrospun is forced; a high voltage source with positive or negative polarity to charge the liquid jet and a ground collector.

Electrospun textiles are exploited in preparing filters, semi-permeable membranes, as scaffolding for tissue engineering and in drug delivery. Electrospinning has flexibility in selecting materials for drug delivery applications.   Either biodegradable or non-degradable materials can be used to control whether drug release occurs via diffusion alone or diffusion and scaffold degradation. Due to the flexibility in material selection a

number of drugs can be delivered including: antibiotics, anticancer drugs, proteins, and DNA.
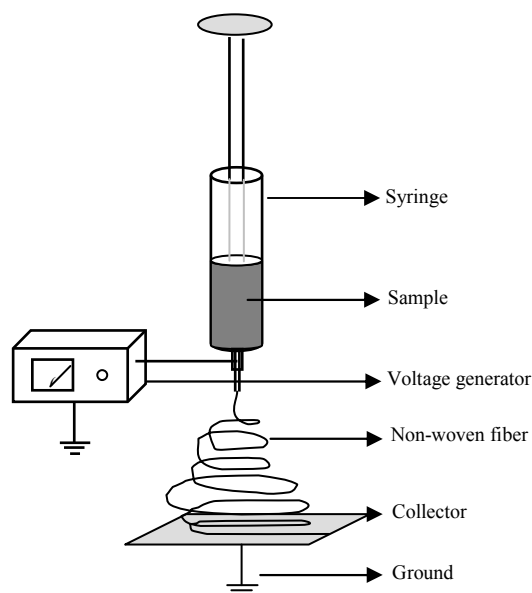
Fig. 11.5. Schematic of an electrospinning system

CONCLUSION

Electrochemical techniques such as anodic oxidation, cathodic reduction, alternating current pulsing, electrospraying and electrospinning provide simple, cost effective alternative routes for the production of micro or nanomaterials, thin films, coating, composites having unique properties and applications. It is hoped that the ease and versatility of this technique will find will find it a permanent place in synthetic chemistry.

REFERENCES

1. G. H. A. Therese and P. V. Kamath, *Chem. Mater.,* 12 (2000) 1195.
2. A. Jaworek, *Powder Technol.,* 176 (2007) 18.
3. A. Jaworek, A.T. Sobczyk *J. Electrosta.,* 66 (2008) 197.
4. N. Arya, S. Chakraborty, N. Dube, D.S Katti, J *Biomed Mater Res B Appl Biomater.,* 2008 (In Press)
5. S. Tan, X. Feng, B. Zhao, Y. Zou, X. Huang, *Mater. Lett.,* 62 (2008) 2419.
6. T. J. Sill, H. A. von Recum, *Biomaterials,* 29 (2008) 1989.

Chapter – 12

NEWER REACTIONS AND PROCEDURES: CATALYTIC AND NONCATALYTIC

M.Banu

The following chapter focuses mainly on some developments of industrially important reactions with and without catalyst. Briefly the contents of this chapter include:

- Introduction
- Biodiesel production with new source by transesterification reaction with and without catalyst
- Conversion of glycerol to valuable chemicals by heterogeneously catalysed liquid-phase oxidation
- Catalytic hydro-desulfurization
- Catalytic and noncatalytic study of oxidative dehydrogenation reaction for ethane conversion to ethylene as the one of the industrially important product
- Noncatalytic supercritical fluid method for the preparation of various polyorganosiloxanes

1.0. INTRODUCTION

The general definition for catalyst is "chemical marriage brokers".
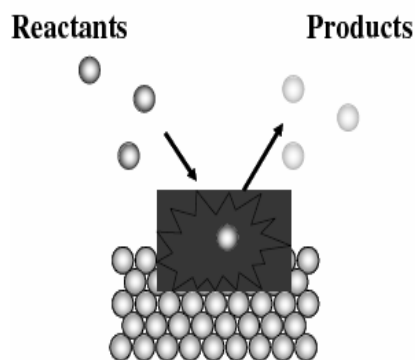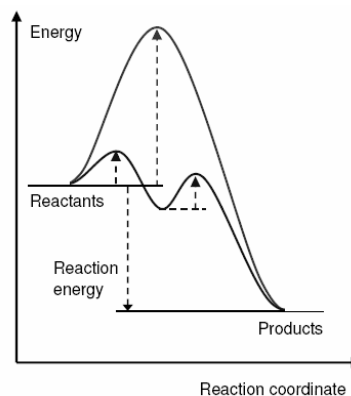
Fig. 1(a)   Fig. 1(b)

Fig. 12.1 (a) General diagram for catalytic reaction; (b) Energy profile diagram for catalytic reaction [1]

The presence of a catalyst facilitates reactions that would be kinetically impossible or very slow without a catalyst. The catalyst does not alter the overall thermodynamics of the reaction.

1.1 IMPORTANCE OF CATALYST

- More than 70 % of all existing processes on an industrial scale rely on catalysis.
- More than 99 % of the world gasoline production occurs via catalytic cracking of oil fractions and other catalytic processes.
- More than 90 % of all new industrial processes are catalytic.
- Enzymes are catalysts that facilitate complex reactions with 100 % selectivity at extremely mild reaction conditions, *i.e.* in our bodies
- The chemical precision displayed in enzymatic reactions is a source of inspiration for all catalysis chemists.

In our life mainly one is depending on oil mostly for transport, food, pharmaceutical, industry and entire basis of modern life. So the demand for energy sources more in India compared to other countries. Biodiesel is the one of the important energy source. Biodiesel is a domestic, renewable fuel for diesel engine derived from natural oils. Biodiesel can be used in any concentration with petroleum based diesel fuel in existing diesel engines with little or no modification. Biodiesel production can be carried out by catalytic route and also by noncatalytic route. Biodiesel is not the same thing as raw vegetable oil. It is produced by a chemical process which removes the glycerin from the oil. The glycerol is the one of the byproducts in the biodiesel production. It can be converted in to valuable products by environmentally friendly catalytic route. The industrial energy sources like petrol and diesel contain more amounts of sulphur and it leads to the formation of more pollution which is very harmful for human beings. For removal of sulphur content in oil, hydrodesulfurisation is the important process which can be carried out by catalytic route with Mo, Ni, and Co loaded on various supports. Although catalytic route is feasible in industrially, some of the noncatalytic routes are also possible for producing industrially important products like ethane and polyorganosiloxanes. Ethene is the second major component of natural gas and it is also abundant in

refinery gases. Polyorganosiloxanes are the important material in chemical industries which can be prepared by catalyst free super critical fluid method.

2.0 BIODIESEL PRODUCTION BY TRANSESTERIFICATION REACTION

Biodiesel is a fuel composed of mono-alkyl esters of long chain fatty acids derived from variety of vegetable oils or animal fats. Biodiesel has become more attractive recently because of its environmental benefits and the fact that it is made from renewable resources. Although there are many ways and procedures to convert vegetable oil into a diesel like fuel, the transesterification process [1] was found to be the most viable oil modification process.

2.1 Transesterification Reaction

Transesterification is the process of using an alcohol (e.g. methanol, ethanol or butanol), in the presence of a catalyst, such as sodium hydroxide or potassium hydroxide, to break the molecule of the raw renewable oil chemically into methyl or ethyl esters of the renewable oil, with glycerol as a by product.

$$
\begin{array}{l}
\underset{\text{Triglyceride}}{
\begin{array}{l}
\text{CH}_2\text{-O-}\overset{\displaystyle O}{\overset{\|}{\text{C}}}\text{-R}_1 \\
\,|\\
\text{CH-O-}\overset{\displaystyle O}{\overset{\|}{\text{C}}}\text{-R}_2 \\
\,|\\
\text{CH}_2\text{-O-}\overset{\displaystyle O}{\overset{\|}{\text{C}}}\text{-R}_3
\end{array}}
\;+\; \underset{\text{methanol}}{3\,\text{CH}_3\text{OH}}
\;\underset{\text{(KOH)}}{\Rightarrow}\;
\underset{\text{mixture of fatty esters}}{
\begin{array}{l}
\text{CH}_3\text{-O-}\overset{\displaystyle O}{\overset{\|}{\text{C}}}\text{-R}_1 \\
\text{CH}_3\text{-O-}\overset{\displaystyle O}{\overset{\|}{\text{C}}}\text{-R}_2 \\
\text{CH}_3\text{-O-}\overset{\displaystyle O}{\overset{\|}{\text{C}}}\text{-R}_3
\end{array}}
\;+\;
\underset{\text{glycerin}}{
\begin{array}{l}
\text{CH}_2\text{-OH} \\
\,|\\
\text{CH-OH} \\
\,|\\
\text{CH}_2\text{-OH}
\end{array}}
\end{array}
$$
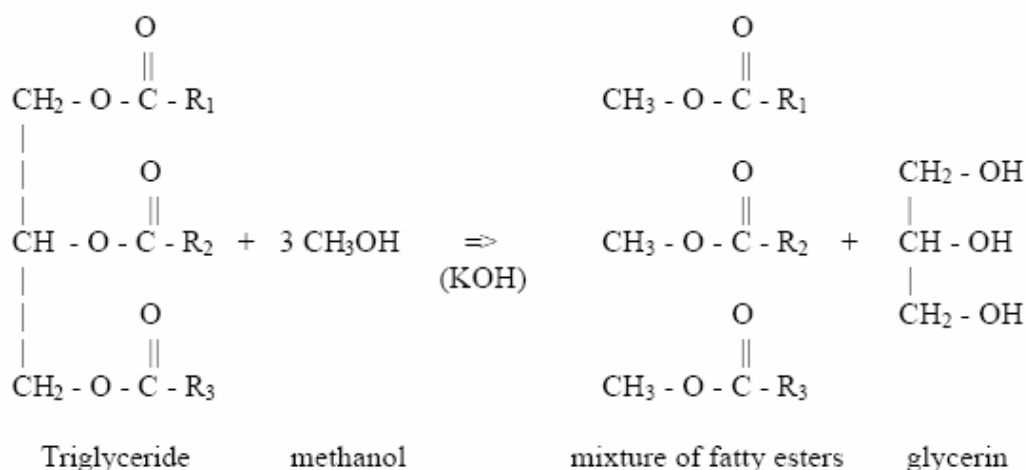
Scheme. 12.1. Transesterification Reaction

The Fats and oils are big molecules with a spinal of glycerol on which are bound three fatty acid rests as shown in Fig. 12.2 (a). The fatty acid rest are removed from the glycerol and it will form bond with methanol by transesterification method. Further it leads to the formation of one mole of glycerol and three moles of fatty acid methylester which is shown in Figs. 12.2 (b) and 12.2 (c).

(a)   (b)   (c)

Fig. 12.2 (a) Molecular structure of fatty acid rests with glycerol; (b) Formation of bond with methanol; (c) formation of glycerol and methylester [1].

The following methods are employed for the preparation of biodiesel

- Batch Base Catalyzed

- Continuous Base Catalyzed

- Acid Catalyzed Processes

- Non-Catalytic Processes

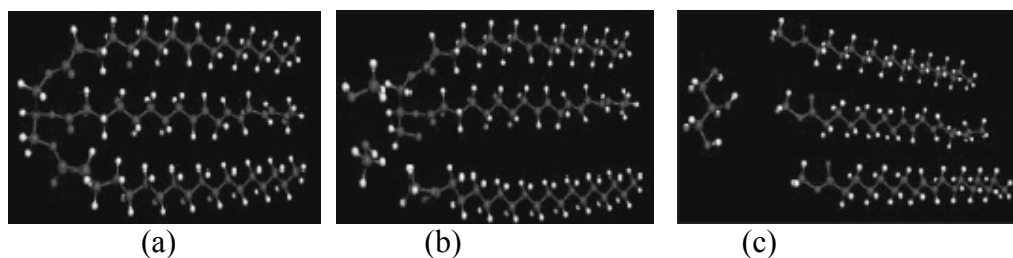Feedstocks used in biodiesel production mainly triacylglycerol or fats and oils (e.g. 100 kg soybean oil), primary alcohol (e.g. 10 kg methanol) and catalyst (e.g. 0.3 kg sodium hydroxide) and also the neutralizer (e.g. 0.25 kg) sulfuric acid. The triglycerids sources are rendered from animal fats like beef tallow, lard, and vegetable oils like soybean, canola, palm, etc and chicken fat and also rendered greases like yellow grease (multiple sources).The recovered materials is brown grease, and soapstock, etc.

2.2 BASE CATALYSED TRANSESTERIFICATION REACTION

Generally in the base catalysed transesterification method the catalyst is dissolved in methanol by vigorous stirring in a small reactor. The oil is transferred into the biodiesel reactor, and then, the catalyst/alcohol mixture is pumped into the oil. The final mixture is stirred vigorously at particular temperature and ambient pressure. A successful transesterification reaction produces two liquid phases that is ester and crude glycerin. Crude glycerin, the heavier liquid, will collect at the bottom after several hours of settling. Phase separation can be observed within 10 min and can be complete within 2 h of settling. Complete settling can take as long as 20h. After settling is complete, water is added at the rate of 5.5 % by volume of the methyl ester of oil and then stirred for 5 min, and the glycerin is allowed to settle again. Washing the ester is a two step process, which is performed with extreme care. A water wash solution at the rate of 28 % by volume of oil and 1 g of tannic acid per liter of water is added to the ester and gently agitated. Air is

carefully introduced into the aqueous layer while simultaneously stirring gently. This process is continued until the ester layer becomes clear. After settling, the aqueous solution is drained, and water alone is added at 28 % by volume of oil for the final washing. The basic batch reactor diagram is given in Fig. 12.3. The transesterification can be carried out by without catalyst also.
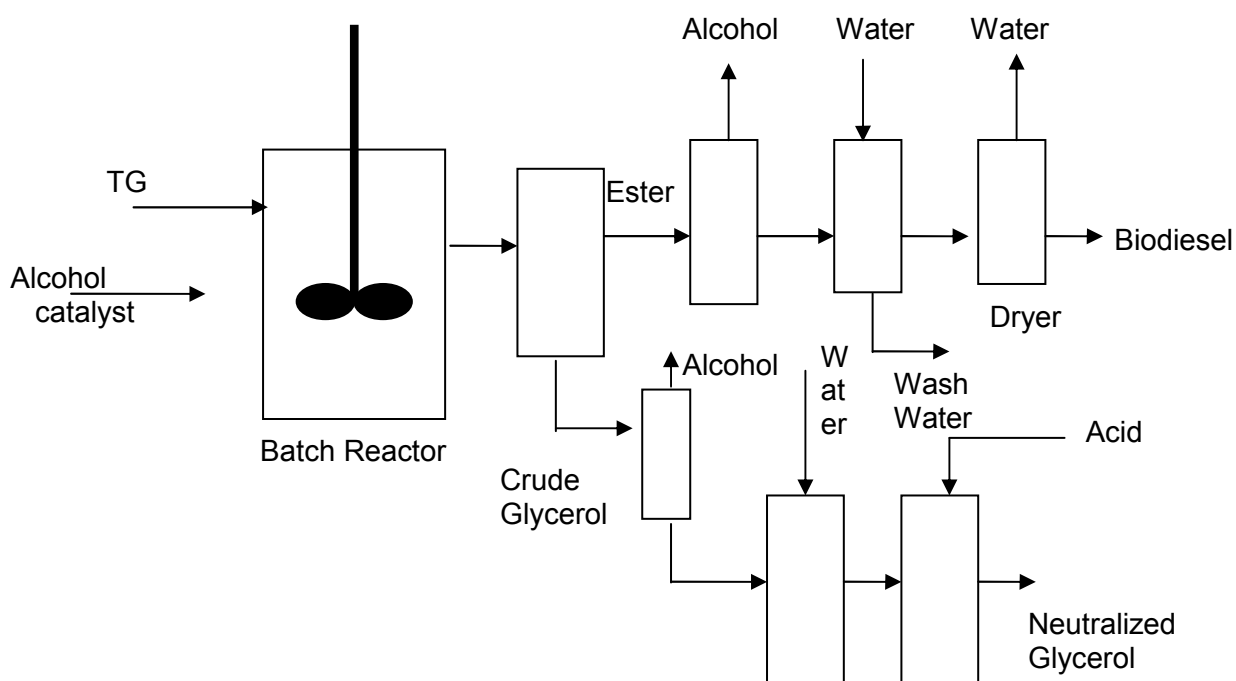
Fig. 12.3. Base Catalysed Reactor System [1]

2.3 ACID CATALYSED PROCESSES

Acid catalyzed processes are used for direct esterification of free fatty acids in a high FFA feedstock, or to make esters from soapstock. The sensitivities of the acid catalysed reaction is high FFA content requires water removal during reaction. In Acid catalyzed reaction the ratio of alcohol: FFA is 40:1 and also this reaction requires large amount (5 to 25 %) of catalyst.
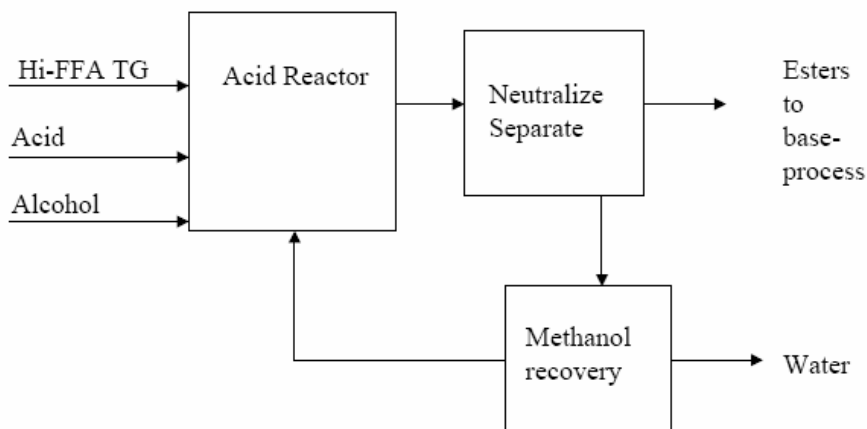
Fig. 4. Acid catalysed FFA pretreat system [1]

2.4 NON-CATALYTIC SUPERCRITICAL METHANOL TRANSESTERIFICAION REACTION

In this method, the reaction is performed by cylindrical autoclave maintained at particular temperature and pressure [2]. The autoclave will be charged with a given amount of vegetable oil and liquid methanol with different molar ratios. After each run, the gas is vented, and the autoclave is poured into a collecting vessel. All the rest of the contents are removed from the autoclave by washing with methanol. The variables affecting the methyl ester yield during the transesterification reaction, such as molar ratio of alcohol to vegetable oil and reaction temperature were already investigated. The viscosities of the methyl esters from the vegetable oils were slightly higher than that of diesel fuel. This method shows that increase in temperature especially critical temperature has a favorable influence of ester conversion. A typical supercritical methanol transesterification system is shown in Fig. 12.5.

The transesterification reaction of rapeseed oil in supercritical methanol was investigated without using any catalyst. In addition, it was found that this new supercritical methanol process requires a shorter reaction time and a simpler purification procedure because of that there is no catalyst.

Biodiesel preparation is also carried out by batch vs continuous flow method. Batch is better suited to smaller plants (<1 million gallons/yr). This batch does not require 24/7 operation. This provides greater flexibility to tune process to feedstock variations. The

continuous operation allows use of high-volume separation systems (centrifuges) which greatly increases the throughput and also hybrid systems are possible.

Fig. 12.5. Supercritical methanol transesterification system. (1) Autoclave, (2) Electrical furnace, (3) Temperature control monitor, (4) Pressure control monitor, (5) Product exit valve, (6) Condenser, (7) Product collecting vessel [2].
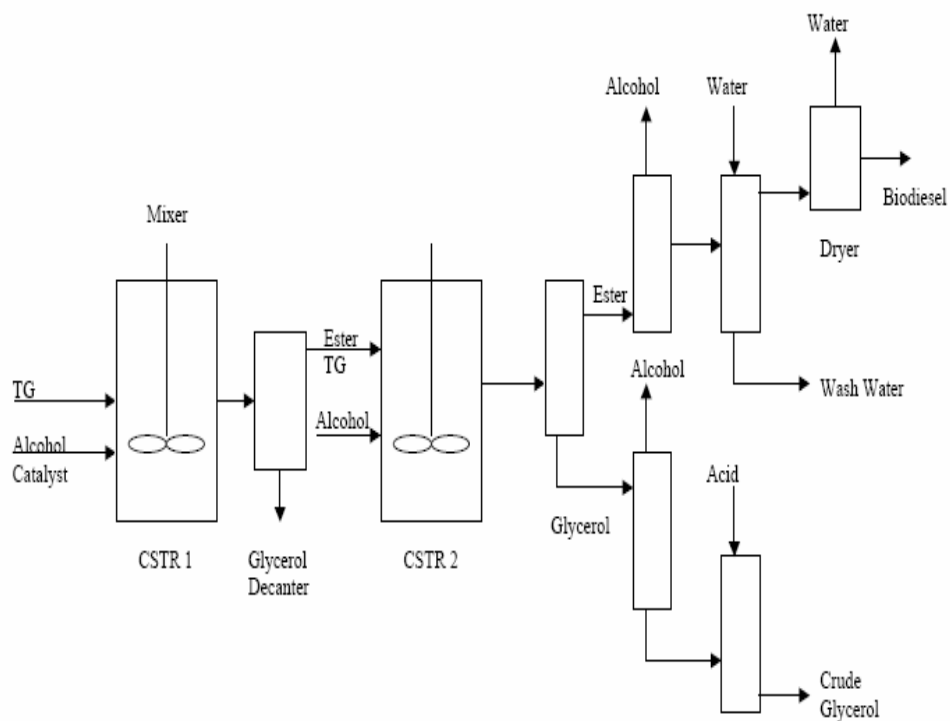
Fig. 12.6. Hybrid Batch/Continuous Base Catalyzed Process [1]
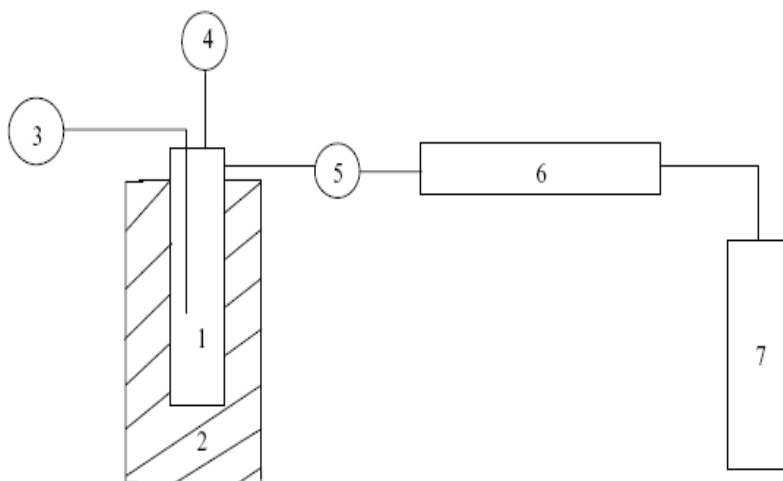
2.5 PROCESS ISSUES

The main issue of the base catalyzed transesterification process is free fatty acid in the oil which when reacted with alkaline catalyst will form soaps and it will lead to loss of catalyst and reduction in the oil.

$$R\text{-}OH + KOH \longrightarrow K\text{-}OR + H_2O$$

$$Acid + KOH \longrightarrow Soap + water$$
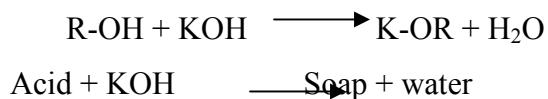
And water formation is another issue in base catalysed transesterification reaction. Water will deactivate the catalysts and also it requires the drying of oil. Water hydrolyses fats to form free fatty acids and the free fatty acids react with alkali catalysts forming soaps.

$$Soaps \longrightarrow semi\ solid\ mixture \longrightarrow glycerol\ separation$$

$$Triglycerids + water \longrightarrow Diglycerids + fatty\ acid$$
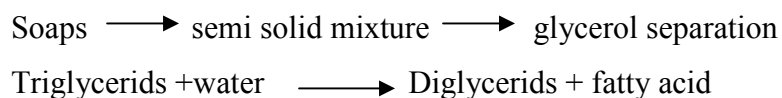
Another issue of the transesterification reaction is the use of alcohol. Methanol is commercially used. In methanolysis, emulsion forms and separated into lower glycerol portion and upper ester portion. Reaction time is small. In ethanolysis, emulsions are stable and require more complicated separation and purification process and also reaction time is large.

This transesterification reaction carried out generally by the use of homogeneous and heterogeneous catalysts. For homogeneous catalysed reaction, the basic catalyst used were NaOH, KOH, NaMeO and acid catalysts like H_2SO_4, PTSA, MSA, H_3PO_4, and $CaCO_3$. For heterogeneous reaction the catalysts employed are sulfated zeolites and clays, hetro-poly acids metal Oxides, Sulfates composite materials.

Base catalyzed reaction is not suitable for high FFA feeds because of soap formation. Most of the non-edible oils available in India contain high FFA (2-12%). In order to decrease the cost of biodiesel, it is imperative to utilize high FFA oil or fatty acids. So the preferred method for high FFA content feedstock is acid catalysis followed by base catalysis.

The main barriers of homogeneous catalyst are the focus on the sensitivity to FFA and water content of the feedstocks, removal of catalyst, formation of soap with FFA

feedstock. A large quantity of effluent water is the main issue as a result of removal of catalyst, which necessities pre-treatment of oil in case of high FFA content and also no scope for regeneration or re-utilization. In heterogeneous catalyst the main utilization is catalyst regeneration, decrease of catalyst cost, utilization of lower quality feed stocks for biodiesel production, simplification of separation process, decrease of production cost and decrease of wastewater and also development of environmental friendly process.

2.6 BIODIESEL FROM JATROPA PLANT

The jatropa plant is a good source for producing biodiesel. It is having the following main advantages

- It thrives on any type of soil and it needs the minimal inputs or management.
- It has no insect pests and it is not browsed by cattle or sheep
- It can survive long periods of drought and the propagation by seed/cutting is easy
- It is having the rapid growth and then it leads to give the yield from the 2nd year onwards.
- The yield from established plantations is 5 tonne per hactare.
- 30% oil from seeds by expelling and the seed meal is excellent organic manure.

Fig. 12.7. Jatropa Plant

The Estimated biodiesel production per hectare = 3,000 litres/700Gal and the potential yields of 12 tonnes per hectare and 55% oil extraction are also attainable. The literature surveys show that the 2500 trees per hectare produces the seed (6.9 tonnes), seedcake (4.2 tonnes), vegetable oil (2.7 tonnes), glycerol (0.27 tonnes). It has some anti erosive property like it reduces wind and water erosion of soil and leads to improved

absorption of water by soil. Mainly the seedling preparation by 10×20 cm bag and allowed to get germination by 3 days.

2.7 CONCLUSION

Finally it is concluded that the biodiesel is a renewable fuel for diesel engines that can be made virtually from any oil or fat feedstock and it can provide huge rural employment potential of 40 to 50 million families and transform the rural economy. It is used in the remote village electrification and power for agriculture application. The technology choice is a function of desired capacity, feedstock type and quality, alcohol recovery, and catalyst recovery. The dominant factor in biodiesel production is the feedstock cost which is around 70%, with capital cost contributing only about 7 % of the product cost. Therefore high FFA, lower quality feedstock should be promoted for biodiesel production in India.

3.0 CONVERSION OF GLYCEROL TO VALUABLE CHEMICALS BY ENVIRONMENTALLY FRIENDLY PROCESS

As a renewable feedstock and due to its high functionality glycerol, is an attractive reactant for the production of a large number of valuable compounds. Oxidation reactions are of industrial importance for the synthesis of fine chemicals, even though stoichiometric oxidizing agents (e.g. permanganate) or biotechnological processes are used and a large number of by-products are often formed which decrease the selectivity to the desired oxidation product. An environmentally friendly alternative is the oxidation in the presence of a heterogeneous catalyst and oxygen [3].

Heterogeneously catalyzed liquid-phase oxidation of glycerol performed under atmospheric pressure and at constant pH using carbon supported on gold as catalyst. The aim of this work is to produce highly interesting chemicals like glyceric acid from the environmentally friendly oxidation of a biosustainable source with high yields. Oxidation reaction of the glycerol can be explained in the following scheme.
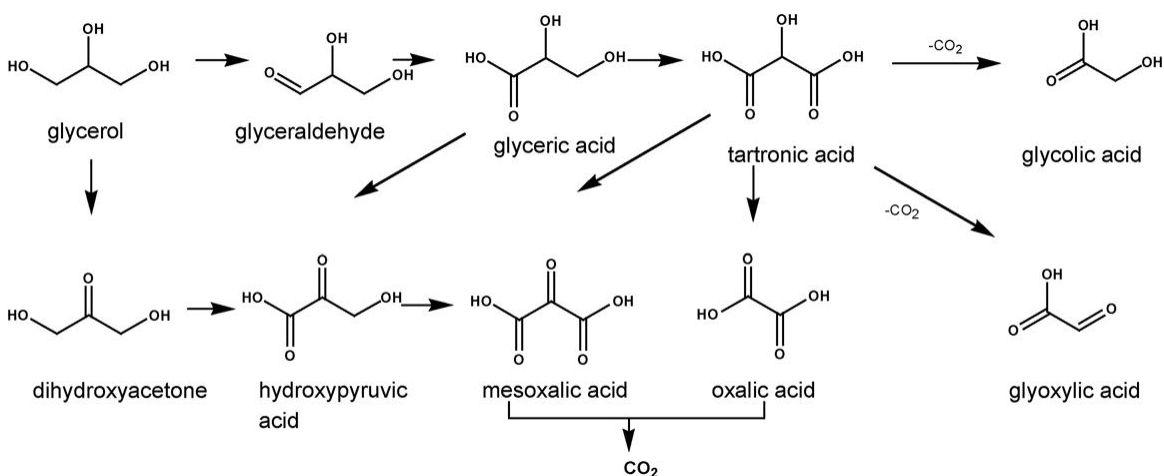
Scheme. 12.2. Reaction network of the glycerol oxidation

3.1 Monometallic and Bimetallic Gold Catalysts Preparation

Monometallic gold catalyst is prepared by gold-sol method. 86 mg of $HAuCl_4$ is dissolved in 5 ml of 1.2 M HCl by adding drop wise within 30 min with stirred carbon suspension (5 g carbon in 133 ml distilled H_2O). After 5 h impregnation time 10 ml of a 20% formaldehyde solution and subsequently 11 ml of a 40% KOH solution were added under stirring. After 30 min the catalyst was filtered, washed with distilled water and dried in air [4]. Bimetallic gold catalyst prepared by the precursor metal solution of $HAuCl_4$ and H_2PtCl_6 added to the THPC solution and then added to the stirred carbon suspension. The ICP-OES analysis shows that the gold catalysts prepared by the gold-sol method typically provide particle sizes smaller than 10 nm.

3.2 Oxidation Experiments

The glycerol oxidation is carried out under atmospheric pressure in a 300 ml semi-batch glass reactor equipped with an automated titrator providing continuous pH control during the reaction time and with a four baffle propeller. The reactions were performed with 150 ml of an aqueous glycerol solution at constant pH, at an oxygen flow rate of 300 ml min^{-1} checked by a mass flow controller, at 60^0C and a stirring rate of 500 rpm. The reactions were started by switching the gas to oxygen and subsequently increasing the stirring to 500 rpm.

3.3 Results and Conclusion

The gold catalysts prepared by the gold-sol methods show a higher activity than the catalyst prepared by the precipitation method. According to this study, the highest Au/C

catalyst activity is achieved by using (i) the gold-sol method and (ii) THPC as reducing agent. To improve the catalyst properties in the glycerol oxidation by modifying gold with a second metal (Pt). Catalysts with 1 wt.% gold and 0.5 wt.% platinum on activated carbons were prepared by the gold-sol method with THPC as reducing agent. The presence of platinum in Au/BP catalysts significantly increases the glycerol conversion rate. The increase in activity can be maximized by promoting the monometallic gold catalysts with platinum by the formation of Au/Pt alloys with a platinum mole fraction in the range from 0.2 to 0.4, which corresponds to a $Au_{0.8}Pt_{0.2}$ composition. Also the selectivity is affected by introducing a second metal in the Au/C catalysts. In fact, by promoting the gold catalyst with platinum, it was possible to increase the selectivity to dihydroxyacetone from 26% to 36% at 50% conversion.

4.0 HYDRODESULFURIZATION REACTION

The basic operation of a refinery is the conversion of crude oil into products such as LPG, gasoline (boiling point <150°C), kerosene (boiling point150-250°C), diesel oil (boiling point 250-370°C), fuel oil (>370°C), base oils for lubricants, bitumen, and feedstocks for petrochemical industries. After separation of the crude oil into different fractions by atmospheric distillation, these streams are transformed into products with a high additional value through a wide variety of catalytically promoted chemical reactions such as hydrogenation, isomerization, aromatization, alkylation, cracking and hydrotreating.

Hydrotreating refers to a variety of catalytic hydrogenation processes in which sulfur, nitrogen, oxygen and metal atoms are removed and unsaturated hydrocarbons are saturated. Characteristic for hydrotreatment operations is that there is essentially no change in molecular size distribution, this in contrast to, for instance, hydrocracking. While hydrodesulfurization (HDS) is assuming an increasingly important role in view of the tightening sulfur specifications, hydrodenitrogenation (HDN) is necessary to assure the viability of subsequent upgrading processes [5].

4.1 Importance of Sulphur Removal from Oil

Hydrodesulfurization first came into practice during World War II in the production of petroleum. Sulfur reduction in gasoline is prompted by several factors.

- Many catalysts in reformer units are sensitive to the amount of sulfur in the feed. In fact, some bimetallic reforming catalysts require the sulfur content to be limited to the vicinity of 1ppm or less.

- Air pollution control standards require removal of sometimes up to 80% or more of the sulfur that would be present in various fuel oils.

- Some of the sulfur in gas oil fed to a catalytic cracker is in the form of coke, which is then hydrogenated and released as sulfur dioxide in the combustion gases.   This is not desired as this proposes environmental harms.   The organosulfur content of the feed to the hydrocracker must be reduced to avoid poisoning of the hydrocracking catalyst.

- The reduction of sulfur reduces the amount of corrosion in the refining process, improves the odour of the product, and reduces the amount of sulfur that can poison the catalytic converter to an automobile.

One of the biggest movements in recent legislation for reduction of sulfur in gasoline products was started by a speech by Bill Clinton on May 1, 1999. He announced a new Environmental Protection Agency regulation calling for a 90% reduction of sulfur content in automobile gasoline in the United States by the year 2004. Similar efforts are underway around the world.

The hydrodesulfurization process involves catalytic treatment with hydrogen to convert the various sulfur compounds present to hydrogen sulfide. The hydrogen sulfide is then separated and converted to elemental sulfur by the Claus process. From this point, some of the hydrogen sulfide is oxidized to sulfur dioxide by air and sulfur is formed by the overall reaction:

$$2H_2S + SO_2 \longrightarrow 3S(s) + 2H_2O$$
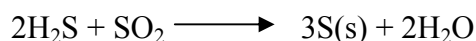
Originally the interest in hydrodesulfurization was initially stimulated to the availability of hydrogen from catalytic reformers. However the demand for hydrogen for hydrodesulfurization and hydrotreating is more than that can be generated by a refinery. Because of this, most refineries recycle the hydrogen formed from side dehydrogenation reactions back to the inlet. Since hydrogen is so expensive to manufacture, it is very

important to run all hydrodesulfurization and hydrotreating processes at their optimum to reduce costs.

The supported molybdenum sulfide catalyst containing cobalt is operated under pressures of 150-160 psi hydrogen at 300-400°C. The sulfur content in oil of 1-5% is reduced to 0.1% in gasoline and future sulfur limits may be reduced to as little as 0.003-0.04%. For low point and middle boiling point distillates, typical HDS reaction conditions are about 300 to 400°C and 0.7 to 5 MPa hydrogen pressure. The higher the boiling point of the feedstock is, the higher the sulfur content. More severe operating conditions are needed for higher fraction boiling points. Then high pressure and low temperature combinations are used to reduce the hydrogen consumption and corresponding costs.

    HDS reactions are exothermic. Most reactors are adiabatic fixed beds and may be multistage. Adding additional hydrogen between the stages usually does cooling; the term "cold-shot cooling" is used to describe this process. If the feed for the reaction conditions is a mixed vapour and liquid, the liquid is normally caused to flow counter-currently downward through a fixed bed catalyst, or "trickle-bed reactor".

 The sulfur is present largely in the form of thiols, sulfides, and various thiophenes and thiophene derivatives. Mercaptans and sulfides react to form hydrogen sulfide and hydrocarbons.

$$RSSR' + H_2 \longrightarrow RH + R'H + H_2S$$

$$RSH + H_2 \longrightarrow RH + H_2S$$

$$RSR' + 2H_2 \longrightarrow RH + R'H + H_2S$$
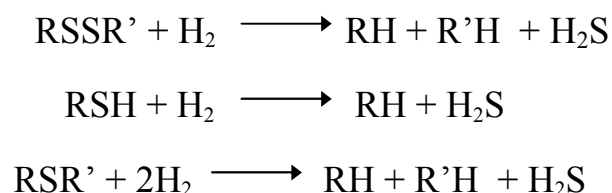
R and R' are various hydrocarbon groups.

$$\text{thiophene} + 2H_2 \longrightarrow H_2S + C_4H_8 \text{ (mixed omers)}$$

Scheme. 12.3. Reaction pathway of thiophene

Studies have indicated that the hydrodesulfurization and subsequent hydrogenation reactions occur on separate sites. The thiophene ring is not hydrogenated before sulfur is removed, although the first step may involve an essentially simultaneous removal of a sulfur atom and donation of two hydrogen atoms to the molecule.

For benzothiophene, substituted or unsubstituted, the thoiphene ring is hydrogenated to the thiophane derivative before the sulfur atom is removed, in contrast to the behavior of thiophene. The reaction pathways for dibenzothiophene are as follows:
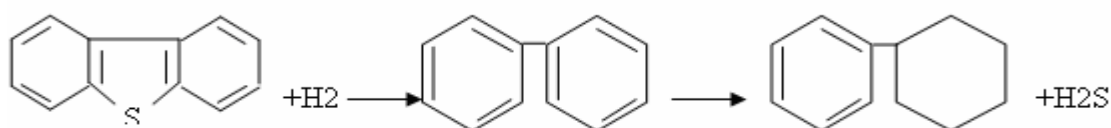
Scheme. 4. Reaction pathway of dibenzothiophene

4.2 Preparation of Catalyst

Catalysts used in industry are derived from oxides of such element like Mo, W, Co, Ni supported on different compounds, although the most commonly used is alumina. The catalyst used in HDS is almost always $CoMo/Al_2O_3$, and sometimes $NiMo/Al_2O_3$. The ratio of molybdenum to cobalt is always considerably greater than 1.

The molybdenum sulfide catalyst is prepared by impregnation of γ-Al_2O_3 with an aqueous solution of ammonium molybdate and cobalt nitrate or nickel nitrate. This precursor is dried and calcined, which converts the molybdenum to MoO_3. This is then treated with a mixture of H_2S and H_2 or a feed containing sulfur compounds and H_2. The resulting molybdenum catalyst is almost completely sulfided. If the catalyst is not completely sulfided, then there is the possibility, that it will not be acting as a active catalyst.

4.3 Conclusion

Since the mechanism for the hydrodesulfurization of thiophenes is not completely understood, there has been extensive work to try and develop the mechanism and kinetics for the reactions in order to develop better catalysts. Nickel treated compounds have had

some success, and while the nickel containing catalysts appear to be better at sulfur removal, the Co-containing catalysts give slightly more oil yield. In the end, it may be a simple matter of economics that determines which catalyst is used.

5.0 CATALYTIC AND NONCATALYTIC STUDY OF OXIDATIVE DEHYDROGENATION REACTION

Ethene is one of the most basic feedstocks in chemical industry and its demand is steadily increasing. The main commercial routes for production of ethene are steam thermal cracking and FCC (fluid catalytic cracking) processes. The drawback of these methods is high energy input required by the highly endothermic reactions, high operation costs due to coke deposition on catalyst and reactor, and generation of low molecular weight alkanes. The reserves of raw materials for these processes are becoming increasingly limited. Consequently, alternative processes with higher efficiency, which utilizes more abundant and economic sources for ethene production, are becoming increasingly necessary. Ethane is the second major component of natural gas and is also abundant in refinery gas.

5.1 Oxidative Dehydrogenation (ODH)

Production of ethene via oxidative dehydrogenation (ODH) of ethane [6] has received increasing attention, owing to its potential advantages, such as exothermic reaction heat and less coke deposition. This method can be carried out at relatively low temperatures in the presence of properly selected catalysts. Until now, numerous catalysts were employed for the ODH of ethane, such as composite oxides between alkaline earths and rare earths, halogen (particularly F and Cl) and/or alkali ion-promoted, as well as some transition metal (Mo, V, Bi, etc.) oxide-based catalysts.

As an alternative to the heterogeneous route, a hetero-homogeneous process for the ODH of ethane at temperatures higher than $900^{\circ}C$, the so-called auto-thermal oxidative dehydrogenation, was also employed. The following reaction carried out by vanadium magnesium catalyst and without catalyst.

5.2 Catalyst Preparation

Meso-VMg catalysts were prepared by using vanadium source like V_2O_5 and the magnesium source like magnesium chloride ($MgCl_2 \cdot 6H_2O$). Surfactants such as cetyltrimethylammonium bromide (CTAB), sodium dodecylbenzene sulfonate (SDBS),

benzyltrimethylammonium bromide (BTAB), and the template is hexadecylamine (HDA) were used for the synthesis of the mesoporous materials.

$MgCl_2·6H_2O$ and the template were dissolved into an aqueous solution of hydrochloric acid. The vanadium source was dispersed homogeneously into distilled water with vigorous stirring. Then the solution containing vanadium was added slowly into that containing magnesium, with vigorous stirring at room temperature. The pH of the mixture was adjusted to 4.0 or 10.0. After stirring at room temperature for 24 h, the mixture was allowed to age statically at room temperature for 2 days. The solid formed was recovered by filtration, washed with distilled water, and dried at $100°C$ for 12 h. To remove the surfactant, the prepared specimens were heated in a flow of argon from room temperature up to $750°C$ at a rate of $10°Cmin^{-1}$ and kept at that temperature for 4 h. Meso-V was prepared using the same procedure, except that no magnesium was introduced and the pH of the mixture was adjusted to 7.0.

The Mix-VMg catalysts were prepared via a solid-state reaction. Powders of vanadium and magnesium source were mixed together and ground thoroughly in a mortar, and the mixture obtained was calcined at $750°C$ for 2 h after it was heated from room temperature at a rate of $4 °Cmin^{-1}$.

5.3 Reaction Set Up

The catalytic performance was determined at atmospheric pressure in a tubular fixed-bed quartz microreactor (internal diameter = 5 mm, operation length = 30 cm). The reactor was packed as the middle of the reactor was plugged with quartz wool and a catalyst (about 0.25 g) was located over it. The space of the reactor above the catalyst bed was filled with quartz granules. The reactor was placed into a tubular furnace with the catalyst bed located in the constant temperature zone.

In addition, four other reactor configurations free of catalyst were employed in the study of the noncatalytic conversion of ethane, namely, ET (the empty tube), FQ (the reactor filled with quartz granules up to a height of 1 cm), HFQ (the upper half of the reactor was filled with quartz granules and the rest of the reactor was empty), and FFQ (the entire reactor was filled with quartz granules). Two thermocouples were employed to monitor and control the temperature. One of them was embedded in the furnace, and the other one was located in the center of the catalyst bed and tightly contacted the external

surface of the quartz reactor. The temperatures measured by these two thermocouples were almost the same. The compositions of reactant mixtures (N_2, O_2, and C_2H_6) and gaseous effluents from reactor were determined by on-line gas chromatography with FID and TCD detector

5.4 Results

The results are shown in Fig 12.8.   At low temperatures, the differences between the yields of ethene for the noncatalytic and catalytic thermolysis and ODH of ethane are small when the conversions of ethane are low. The highest yield of ethene for the noncatalytic ODH occurs for a conversion of about 7%; however, the yield to ethene for the catalytic ODH can be higher, being larger for the Meso-VMg catalysts than the Mix-VMg ones and the highest for the Meso-VMg-3 catalyst.
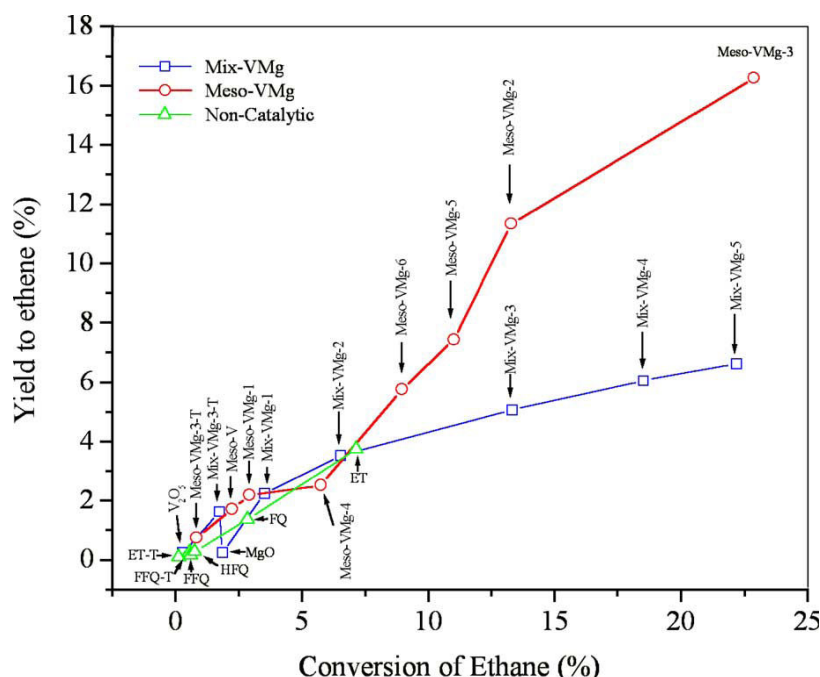

Fig. 8(a). Yield of ethene as a function of conversion of ethane for noncatalytic and catalytic thermolysis and ODH of ethane at 550 $^{\circ}$C (The thermolysis cases are marked by -T.) [6]
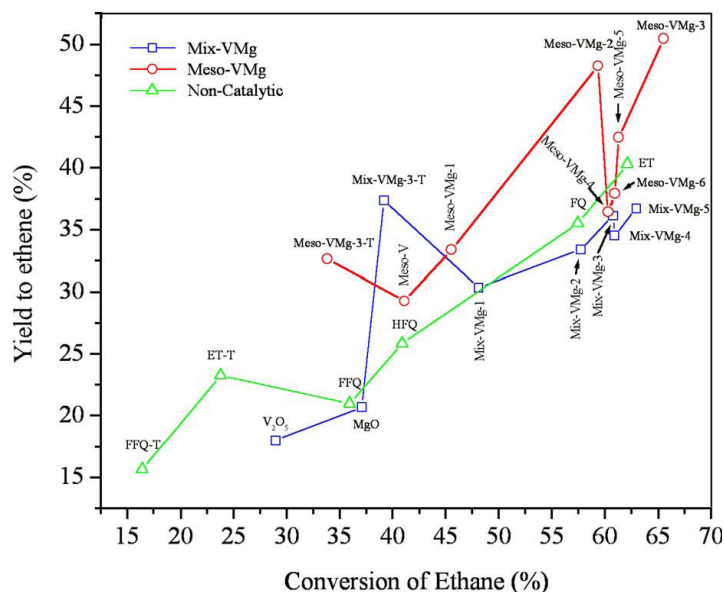
Fig. 8 (b) Yield of ethene as a function of conversion of ethane for noncatalytic and catalytic thermolysis and ODH of ethane at 700°C. (The thermolysis cases are marked by -T.) [6]

The higher performance of the meso-VMg for ODH of ethane than the Mix-VMg ones may be due to the V_2O_3 phase containing highly dispersed magnesium species and possessing large specific surface area in the former case. The Mg species probably moderate the redox capability of V_2O_3, thus controlling the activations of ethane and oxygen. The activation mechanism of ethane over these catalysts is dependent on temperature and the heterogeneous processes occur at low temperatures, whereas heterogeneous–homogeneous ones account for the behavior of the catalysts at high temperatures.

6.0 PREPARATION OF POLYORGANOSILOXANES BY SUPERCRITICAL FLUID METHOD

Polyorganosiloxanes or silicones are the most popular silicon-based polymeric materials in which the backbone is composed of repeating Si–O linkages. It has good thermal stability, low-temperature stability, weather ability, transparency, and electric insulation. The materials are used in almost all industries including automobile, construction, electronics, personal and household care, and chemical industries. Silicones manufactured by sequential hydrolysis and polycondensation reactions of chlorosilanes with or without using organic solvents.

The hydrolysis and polycondensation processes in an organic solvent are conducted in the presence of an acid catalyst because the hydrolysis rate of alkoxysilanes is smaller than that of chlorosilanes. The neutralization process is also necessary to obtain final products even though alkoxysilanes were used as the substrates. In addition, a large amount of organic solvent waste is generated in both cases. According to these facts, the current silicone manufacturing processes cannot be regarded as an environmentally benign process. Typical examples for syntheses of poly(phenylsilsesquioxane) starting from phenyltrialkoxysilanes and from phenyltrichlorosilane, both of which are performed in a significant amount of an organic solvent for more than 10 h, have been reported

6.1 Supercritical Fluid Method

This technology has attracted significant interest for the last two decades from an environmental viewpoint. The most attractive aspect of this technology is to reduce or eliminate the use of organic solvents in process. Supercritical carbon dioxide ($scCO_2$) or supercritical water (scH_2O), is used as a solvent. Many industrial applications are under development of several which have been globally been commercialized basically due to reduction of hazardous material waste. Several SCF-based technologies have been proposed to synthesize silicones and other Si-containing materials without using organic solvents like Polysiloxane synthesis by a catalytic polymerization of siloxane cyclics and silanol-terminated siloxane oligomers, a hydrosilylation process yielding functional polysiloxanes, and silica aerogel production by sc-CO_2 drying were reported as $scCO_2$-assisted technologies. On the other hand, scH_2O-assisted technologies include i) recycling of waste silicone elastomers via treatment with $MeOH/H_2O$ mixture at high temperature, ii) silicone particle formation by degradation of electrophotographic developer carriers, iii) silicon nanotubes formation, and iv) silicon oxide nanowires formation. These technologies are not tailor-made silicone synthetic processes. The following method is the first example of a catalyst-free silicone synthesis via sequential hydrolysis and polycondensation reactions of alkoxysilanes [7]. Organic solvent-soluble non-linear silicones such as silsesquioxanes were selected as target materials due to their high potential for development of value-added products.
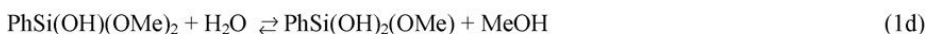
6.2 Equipment

This method need the following equipments

- A reactor and narrow tubing for the high T&P process were made of ½"and 1/8" stainless steel tubing.

- The internal volumes of the reactor are 10 and the tubing were 2 mL.

- A pressure gauge was a KH15 pressure transmitter and a sand bath was used as a heat source in which sand is circulated by a compressor to maintain the temperature deviation within $\pm 3°C$.

- Products are analyzed by GC-MS

6.3 Synthesis of Poly(phenylsilsesquioxane) (PPSQ)

PTMS and deionized water were loaded in a one-end capped reactor and sealed with a connector attached to narrow tubing (stainless steel coil with the diameter of 1/8"; length: 90 cm; internal volume: 2 mL) as a trap and a pressure gauge. The reactor was placed in a preheated sand bath at $300°C$ to start the reaction. During heating, pressure inside the reactor was monitored periodically. After the pressure value became constant, the reactor was pulled out of the sand bath and poured into a water bath to terminate the reaction. After the work-up similar to that for the trap-free system, a solid product was obtained.

$$PTMS + H_2O \rightleftarrows PhSi(OH)(OMe)_2 + MeOH \tag{1a}$$

$$PhSi(OH)(OMe)_2 + PTMS \rightleftarrows PhSi(OMe)_2\text{-O-SiPh}(OMe)_2 + MeOH \tag{1b}$$

$$PhSi(OH)(OMe)_2 + PhSi(OMe)_2\text{-O-SiPh}(OMe)_2 \rightleftarrows PhSi(OMe)_2\text{-O-SiPh}(OMe)\text{-OSiPh}(OMe)_2 + MeOH \tag{1c}$$

$$PhSi(OH)(OMe)_2 + H_2O \rightleftarrows PhSi(OH)_2(OMe) + MeOH \tag{1d}$$

$$PhSi(OMe)_2\text{-O-SiPh}(OMe)_2 + H_2O \rightleftarrows PhSi(OMe)_2\text{-O-SiPh}(OH)(OMe) + MeOH \tag{1e}$$

Scheme. 12.5. Reactions yielding phenylsilsesquioxane by hydrolysis and condensation of PTMS

This process shows that the organic solvents are not needed to increase the diffusability of substrates in the high T and P water-assisted process indicating that an organic solvent-free process be essentially possible. In addition, a catalyst-free process can be expected if the ion product of high T&P water such as subcritical water is high enough for hydrolysis

of alkoxysilanes. In this study, alkoxysilanes were used as substrates since chlorosilanes are not appropriate due to evolving corrosive gas of HCl.

Synthesis of PPSQ via hydrolysis and subsequent polycondensation reactions of PTMS was selected as the first process because hydrolysis of phenyl-based alkoxysilanes at high temperatures proved to be more controllable than that of methyl-based alkoxysilanes. The overall reaction intended is as follows:

$$C_6H_5Si(OCH_3)_3 + 3/2H_2O \longrightarrow C_6H_5SiO_{3/2} + 3CH_3OH$$

The initial study was made by a batch process using a stainless tube reactor with the diameter of ½" and the volume of 10 ml. The reactor containing PTMS and excess amount of water was heated at $300^{\circ}C$. During this reaction methanol formed above $200^{\circ}C$ as a byproduct.
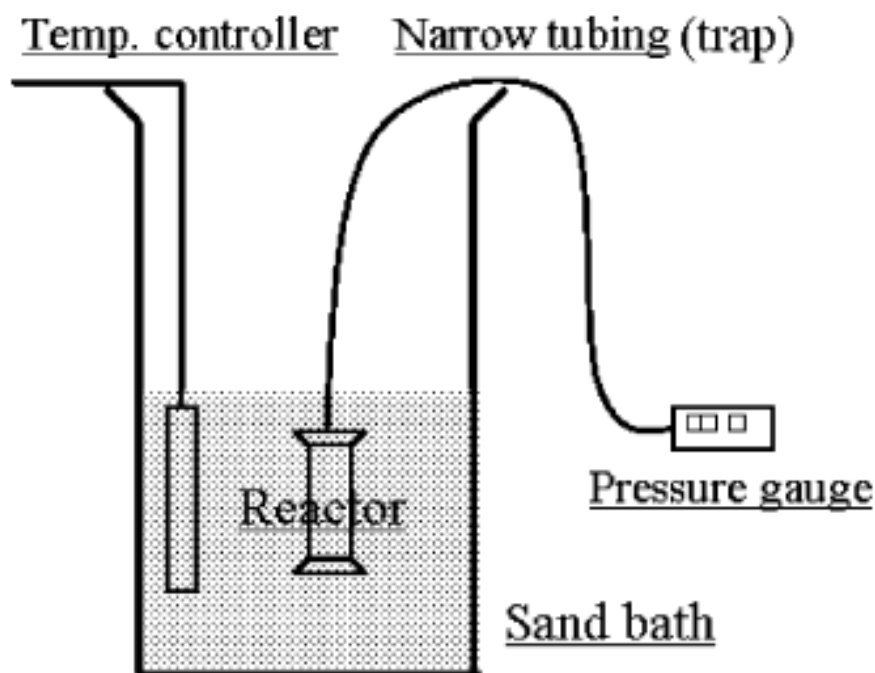
Fig. 12.9. Reaction equipment for a trap-attached system in which the narrow tubing between the reactor and the pressure gauge acts as the trap. The sizes of the reactor and the trap are 10 and 2 ml, respectively [7]

As the amount of substrates increases, the molecular weight of PPSQ increases to the top value and then decreases indicating that the reaction is strongly depending on the pressure. This is because the reaction is an equilibrium reaction in which three molar methanol as a byproduct generates from one molar phenyltrimethoxysilane. The pressure range at which the PPSQ's molecular weight becomes the maximum is between

approximately 3 and 7. It is notable that the molecular weight of PPSQ increased by introducing narrow tubing as a trap in the reaction system. This is because trapping of methanol shifts the equilibration to the product-side. The process yields polyorganosiloxanes with relatively high content of Si–OH and Si–OMe groups. Synthesis of polysiloxanes with other structural units by using various alkoxysilanes is also prepared by the same method. It can explain in the following manner.

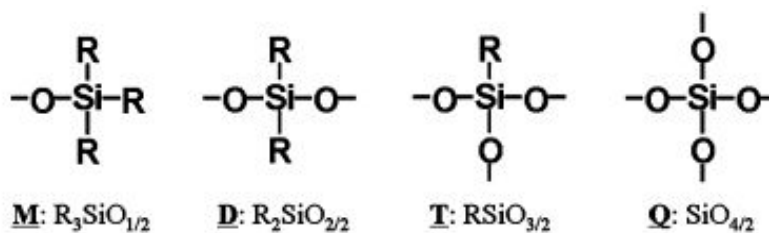## 6.4 STRUCTURAL UNITS OF POLYORGANOSILOXANES

Fig. 12.10. Structural units of polyorganosiloxanes. R: methyl, phenyl, vinyl, H, and other reactive groups such as aminopropyl and glycidoxypropyl.

Q unit: SiO$_{4/2}$

Tetramethoxysilane (TMOS) yielded an insoluble solid product based on Q units with significant amount of OH/OR groups. This can be as a part of the alkoxysilanes was trapped into the tubing by evaporation as water is and then undergoes hydrolysis to yield insoluble solid in the tubing.

T unit: MeSiO$_{3/2}$

Methyltrimethoxysilane (MTMS) was used as a T source. This reaction carried out by without trap because of the high volatility of this compound and it leads to the formation of highly reactive hydrolysate with high content of silanol/methoxy that turned into an insoluble material.

D unit: Me$_2$SiO$_{2/2}$

Polycondensation between a silanol-terminated oligodimethylsiloxane as a D source and other alkoxysilanes such as PTMS, MTMS, and methylphenyldimethoxysilane (MPDMS) proved to be possible. This reaction shows that this oligomer is stable at 300°C in the presence of excess water without both of dehydrative self-condensation as shown in the following Scheme and siloxane bond cleavage. These results indicate that the polycondensation observed here proceeds by a de-methanol reaction.
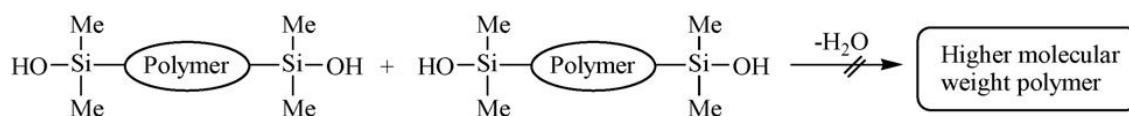
Scheme. 12.6. Dehydrative condensation of silanol-terminated polydimethylsiloxanes

6.5 CONCLUSION

It can be concluded that polysiloxanes composed of any D, T, and Q units are easily synthesized. The volatility of the substrates is a critical factor to select the reaction system with narrow tubing as a methanol trap. Since siloxane bond cleavage hardly takes place, the present system is advantageous for the material design by which the structure of siloxane-containing staring material remains in the polysiloxane product. The largest advantage of this new process is no contamination of volatile organic compounds in the product because the product is obtained as a solvent-free form. In addition, as the present synthetic method is simplified due to skip of the neutralization process being necessary for a conventional solution-based process, this is also advantageous from the economical standpoint.

7.0 REFERENCES

1. http://biofuels.coop/pdfs/4_commercial.pdf

2. Ayhan Demirbas, Energy Conversion and Management, 44 (2003) 2093.

3. S. Demirel, K. Lehnert, M. Lucas, P. Claus, Appl. Catal. B: Environmental 70 (2007) 637.

4. R. Garcia, M. Besson, P. Gallezot, Appl. Catal. A: Gen. 127 (1995) 165.

5. http://www.che.lsu.edu/COURSES/4205/2000/Mattson/HDS.htm

6. Zi-Sheng Chao and Eli Ruckenstein, Journal of Catalysis 222 (2004) 17.

7. Takuya Ogawa, Jun Watanabe, Yoshito Oshima, Journal of Supercritical Fluids 45 (2008) 80.

Chapter - 13
SYNTHETIC STRATEGIES - FROM LABORATORY TO INDUSTRY

S. Chandravathanam

INTRODUCTION

Scale-up is an act of transferring a laboratory process to the larger equipment typical of a commercial plant, or designing a piece of commercial equipment based on research-scale models. This is often a complex matter in which, for some processes, trail and error still has a significant foothold. Even with careful planning and strict methodology, scale-up can be fraught with difficulty and unexpected problems. The reasons for this are numerous; many common laboratory methods cannot be applied at the large scale, equipment may exhibit unexpected behaviour at sizes never used before, or critical heat or mass transfer phenomena may not be discernible at laboratory scale.

The design of a new plant or commercialization of a new chemical process represents a tremendous investment of time and money. The risk is considerable and the economic penalty, if the plant or process fails to produce as expected is severe. To minimize such risks, industries undertake lengthy and expensive process research and development programs.

An invention might sometimes lay unused for ages without paying back in terms of industrial realization and of profitable business for its lack of technical know-how. For example, the pigment indigo was extracted from the sea animals during the 13th century. One gram of the pigment could be obtained from almost 10,000 numbers of the animal. So that it was the very expensive dye material, and the colour was restricted to the Royal family only, and so named as the Royal purple. It was the situation till Bayer in the 19th century studied the dye material, and started synthesizing it from the easily available raw materials.

This text deals with the technical knowledge and on the tools that are necessary to change an invention into a true innovation. The term scale-up has usually been explained as how to design an industrial reactor able to replicate the results obtained in the laboratory. These are done with most of the time innovative ideas, and sometimes with

many mistakes.The scale-up usually means that the scaling facor of 1000 times from the laboratory process to the pilot plant scale, and further 1000 times from the pilot to the industrial scale. Typical laboratory scale preparation lies with in the production of 100 g/day. A pilot plant will typically produce 1-50 Kg/day, and the industrial plant will be aimed with the production of tons/day.

Few of the indispensable steps which are undertaken while going from the laboratory scale to the commercial or industrial scale are, cost estimation, process design, pilot plant studies may or may not be accompanying with the dimensional analysis.

COST ESTIMATION

The cost estimation for the scale-up of production is a very crucial step. For this process, chemical engineers long been relying as a rule a thumb on the use of power law. As per the law the investment is proportional to the scale of a production facility raised to some constant power, characteristic of the particular process.

The so called power law of investment takes the form,

$I_2/I_1 = k \ (V_{t,2}/V_{t,1})^{1/n}$

Where I is investment, V_t is production rate and k and n are constants.

The power law is based on the 'minimization law', which states that people minimize their efforts per unit of dimension whenever a change of scale or volume is required. The constant n is the number of dimensions of the production rate-limiting activity, typically is either one, two or three corresponding to the linear, area and volumetric dimensions.

PROCESS DESIGN

Process Design is the heart of the process of scale-up. When the research department discovers a new reaction to make an existing product or a new material, the process department will have to translate these discoveries into a new process which could be commercially and technically feasible.

The few of the factors of importance during this process design stage are,

- Production rate
- Temperature and pressure conditions of the reaction
- Every available information about operating variables, thermodynamics and kinetics of the chemical reaction
- Stoichiometry of the main reaction

- Desired yield of the product

- Desired product purity and the possibility of the feed recycling

The importance of the process design step can be explained with one of the case studies with the process design for the manufacture of Grignard Reagent. Grignard reagent is one of the important reagents in organic synthesis for the introduction of alkyl groups on carbonyl carbon atoms. It's requirement is vast but its manufacturing in large scale was not undertaken for a long time for some reasons like the high exothermicity of the reaction, the high inflammability of the solvent diethyl ether, and the high sensitivity of the reagent for water, which needs to be used for cooling purpose.
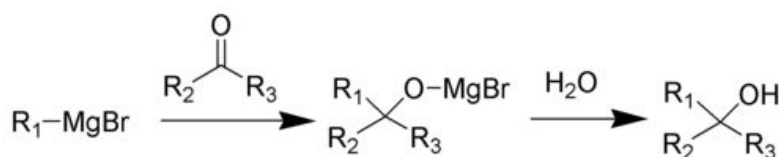
Grignard reagent is prepared in situ when alkyl halide reacts with Mg metal scraps in diethyl ether.

Through careful process design studies, these drawbacks had been overcome; with the use of alkyl chlorides or bromides instead of iodides, the exothermicity of the reaction can be reduced as a result of the reduction in the reaction rate of chlorides and bromides compared to their iodide counterpart. Along with that, it could also reduce the cost as the chloride is cheaper than the iodide. The risky diethyl ether was replaced with tetrahydrofuran (THF), which has atleast 30 °C higher boiling point than the former. Inert gases which can play both as the cooling system and blanket replaced water, as the product Grignard reagent is more sensitive to water, if there is any leakage.

PILOT PLANT

A pilot plant is generally a collection of equipment designed to allow operation of a novel process at a scale small enough to be safely manageable but large enough to provide a realistic demonstration of operations and physical principles as they might apply in a commercial facility and to allow the collection of meaningful engineering data for a further scale-up.

Pilot plants provide important information on the best ways to handle reactants, intermediates, products and waste streams, on energy transfer, on the best choice of

separation technologies and an operating procedures. Some of the many areas of process development in which a pilot plant can play an important role are,

- Confirming the operational feasibility of a new process

- Identifying scale-up effects on yield and selectivity

- Collecting kinetics and design data

- Testing materials of construction

- Testing the operability of control schemes

- Assessing process hazards and safety issues

- Commercial viability of the raw material

- Process troubleshooting and optimization

- Testing process recycle streams

Pilot plants can be classified according to numerous criteria. Foremost is the fundamental distinction between a pilot plant for a continuous process versus one for a batch or semibatch process. In the continuous process, pilot plants tend to be single-purpose, product dedicated facilities that are generally smaller. Batch pilot plants, typical of the fine chemical industry, tend to be multipurpose. The requisite flexibility to handle a wide variety of products and processes can add considerably to the complexity and cost of a plant.

DIMENSIONAL ANALYSIS

Dimensional analysis is a process by which the dimensions of equations and physical phenomena are examined to give new insight into their solutions. It is a powerful technique for spotting errors in equations. It shows how physical dimensions of the variables that govern a problem can be used to find physical laws. The main requirement for dimensional analysis is dimensional homogeneity – it states that all parts of an equation must have the same dimension. In other words, we can add or compare quantities that have similar dimensions only.

Dimensional analysis results in many advantages like

- the reduction of number of variables in a variable set; if there are 'n' variables or parameters of concern, then the total number of dimensionless numbers is reduced to n - r, where 'r' is the number of basic dimensions of all the parameters of concern (Buckingham pi theorem).

- Gives the guidelines for scaling the results from model test to the full-scale. Otherwise dimensional analysis sets the rule under which full similarity in model test can be achieved.

- Nondimensional parameters are more convenient than dimensional parameters since they are independent of the system of units.

In the following passage two case studies of application of dimensional analysis are given.

CASE STUDY 1: Correlation between Meat Size and Roasting Time

What is the roasting time for two times the mass of the meat?

The main parameters of concern for this problem are listed below along with their dimensions.

Physical quantity	Symbol	dimension
roasting time	θ	T
meat surface	A	L^2
thermal diffusivity	a	$L^2 T^{-1}$
surface temperature	T_0	Θ
temperature distribution	T	Θ

The higher the heat conductivity k, of the meat, the faster is the cooking.

The higher the heat capacity ρC_p, the slower is the heat transfer.

$\therefore$ Thermal diffusivity $a = k/\rho C_p$

The total number of dimensionless numbers are 5-3 = 2.

$\Pi_1 = T/T_0$ **or** $(T_0-T)/T_0)$

$\Pi_2 = a\theta/A \equiv F_0$

When the temperature distribution T/T_0 is achieved throughout the meat then it can be said that the meat is cooked.

$T/T_0 = f(F_0)$

$T/T_0 = idem \longrightarrow F_0 \equiv a\theta/A = idem \longrightarrow \theta \propto A$ idem = identical

This equation relates the roasting time with the area of the meat. But in reality the roasting time needs to be calculated with respected to the mass of the meat. mass is related to area with the following equation.

$$m = \rho V \propto \rho L^3 \propto \rho A^{3/2}$$

the density ρ remains the same irrespective of the meat size. Therefore,

$$\rho = idem$$

and

$$A \propto m^{2/3}$$

$$\theta_2/\theta_1 \propto (m_2/m_1)^{2/3}$$

That is,

$$\theta \propto m^{2/3} = m^{0.67}$$

$\therefore$ doubling the mass of meat, the roasting time increases by, $2^{2/3} = 1.58$ times. The final equation contains only two parameters, instead of the initial five parameters, therefore, the number of supplementary experimental runs is getting drastically reduced.

CASE STUDY 2: Homogeneous Irreversible 1st Order Reaction in a Tubular Reactor

How much is the volume and residence time of the reactor to be increased for the increase of volume throughput by a factor of n ($q_T = nq_M$)?

The important parameters of concern are, v - flow rate, d, L – diameter and length of the tubular reactor, ρ,μ - fluid density and viscosity respectively. T_0 – inlet temp.

c_{in}, c_{out} – inlet and outlet conc. $k_{eff.}$ – effective reaction rate constant

$$k_{eff.} = k_0 \exp(E/RT)$$

The parameters of mass and heat transfer are, D - Diffusion coefficient, Cp – heat capacity, k - thermal conductivity, $c_{in} \Delta H_R$ - heat of reaction per unit time and volume, T_0 - inlet temp., ΔT - temp. difference between fluid and tube wall.

The complete relevant list of parameters is,

$$\left\{ v, d, L, \rho, \mu, c_{out}, c_{in}, k_0, E/R, D, Cp, k, c_{in}\Delta H_R, T_0, \Delta T \right\}$$

From the pi theorem, the number of nondimensional parameters should be, 15 - 6 = 9.

The obvious five nondimensional numbers are,

L/d, C_{out}/C_{in}, E/RT_0 and $\Delta T/T_0$

The remaining four nondimensional numbers are derived using the following combination of the parameters.

$\Pi_1 = v/Lk_0 \quad = (k_0 \tau)^{-1}$ (mean residence time $\tau \equiv L/v$ at pipe flow)

$\Pi_2 = \mu/\rho d^2 k_0 \quad = (k_0 \tau \text{ Re } L/d)^{-1}$

$\Pi_3 = D/L^2 k_0 \quad = (k_0 \tau \text{ Re Sc } L/d)^{-1}$

$\Pi_4 = (\rho C_p T_0) / c_{in} \Delta H_R \quad = D_a^{-1}$ (Da = Damkohler number)

$\Pi_5 = (kT_0) / c_{in} \Delta H_R d^2 k_0 = (k_0 \tau \text{ Re Pr Da } L/d)^{-1}$

$\therefore$ The nine dimensionless numbers are,

$\left\{ L/d, C_{out}/C_{in}, E/RT_0, \Delta T/T_0, \kappa_0 \tau, \text{ Re, Sc, Pr, Da} \right\}$

During scale up

- No change of reaction temp. $\therefore$ **T_0 and k_0 are constant**
- No change in the physical and chemical partners of the reaction $\therefore$ the kinetic and material numbers, remain unchanged.
- **L/d = identical**
- To attain specified degree of conversion, **c_{out}/c_{in} = identical**

Therefore, the following two are the only two parameters need to be adjusted.

$\text{Re} = (v d \rho) /\mu$ and $k_0 \tau \equiv (k_0 L)/v$

But it is impossible to have both,

$v d \longrightarrow v L = \text{idem}$ and $L/v = \text{idem}$ and $L/d = \text{idem}$

For the given condition of $q_T = nq_{M,}$, $d_T = nd_{M,}$

$q \propto vd^2$ and $v_T d_T^2 = n \ v_M d_M^2$

as, $Re \alpha \, v \, d = idem$

$$V_T = (V_M)/n$$

$$V_T = n^3 \, V_M \text{ and hence } \tau_T = n^2 \, \tau_M \quad (\tau = V/q)$$

Where,

M - model scale

T - technological or industrial scale

q – volume throughput

n – factor

V – volume of the reactor

The results state that for the increase of volume throughput n times the volume of the reactor needs to be increased by n^3 times and the residence time needs to be increased by n^2 times.

REFERENCES

1. Kirk-Othmer, Concise Encyclopedia of Chemical Technology, Fifth Edition, Vol. 2, John-Wiley & Sons, 2007.

2. John J. Mcketta (Ed.,), Encyclopedia of Chemical Processing and Design, Vol. 49, 1994.

3. Marko Zlokarnik, Scale-up in Chemical Engineering, , Wiley-VCH, 2002.

4. Keld Johansen, 'Aspects of scale-up of catalyst production', Studies in Surface Science and Catalysis, 143 (2002) 1.

5. Gianni Donati, Renato Paludetto, Catalysis Today, 34 (1997) 483.

Chapter - 14

SYNTHESIS OF CHEMICALS FROM CARBON DIOXIDE

T. M. Sankaranarayanan

INTRODUCTION

Carbon dioxide is an atmospheric gas contains one carbon and two oxygen atoms. It is well known chemical compound and its chemical formula CO_2. *Dry ice* is nothing but solid-state carbon dioxide. It was one of the first gases to be described as a substance distinct from air.

In the 17th century, the Flemish chemist Jan Baptist van Helmont observed that when he burnt charcoal in a closed vessel, the mass of the resulting ash was much less than that of the original charcoal. His interpretation was that the rest of the charcoal had been transmuted into an invisible substance he termed a "gas" or "wild spirit" (*spiritus sylvestre*). The Scottish physician Joseph Black studied some of the properties more thoroughly in the 1750's. He found that limestone (calcium carbonate) could be heated or treated with acids to yield a gas as he termed "fixed air." He observed that the fixed air was denser than air and did not support either flame or animal life. He also found that it would, when bubbled through an aqueous solution of lime (calcium hydroxide), precipitate calcium carbonate, and used this phenomenon to demonstrate that carbon dioxide is produced by animal respiration and microbial fermentation. In 1772, Joseph Priestley used carbon dioxide produced from the action of sulfuric acid on limestone to prepare soda water, the first known instance of an artificially carbonated beverage. CO_2 was first liquefied (at elevated pressures) in 1823 by Humphrey Davy and Michael Faraday. The earliest description of solid carbon dioxide was given by Charles Thilorier, who in 1834 opened a pressurized container of liquid carbon dioxide, only to find that the cooling produced by the rapid evaporation of the liquid yielded a "snow" of solid CO_2.

Most of the combustion of organic matter, volcanic out gassing and respiration processes of living aerobic organisms are the main sources of the carbon dioxide. Various microorganisms from fermentation and cellular respiration also produce it. During the photosynthesis plants take in the carbon dioxide and using both the carbon and oxygen to form carbohydrates. In addition, plants also release oxygen to the atmosphere, which is subsequently used for respiration by heterotrophic organisms, forming a cycle. It is

present in the earth's atmosphere at a low concentration and acts as a greenhouse gas. It is a major component of the cycle.

Green house effect is nothing but an increase in the absorption of radiation energy from sun caused by the existence of gases in the earth atmosphere. Because of this absorption the earth atmospheric temperature is raising which is called "global warming". Some of the gases like CO_2, CH_4, O_3, CFCs and H_2O vapors are called "green house gases". Mainly these gases are responsible for this absorption. CO_2 being an important member of these gases is responsible for many climatic changes demonstrating the importance of CO_2 content in atmosphere. Because of mounting of Industrial Revolution, the Percentage of carbon dioxide in the earth atmosphere is increasing virtually at the rate of 1% per annum; from 250ppm of the pre-industrial period to a present level of 400ppm (315ppm in 1958, 340ppm in1984). Because of this global warming the snow cover in the northern hemisphere and floating ice in the artic ocean have decreased considerably. Moreover, globally sea water level increased up to 8 inches in the last decade. There is an increase in worldwide precipitation by one percent. There is abnormal rainfall through out the world. Unfortunately, greenhouse gases are likely to increase the rate of climate changes.

CARBON DIOXIDE - CHEMICAL AND PHYSICAL PROPERTIES

1) Carbon dioxide is a colorless gas.

2) When inhaled at high concentrations (a dangerous activity because of the associated asphyxiation risk), it produces a sour taste in the mouth and a stinging sensation in the nose and throat.

3) These kind of effects result from the gas dissolving in the mucous membranes and saliva, forming a weak solution of carbonic acid.

4) Its density at 25 °C is 1.98 kg m^{-3}, about 1.5 times that of air.

5) It has no electrical dipole. As it is fully oxidized, it is not very reactive and, in particular, not flammable.

6) At temperatures below −78 °C, carbon dioxide condenses into a white solid called dry ice. Liquid carbon dioxide forms only at pressures above 5.1 atm; at atmospheric pressure, it passes directly between the gaseous and solid phases in a process called sublimation.

7) Water will absorb its own volume of carbon dioxide, and more than this under pressure. About 1% of the dissolved carbon dioxide turns into carbonic acid. The carbonic acid in turn dissociates partly to form bicarbonate and carbonate ions.

Test for Carbon dioxide

When a lighted splint is inserted into a test tube containing carbon dioxide, the flame is immediately extinguished, as carbon dioxide does not support combustion. (Certain fire extinguishers contain carbon dioxide to extinguish the flame). To further confirm that the gas is carbon dioxide, the gas may be bubbled into calcium hydroxide solution. The calcium hydroxide turns milky because of the formation of calcium carbonate.

Applications

1) Liquid and solid carbon dioxide are important refrigerants, especially in the food industry, where they are employed during the transportation and storage of ice cream and other frozen foods. Solid carbon dioxide is called "dry ice" and is used for small shipments where refrigeration equipment is not practical.

2) Carbon dioxide is used to produce carbonated soft drinks and soda water. Traditionally, the carbonation in beer and sparkling wine come about through natural fermentation, but some manufacturers carbonate these beverages artificially.

3) The leavening agents used in baking produce carbon dioxide to cause dough to rise. Baker's yeast produces carbon dioxide by fermentation within the dough, while chemical leaveners such as baking powder and baking soda release carbon dioxide when heated or exposed to acids.

4) Carbon dioxide is often used as an inexpensive, nonflammable pressurized gas. Life jackets often contain canisters of pressured carbon dioxide for quick inflation. Steel capsules are also sold as supplies of compressed gas for air guns, paintball markers, for inflating bicycle tires, and for making seltzer. Rapid vaporization of liquid CO_2 is used for blasting in coal mines.

5) Carbon dioxide extinguishes flames, and some fire extinguishers, especially those designed for electrical fires; contain liquid carbon dioxide under pressure. Carbon dioxide also finds use as an atmosphere for welding, although in the welding arc, it reacts to oxidize most metals. Use in the automotive industry is common despite

significant evidence that welds made in carbon dioxide are quite delicate than those made in more inert atmospheres, and that such weld joints depreciate over time because of the formation of carbonic acid. It is used as a welding gas primarily because it is less expensive than more inert gases such as argon or helium.

6) Liquid carbon dioxide is a good solvent for many organic compounds and it has begun to attract attention in the pharmaceutical and other chemical processing industries as a less toxic alternative to more traditional solvents such as organic chlorides. It's used by some dry cleaners for this reason.

7) Plants require carbon dioxide to conduct photosynthesis, and greenhouses may enrich their atmospheres with additional CO_2 to boost plant growth. It has been proposed that carbon dioxide from power generation be bubbled into ponds to grow algae that could then be converted into biodiesel fuel. High levels of carbon dioxide in the atmosphere effectively exterminate many pests. Greenhouses will raise the level of CO_2 to 10,000 ppm (1%) for several hours to eliminate pests such as whitefly, spider mites, and others.

8) In medicine, up to 5% carbon dioxide is added to pure oxygen for stimulation of breathing after apnea and to stabilize the O_2/CO_2 balance in blood.

9) A common type of industrial gas laser, the carbon dioxide laser, uses carbon dioxide as a medium.

10) Carbon dioxide is commonly injected into or adjacent to producing oil wells. It will act as both a pressurizing agent and, when dissolved into the underground crude oil, will significantly reduce its viscosity, enabling the oil to flow more rapidly through the earth to the removal well. In mature oil fields, extensive pipe networks are used to carry the carbon dioxide to the injection points.

Carbon dioxide - Dry Ice

1) Dry ice is a generalized trademark for solid ("frozen") carbon dioxide. Prest Air Devices, a company formed in Long Island City, New York in 1923, coined the term in 1925.

2) Dry ice at normal pressures does not melt into liquid carbon dioxide but rather sublimates directly into carbon dioxide gas at $-78.5\,°C$ ($-109.3\,°F$). Hence it is called "dry ice" as opposed to normal "wet" ice (frozen water).

3) Compressing carbon dioxide gas to a liquid form, removing the heat produced by the compression, and then letting the liquid carbon dioxide expand quickly produce dry ice. This expansion causes a drop in temperature so that some of the CO_2 freezes into "snow", which is then compressed into pellets or blocks.

Supercritical Carbon dioxide

Carbon dioxide also could be used more widely as a solvent and for example super critical CO_2 (the state existing at $31.^0C$ and 72.8 atm). Now a days Carbon dioxide could be used more widely as a solvent and for example supercritical carbon dioxide offers advantages in terms of stereo chemical control, product purification synthesizing fine chemicals and pharmaceuticals. People are extracting caffeine from coffee by using supercritical carbon dioxide. More over the advantage of using CO_2 is oil gas recovery and ponds of genetically modified algae that can convert power plant CO_2 into biodiesel.

As noted above, CO_2 is generally considered to be a green or environmentally benign solvent and is naturally abundant. CO_2 has been suggested as a sustainable replacement for organic solvents in a number of chemical processes and is currently used in the dry cleaning, and in parts degreasing. While CO_2 is certainly not a panacea, there are a number of characteristics, which suggest that CO_2 could provide environmental and economic benefits. The nontoxic nature of CO_2 has a number of advantages. For example, in food and pharmaceutical applications, usage of CO_2 greatly reduces future liability costs and can also facilitate regulatory approval of certain processes. An example is the conversion of pharmaceuticals into nanometer-size particles for injectable use. Another instance in which supercritical carbon dioxide could be advantageous is in situations involving contact between hydrophilic and hydrophobic solvents. In this case, the mutual solubility of the two phases is designed to be small. However, some cross-contamination is inevitable, typically leading to a costly remediation. The use of CO_2 as the hydrophobic phase produces contamination that is both benign and readily reversible. Examples include liquid-liquid extraction between organic and aqueous phases as well as emulsion polymerization of water-soluble monomers. In applications where emissions are

unavoidable, CO_2 is relatively benign to the environment. Examples range from use of CO_2 in enhanced oil recovery to use as a foaming agent or as the solvent in dry cleaning. Using supercritical CO_2 as a solvent also has advantages that arise from chemical and/or physical properties. In reactions involving gaseous reactants in liquid phases, the use of supercritical CO_2 with its ability to dissolve large amounts of most gases could allow kinetic control of reactions as opposed to limiting of reaction rates by the transport of the gaseous reactant across the gas-liquid interface. In reactions where CO_2 is a reagent, its use as a solvent would also favor the reaction. Carbon dioxide may also offer advantages in reactions such as free-radical polymerizations and oxidations where a chemically inert solvent is required.

CHEMICALS SYNTHESIS FROM CARBON DIOXIDE

It is well known that CO_2 is very stable gas and highly unreactive but plants are utilizing it for example in the photosynthesis of carbohydrate from CO_2. Can we also find the ways to make chemicals from CO_2 artificially? Surely it will be an environmentally benign route, and this process will lead to green chemistry. The main process which use CO_2 are

1) Synthesis of urea.
2) Synthesis of salicylic acid
3) Synthesis of cyclic carbonate and polycarbonate
4) Synthesis of methanol.

Synthesis of urea by using CO_2 currently is a well-established process. The capacity is approximately 90 million metric tons per annum as per 1997 statistics. Other reactions are in pilot plant scale. Besides to these reactions there are many reactions, which utilize CO_2. It will be a great feed stock for making commodity chemicals, fuels and materials. It already plays a major role for a variety of applications. But there are few catches. One is that CO_2 is very stable, which means it takes extra effort to achieve the molecules so that it will react.   Professor Christopher. M. Rayner of the University of Leeds, in England, has been working on CO_2 conversion. He published a review article recently on the potential of CO_2 in synthetic organic chemistry. Approximately 115 million metric tons of CO_2 is used annually by the global chemical industries but really that does not compare to the approximate 24 billion metric tons. Bulk chemicals already produced

routinely from CO_2 include urea to make nitrogen fertilizers, salicylic acid as a pharmaceutical ingredient, and polycarbonate based and plastics. The simplest reactions of CO_2 are those in which it is simply inserted into an X-H bond. Examples are the insertion of CO_2 into organic amines to afford carbamic acids, which may be converted into organic carbamates. More recent examples include the insertion of CO_2 in P-N bonds of P $(NR_2)_3$ compounds to form P $(NR_2)(OCONR_2)_2$ compounds and the reaction of ammonium carbamates (derived from CO_2) with alkyl halides in the presence of crown ethers to form useful urethane intermediates. This is an example of using CO_2 to replace phosgene, a highly toxic intermediate in chemical synthesis. Reactions are known in which CO_2 undergoes insertion into Sn-C bonds of allyl tin compounds to form carboxylated allyl derivatives and which are catalyzed by Pd complexes. Another interesting reaction is the insertion of CO_2 into alkanes such as methane to form acetic acid.

The activation of a C-H bond and CO_2 insertion are much fascinating .The thermodynamics of this reaction are marginal; however, adjusting the reaction conditions and coupling this reaction with energetically favorable product processes could improve conversion efficiencies. Carbonates, $(RO)_2CO$, can also be prepared by inserting CO_2 into O-H bonds followed by dehydration or by oxidative carboxylation of olefins. This synthetic approach has the possibility of providing a new route to compounds that have very large potential markets. Related reactions in which CO_2 is incorporated into product molecules without reduction have been used in the synthesis of polymers.

The groups of Inoue and Kuran performed initial work in this area. In recent years, a number of new catalysts have been developed for co polymerization of CO_2 and oxiranes to form polycarbonate. These studies have increased the productivity of this reaction by 100 times and have also expanded the range of applicable monomers (oxiranes). Polypyrones are another potentially interesting new class of polymer. It has been prepared from diacetylenes and CO_2 in the presence of Ni catalysts; a related reaction is the telomerization of butadiene and CO_2 to produce lactones. Urethanes have also been prepared by the reactions of dicarbamate ions formed by insertion of CO_2 into diamines, followed by Pd-catalyzed coupling to 1,4-dichloro-2-butene. Reductive carboxylations in which the CO_2 unit is incorporated into the product are also known.

In the case of alkynes and olefins, electrochemical reductive carboxylations result in effective addition of the formic acid C-H bond to C-C double or triple bonds. For example, building on the earlier stoichiometric results of Hoberg, Dunach and co-workers used Ni bipyridine complexes and sacrificial Mg anodes to reductively couple acetylene and CO_2 to form propenic acid. Similarly, Sylvestri reported that the reductive coupling of CO_2 with styrene is catalyzed by benzonitrile. Bromoarenes can also be reductively carboxylated to form the corresponding carboxylic acid using Ni diphosphine catalysts. More recently, the sequential reductive coupling of two molecules of CO_2 to butadiene to form 3-hexen- 1,6-dioic acid has been reported. This approach provides a new route to a Nylon precursor. Another important monomer, ethylene, can be prepared by electrochemical reduction of CO_2 in aqueous solutions with current efficiencies as high as 48%. The production of this monomer by this remarkable 12-electrons reduction offers a potential route to polyethylene from CO_2. The preceding results clearly indicate that it may be possible to produce a large variety of polymers in the future using materials derived from CO_2.

Under oxidative conditions, CO_2 may react with olefins to give cyclic carbonates that find wide industrial applications. In these transformations heterogeneous catalysts are currently more promising and viable than homogeneous ones. Another potentially useful reaction of CO_2 is the dehydrogenation of hydrocarbons. Examples are the dehydrogenation of ethyl benzene and propane over metal oxides to form styrene and propene, respectively. In these reactions, no part of the CO_2 molecule is incorporated into the organic product, rather the oxygen of CO_2 serves to remove two H atoms of the hydrocarbon. CO_2 is currently used as an additive in the synthesis of methanol from CO and H_2, and it is believed that reduced forms of CO_2 are kinetically important intermediates in this process. Recently, efficient heterogeneous catalysts have been developed for CO_2 hydrogenation to methanol. However, the thermodynamics for methanol production from H_2 and CO_2 are not as favorable as that for production of methanol from H_2 and CO. For example, at 200 °C the equilibrium yield of methanol from CO_2 is slightly less than 40% while the yield from CO is greater than 80%. The reduction of CO_2 can be rendered more favorable by the use of hybrid catalysts that dehydrate methanol to form Dimethyl ether. Other copper-zinc based catalysts have also

been used for methanol synthesis. Fisher and Bell *et al.* studied $Cu/ZrO_2/SiO_2$ catalysts by *in-situ* infrared spectroscopy and suggested some mechanism for the route to methanol. Ethanol has also been produced by the hydrogenation of CO_2. This fuel is attractive because it has a somewhat higher energy density than methanol and it is not as toxic. However, the selectivity for ethanol production is comparatively low (<40%).

The hydrogenation of CO_2 to methane and higher hydrocarbons is also known. For C_2 and higher hydrocarbons, hybrid catalysts such as $Cu-ZnO-Cr_2O_3$ and H-Y zeolite are generally used. Noyori *et al.* have carried out pioneering work on the catalytic synthesis of formic acid derivatives by CO_2 hydrogenation, together with other substrates, in supercritical CO_2. In part because of the high solubility of H_2 in CO_2, an economical synthesis of dimethylformamide is achieved.

Homogeneous catalysts are also known to mediate the rapid hydrogenation of CO_2 to formate, because this reaction is not thermodynamically preferential, amines and supercritical CO_2 have been used to drive this reaction. Under the appropriate conditions, very high turnover numbers and rates can be achieved. For example, Leitner *et al.* examined complexes of the general type $[R_2P-(X)-PR_2]Rh-(hfacac)$ (X = bridging group; hfacac) 1,3-bis-(trifluoromethyl)-acetonylacetonate). All the compounds are active catalysts for formic acid production from H_2 and CO_2, but the most effective has X= $(CH_2)_4$ and R= cyclohexyl showing good results at 25 °C and 40 atm of 1:1 H_2: CO_2. The selectivity to formic acid is nearly 100%.

Possible pathways for the opposing interaction of Low-Valent Catalysts with Protons or CO_2 of the CO_2 reduction product observed. If the reduced form of the catalysts reacts with CO_2 to form a $M-CO_2$ complex, protonation yields a metallo carboxylic acid; further reaction can then produce CO by C-O bond cleavage to form hydroxide or water. Thus, reaction of a reduced form of the catalyst with CO_2, as opposed to protons, leads to CO formation. If the reduced form of the catalyst reacts with protons to form a hydride complex, subsequent reaction of the hydride with CO_2 leads to formate production. An interesting example of such selectivity is CO_2 electrochemical reduction catalyzed by polymeric films based on $[Ru(N-N)(CO)_2]_n$ (N-N=poly pyridine ligand) in aqueous media. Deronzier and Ziessel *et al.* found that bipyridyl ligands with electron withdrawing groups in the 4,4 positions gave catalysts which are highly selective for

formate at pH >5 while those derived from the unsubstantiated 2, 2□-bipyridine or the 4, 4□-dimethyl analogue primarily give CO at pH > 7.165 Formate was thought to arise from an intermediate metal hydride, whereas CO was thought to arise from a metallo carboxylicacid generated by carbonation of an intermediate anion followed by protonation. It is unusual for homogeneous catalysts to form reduction products that require more than two electrons.

However, Tanaka and co-workers, reported that the formation of glycolate ($HOCH_2COO-$), glyoxylate (OCHCOO-), formic acid, formaldehyde, and methanol as CO_2 reduction products using $[Ru(tpy)(bpy)(CO)]^{2+}$ complexes as electro catalysts (bpy = 2,2□-bipyridine, and tpy =2,2□:6□,2□□-terpyridine).Although turnover numbers were not given for these highly reduced species, their formation raises the exciting possibility that a single-site catalyst can result in multi electron reductions of CO_2 and even C-C bond formation.

Tanaka and Gibson *et al*. recently succeeded in isolating key Ru C_1 compounds with polypyridine ligands that are models for catalytic intermediates. Gibson *et al*. also isolated ReC_1 complexes with polypyridine ligands. The importance of photochemistry in reactions of some have the Re and Ru complexes has been demonstrated. The formation of formaldehyde has also been reported in electrochemical CO_2 reduction using transition metal terpyridine complexes polymerized on glassy carbon electrodes. The relatively mild conditions and low over potentials required for some of the homogeneous catalysts make them attractive for future studies; however, a number of barriers must be defeated before useful catalysts are available for fuel production.

Photochemical reduction of CO_2 is one of the significant reactions many of the reactions described above rely on energy input either in the form of reactive bonds (alkenes, alkynes, etc.), hydrogen, or electricity. Photochemical systems have been studied in an effort to develop systems capable of directly reducing CO_2 to fuels or chemicals using solar energy. Transition-metal complexes have been used as both catalysts and solar energy converters, since they can absorb a significant portion of the solar spectrum, have long-lived excited states are able to promote the activation of small molecules, and are forceful. Carbon dioxide utilization by artificial photo conversion presents a challenging alternative to thermal hydrogenation reactions, which require H_2.

The systems studied for photochemical CO_2 reduction studies can be divided into several groups: $Ru(bpy)_3^{2+}$ both as a photo sensitizer and as a catalyst. $Ru(bpy)_3^{2+}$ as a photo sensitizer and another metal complex as a catalyst. $ReX(CO)_3(bpy)$ or a similar complex as a photosensitizers. $Ru(bpy)_3^{2+}$ and $Ru(bpy)_3^{2+}$ type complexes as photo sensitizers in microheterogeneous systems. Metalloporphyrins also act as a photosensitizers and catalyst. Photochemical CO_2 reduction is normally carried out less than 1.0 atm CO_2 at room temperature. Therefore, the concentration of dissolved CO_2 in the solution is low (e.g., 0.28 M in CH_3-CN, 0.03Min water). These systems produce formate and CO as products. In the most efficient systems, the total quantum yield for all reduced products reaches 40%. In some cases with Ru or Os colloid, CH_4 is produced with a low quantum yield. Under photochemical conditions, the turnover number and the turnover frequency are dependent on irradiation wavelength, light intensity, irradiation time, and catalyst concentration, and they have not been optimized in most of the photochemical experiments described. Typical turnover frequencies for CO or $HCOO^-$ are between 1 and $10h^{-1}$, and turnover numbers are generally 100 or less. The abovementioned molecular sensitizers can be replaced with semiconductor electrodes or particles to achieve light harvesting. These systems may use enzymes or catalysts to promote electron transfer from the semiconductor-solution interface to CO_2 or reduce CO_2 directly. Typically these reductions require a potential bias in addition to solar energy input to achieve CO_2 reduction and electrode corrosions a major concern. This corrosion can some times be defeated using high CO_2 pressures. Fascinating examples of stoichiometric photochemical reactions of CO_2 promoted by metal complexes have also been reported. Thus, Aresta *et al.* found that CO_2 can be incorporated into cyclopropane to afford butyrolactone. Kubiak *et al.* demonstrated the reduction of CO_2 to the radical anion and subsequent coupling to cyclohexene by the use of a Ni complex.

Ranyar *et al.* have worked on the catalytic processes for reducing CO_2 to formic acid. It has potential of power fuel cell for electricity generation and automobiles and as a precursor for other fuels, synthetic chemicals and fibers, including polymers.

Conversion of CO_2 to CO will be more challenging process because CO can be used in a host of organic synthesis and one of the important feed stock in the chemical industry for making higher hydrocarbon through Fisher-Tropsch Synthesis.

Nicolas Eghbali and his group working on conversion of CO_2 and olefins into cyclic carbonates in water. Geoffrey W.Coates *et al.* have developed the catalyst to incorporate CO_2 into polymers by using β-diminate zinc acetate and salen cobalt carboxylate complexes. These catalysts promote alternating co polymerization of various epoxides with CO_2 to make biodegradable aliphatic polycarbonate. The polymers which contain 30-50% CO_2 by weight have gas barrier and degradation properties that make them attractive for feed packaging foam-casting to make automotive parts and electronic processing applications. These kinds of polymers also can be used to replace propylene oxide segments in polyurethane foams, which would help cut costs. The foams are used for insulation and seat cushions, among other applications

About 150 million tons of plastics produced globally in a year, and most of it is non-bio degradable and from energy intensive processes that use petroleum-based feedstocks.

Coastes *et al.* working on limeonene oxide derived from citrus fruit waste as a potential epoxide monomer for co-polymerization with CO_2.other research in progress involves developing a catalytic system that can use untreated CO_2 directly from industrial waste streams to make polymer.

Artificial bio inspired systems is far less complicated and therefore easier to study than natural photosynthesis, in which sun light water and CO_2 are converted into O_2 and carbohydrates.

By using inorganic material, people are utilizing the carbon dioxide. The reaction of $CaCO_3$ and CO_2 in water to form Ca $(HCO_3)_2$ is responsible for the fixation of large quantities of CO_2 in the oceans. However, it is kinetically slow. Similarly, CO_2 can also be fixed by naturally occurring minerals. Even though the reactions are thermodynamically favorable, they are slow and would need to be enhanced kinetically before they could contribute significantly to adjusting the carbon balance. In addition, this would generally require mining and processing enormous amounts of materials to store relatively little CO_2.Currently, large quantities of $CaCO_3$ are converted into CaO and CO_2 (which is released into the atmosphere) in cement manufacture. If a natural ore could be substituted for CaO, a significant release of CO_2 into the atmosphere could, in principle, be avoided.

Fujita has found success by using rhenium tri carbonyl complexes to mediate CO_2 reduction. The researchers homed in on one set of catalysts bearing bipyridine (bpy) ligands which includes (bpy) $Re(CO)_3$ and its di rhenium analog. But the reaction rates for co production are slow due to the stability of CO_2

People are working on $CO_2 \rightarrow CO$ but ultimate target is CO_2 to Methanol that could be used as a fuel.

All Possible Reactions
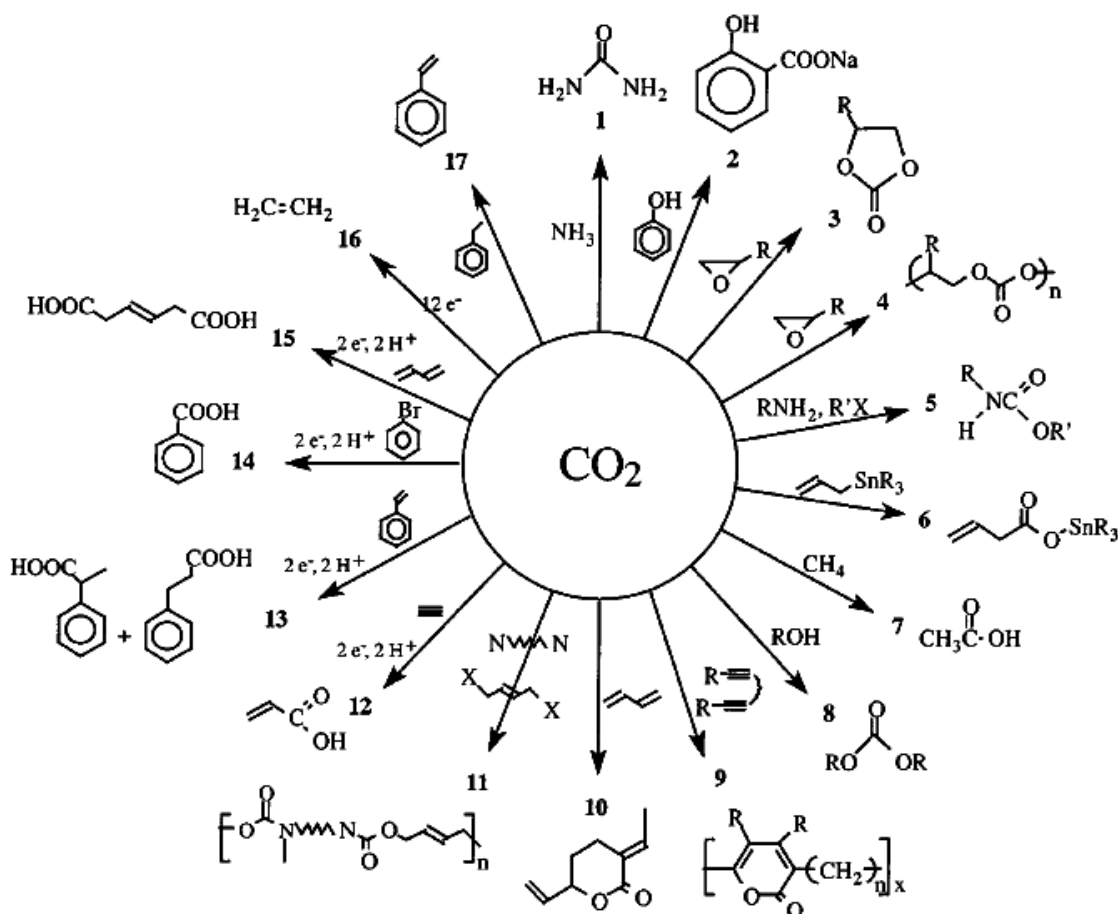
Fig. 14.1. Overall chemical transformations

(reproduced from Hironiri Arakawa, *chemical Reviews, 101* (2001) 976)

CONCLUSION

Synthesizing chemicals from carbon dioxide is one of the challenging process as well as eco-friendly and environmentally benign route. Using carbon dioxide as a raw material

never going to reduce atmosphere CO_2 level or it will be very little the effect on climate change but we can reduce the production of CO_2 and reduce the usage of fossil fuel and shall we make it?

REFERENCES

1. J. M. Desimone, *Science, 265* (1994) 359

2. Hironiri Arakawa, *chemical Reviews*, *101* (2001) 976

3. Chemical & Engineering News, *April 30*, 2007, 11

4. Chemistry & Industry, *July13*, 2007, 13

5. X. Xiaoding, J. A. Moulijin Energy and Fuels, *10* (1996) 305

6. *Greenhouse issues* 1992 Feb

7. M. A.Scibioh and B.Viswanathan Proc.*Indian Natn Sci Acad.*, 70 A (3) (2004) 407

Chapter -15

CARBOHYDRATES TO CHEMICALS

Vamsi Krishna Nunna,

INTRODUCTION

Carbohydrates are the most abundant class of organic compounds found in living organisms. They originate as products of **photosynthesis**, an endothermic reductive condensation of carbon dioxide requiring light energy and the pigment chlorophyll. Carbohydrates can be written as carbon hydrates, $C_n(H_2O)_n$, hence their name.

$$n\,CO_2 \;+\; n\,H_2O \;+\; energy \longrightarrow C_nH_{2n}O_n \;+\; n\,O_2$$

The carbohydrates are a major source energy required for metabolism. Aside from the sugars and starches that meet this vital nutritional role, carbohydrates also serve as a structural material (cellulose), a component of the energy transport compound ATP, recognition sites on cell surfaces, and one of three essential components of DNA and RNA.

MONOSACCHARIDES

Monosaccharides can be in turn can be classified as ketoses and aldoses basing on the functional group present, i.e. ketone or aldehyde.
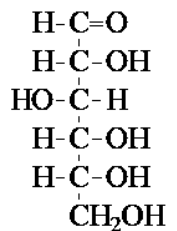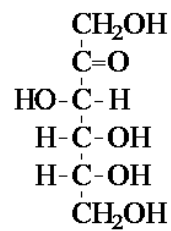
<pre>
    H-C=O   CH₂OH
    H-C-OH   C=O
   HO-C-H   HO-C-H
    H-C-OH   H-C-OH
    H-C-OH   H-C-OH
     CH₂OH   CH₂OH
    Glucose   Fructose
  (aldohexose)   (ketohexose)
</pre>

Glucose is a monosaccharide, an aldohexose and a reducing sugar. The general structure of glucose and many other aldohexoses was established by simple chemical reactions.Hot hydriodic acid (HI) was often used to reductively remove oxygen functional groups from a molecule, and in the case of glucose this treatment gave hexane (in low yield). From this it was concluded that the six carbons are in an unbranched chain. The presence of an aldehyde carbonyl group was deduced from cyanohydrin formation, its reduction to the hexa-alcohol sorbitol, also called glucitol, and mild oxidation to the mono-carboxylic acid, glucuronic

acid. Somewhat stronger oxidation by dilute nitric acid gave the diacid, glucaric acid, supporting the proposal of a six-carbon chain.
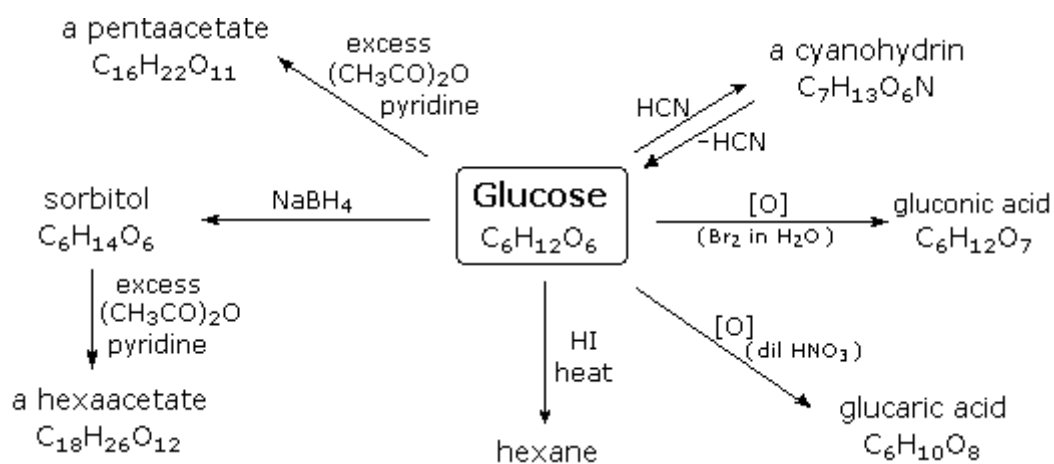

Fig. 15.1. Reactions of glucose

The five oxygens remaining in glucose after the aldehyde was accounted for were thought to be in hydroxyl groups, since a penta-acetate derivative could be made. These hydroxyl groups were assigned, one each, to the last five carbon atoms, because geminal hydroxyl groups are normally unstable relative to the carbonyl compound formed by loss of water. Glucose and other saccharides are extensively cleaved by periodic acid, thanks to the abundance of vicinal diol moieties in their structure. This oxidative cleavage, known as the Malaprade reaction is particularly useful for the analysis of selective O-substituted derivatives of saccharides, since ether functions do not react. The stoichiometry of aldohexose cleavage is shown in the following equation.

$$HOCH_2(CHOH)_4CHO + 5\ HIO_4 \longrightarrow H_2C{=}O + 5\ HCO_2H + 5\ HIO_3$$
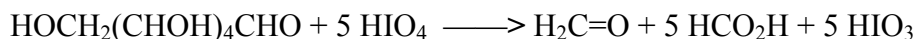
Configuration of Glucose

The four chiral centers in glucose indicate there may be as many as sixteen (2^4) stereoisomers having this constitution. These would exist as eight diasteromeric pairs of enantiomers, and the initial challenge was to determine which of the eight corresponded to glucose. This challenge was accepted and met in 1891 by the German chemist Emil Fischer.

The last chiral center in an aldose chain (farthest from the aldehyde group) was chosen by Fischer as the D / L designator site. If the hydroxyl group in the projection formula pointed to the right, it was defined as a member of the D-family. A left directed hydroxyl group (the mirror image) then represented the L-family. It is important to recognize that the sign of a compound's specific rotation (an experimental number) does not correlate with its configuration (D or L). It is a simple matter to measure an optical rotation with a polarimeter. Determining an absolute configuration usually requires chemical interconversion with known compounds by stereospecific reaction paths.

D-Glyceraldehyde   L-Glyceraldehyde

Fischer projection formulas
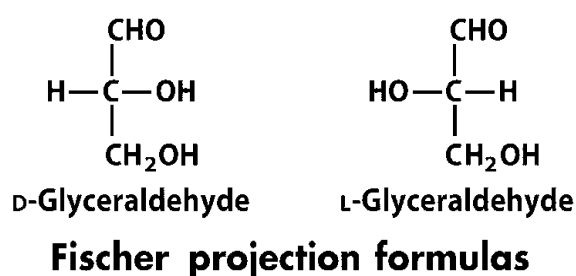
Fischer projection formulas and names for the D-aldose family (three to six-carbon atoms) are shown below.
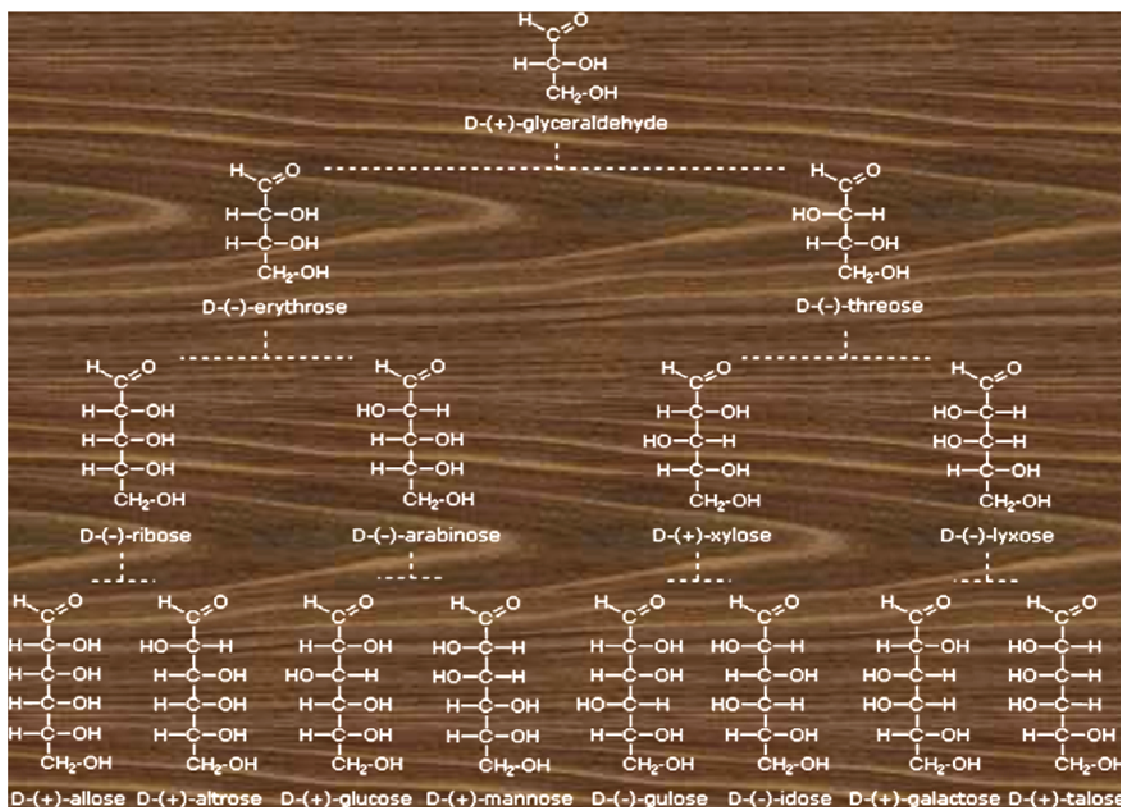
Emil Fischer made use of several key reactions in the course of his carbohydrate studies. These are described here

Oxidation

Sugars may be classified as reducing or non-reducing based on their reactivity with Tollens', Benedict's or Fehling's reagents. If a sugar is oxidized by these reagents it is called reducing, since the oxidant ($Ag^{(+)}$ or $Cu^{(+2)}$) is reduced in the reaction, as evidenced by formation of a silver mirror or precipitation of cuprous oxide. The Tollens' test is commonly used to detect aldehyde functions; and because of the facile interconversion of ketoses and aldoses under the basic conditions of this test, ketoses such as fructose also react and are classified as reducing sugars.

1. D-(-)-ribose →(HOBr, pH ~ 8)→ ribonic acid

2. D-(-)-ribose →(HNO₃ dilute)→ ribaric acid (achiral) --- mirror This aldaric acid is achiral and is optically inactive

3. D-(-)-arabinose →(HNO₃ dilute)→ D-arabinaric acid ≡ D-lyxaric acid ←(HNO₃ dilute)← D-(-)-lyxose
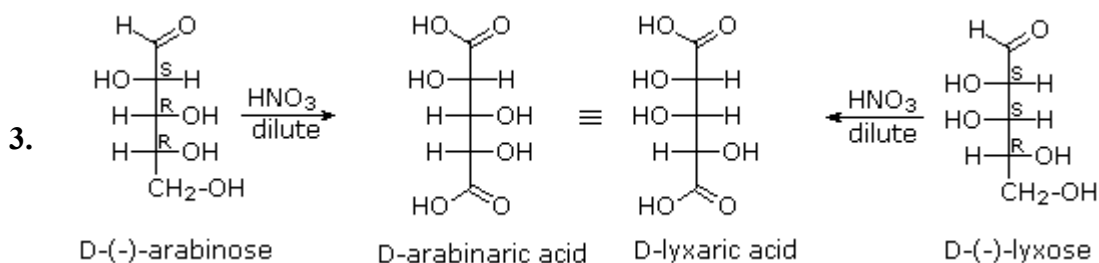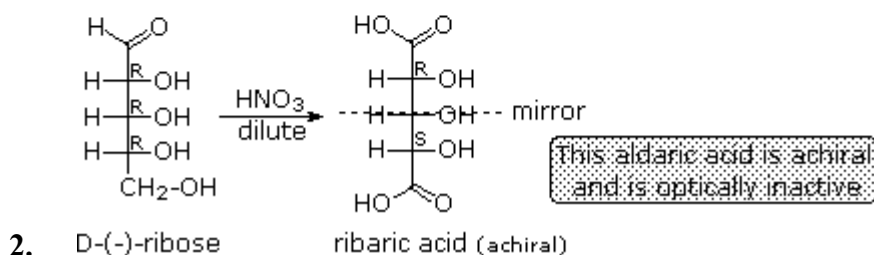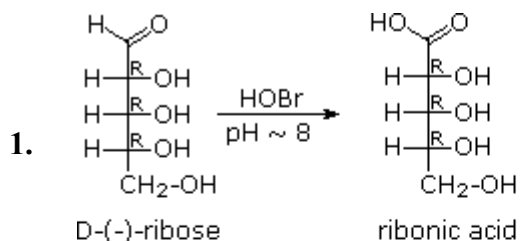
When the aldehyde function of an aldose is oxidized to a carboxylic acid the product is called an aldonic acid. Because of the 2° hydroxyl functions that are also present in these compounds, a mild oxidizing agent such as hypobromite must be used for this conversion (equation 1). If both ends of an aldose chain are oxidized to carboxylic acids the product is called an aldaric acid. By converting aldoses to its corresponding aldaric acid derivative, the ends of the chain become identical .

Thus, ribose, xylose, allose and galactose yield achiral aldaric acids which are, of course, not optically active. The ribose oxidation is shown in equation 2 below. Other aldose sugars may give identical chiral aldaric acid products, implying a unique configurational relationship. The examples of arabinose and lyxose shown in equation 3 above illustrate this result. A Fischer projection formula may be rotated by 180° in the plane of projection without changing its configuration.

Reduction

Sodium borohydride reduction of an aldose makes the ends of the resulting alditol chain identical, $HOCH_2(CHOH)_nCH_2OH$, there by accomplishing the same configurational change produced by oxidation to an aldaric acid. Thus, allitol and galactitol from reduction of allose and galactose are achiral, and altrose and talose are reduced to the same chiral alditol.

Derivatives of $HOCH_2(CHOH)_nCHO$

HOBr Oxidation $\longrightarrow$ $HOCH_2(CHOH)_nCO_2H$ (an Aldonic Acid)

HNO_3 Oxidation $\longrightarrow$ $H_2OC(CHOH)_nCO_2H$ (an Aldaric Acid)

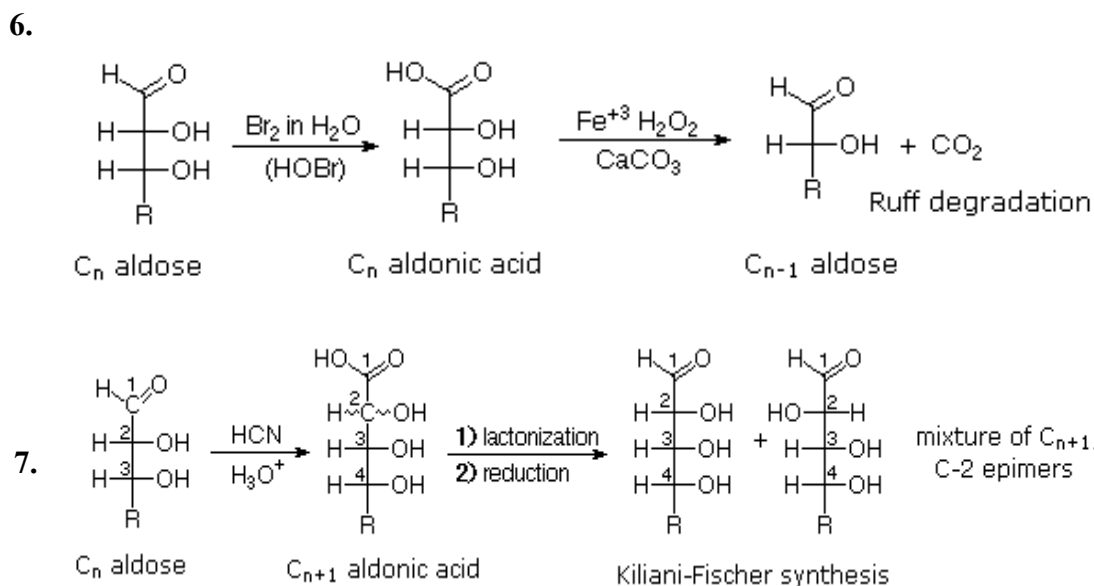$NaBH_4$ Reduction $\longrightarrow$ $HOCH_2(CHOH)_nCH_2OH$ (an Alditol)

Osazone Formation

The Osazone reaction was developed and used by Emil Fischer to identify aldose sugars differing in configuration only at the alpha-carbon. The equation shows the general form of the osazone reaction, which effects an alpha-carbon oxidation with formation of a bis-phenylhydrazone, known as an osazone. Application of the Osazone reaction to D-glucose and D-mannose demonstrates that these compounds differ in configuration only at C-2.

4.

5.

D-(+)-glucose   common D-osazone   D-(+)-mannose
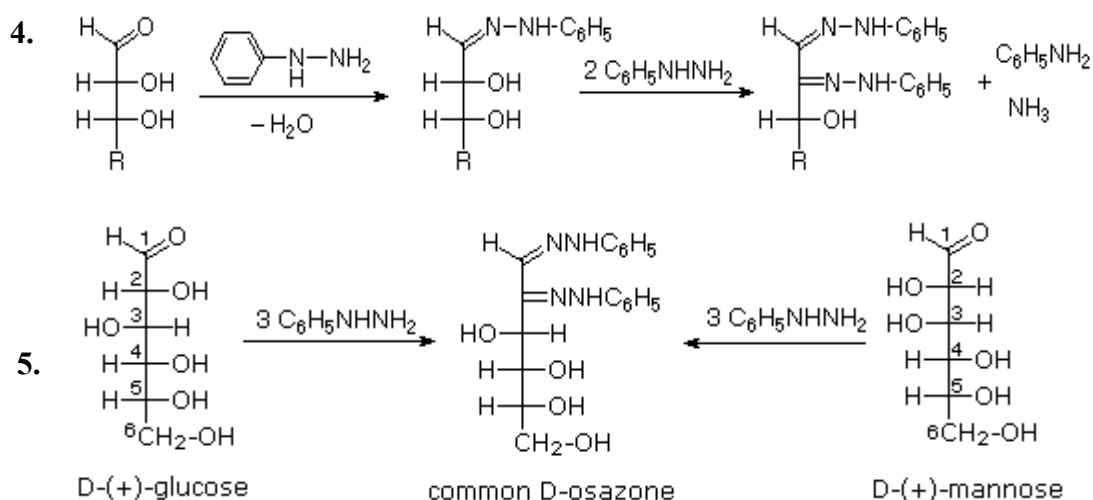
Chain Shortening and Lengthening

6.

C_n aldose C_n aldonic acid C_{n-1} aldose

7.

C_n aldose C_{n+1} aldonic acid   Kiliani-Fischer synthesis

These two procedures permit an aldose of a given size to be related to homologous smaller and larger aldoses. Thus Ruff degradation of the pentose arabinose gives the tetrose erythrose. Working in the opposite direction, a Kiliani-Fischer synthesis applied to arabinose gives a mixture of glucose and mannose. Using these reactions, we can understand the Fischer's train of logic in assigning the configuration of D-glucose.

Anomeric Forms of Glucose

Two different crystalline forms of glucose were reported in 1895. Each of these gave all the characteristic reactions of glucose, and when dissolved in water equilibrated to the same mixture. This equilibration takes place over a period of many minutes, and the change in optical activity that occurs is called **mutarotation**. These facts are summarized in the diagram,
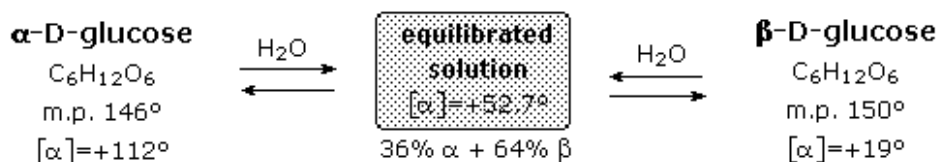
A simple solution to this dilemma is achieved by converting the open aldehyde structure for glucose into a cyclic hemiacetal, called a glucopyranose, as shown in the following diagram. The linear aldehyde is tipped on its side, and rotation about the C4-C5 bond brings the C5-hydroxyl function close to the aldehyde carbon. For ease of viewing, the six-membered hemiacetal structure is drawn as a flat hexagon, but it actually assumes a chair conformation. The hemiacetal carbon atom (C-1) becomes a new stereogenic center, commonly referred to as the anomeric carbon, and the α and β-isomers are called anomers.
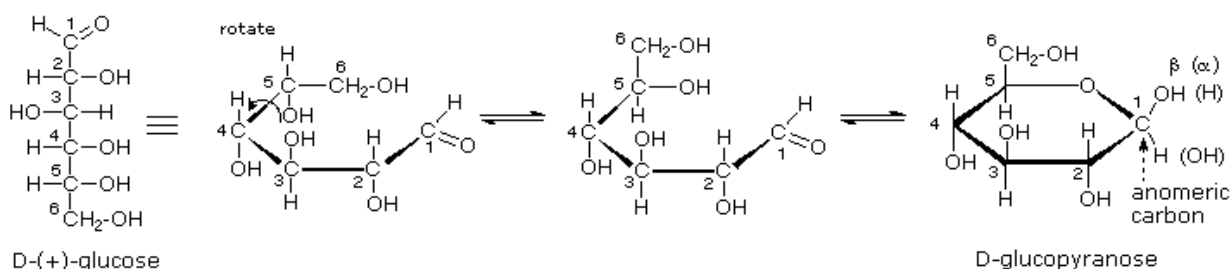
Fig. 15.2.   Anomers of glucose

Cyclic Forms of Monosaccharides

The preferred structural form of many monosaccharides may be that of a cyclic hemiacetal. Five and six-membered rings are favored over other ring sizes because of their low angle and eclipsing strain. Cyclic structures of this kind are termed furanose (five-membered) or

pyranose (six-membered), reflecting the ring size relationship to the common heterocyclic compounds furan and pyran shown on the right.

 Ribose, an important aldopentose, commonly adopts a furanose structure, as shown in the following illustration. The upper bond to this carbon is defined as beta, the lower bond then is alpha**.**
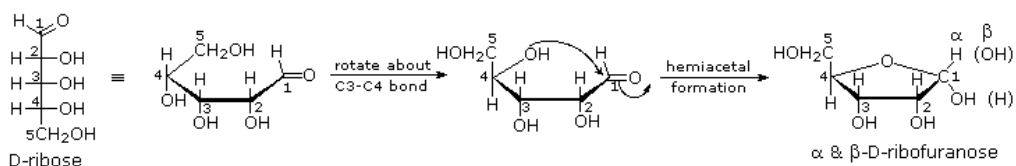

Fig. 15.3. Formation of ribofuranose

The cyclic pyranose forms of various monosaccharides are often drawn in a flat projection known as a Haworth formula, after the British chemist, Norman Haworth. These Haworth formulas are convenient for displaying stereochemical relationships, but do not represent the true shape of the molecules. These molecules are actually puckered in a chair conformation. Examples of four typical pyranose structures are shown below, both as Haworth projections and as the more representative chair conformers.

Examples of Some Pyranose Forms of Hexoses

α-D-glucopyranose   β-D-galactopyranose   α-D-mannopyranose   β-D-allopyranose
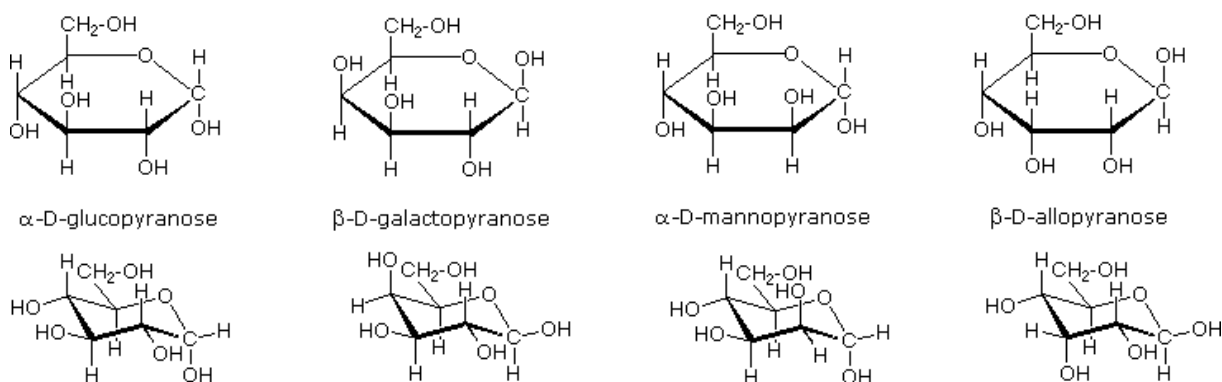
The size of the cyclic hemiacetal ring adopted by a given sugar is not constant, but may vary with substituents and other structural features. Aldolhexoses usually form pyranose rings and their pentose homologs tend to prefer the furanose form, but there are many counter examples.
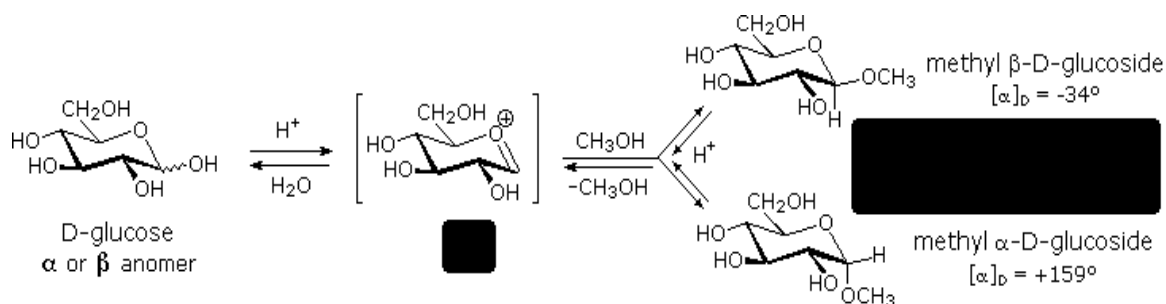
Glycosides

Fig. 15.4. Glycoside formation

Acetal derivatives formed when a monosaccharide reacts with an alcohol in the presence of an acid catalyst are called glycosides. This reaction is illustrated for glucose and methanol in the diagram below. In naming of glycosides, the "ose" suffix of the sugar name is replaced by "oside", and the alcohol group name is placed first. As is generally true for most aldols, glycoside formation involves the loss of an equivalent of water. Since acid-catalyzed aldolization is reversible, glycosides may be hydrolyzed back to their alcohol and sugar components by aqueous acid.

Glycosides abound in biological systems. By attaching a sugar moiety to a lipid or benzenoid structure, the solubility and other properties of the compound may be changed substantially. Because of the important modifying influence of such derivatization, numerous enzyme systems, known as glycosidases, have evolved for the attachment and removal of sugars from alcohols, phenols and amines.

Chemists refer to the sugar component of natural glycosides as the glycon and the alcohol component as the aglycon.Salicin, one of the oldest herbal remedies known, was the model for the synthetic analgesic aspirin. Large classes of hydroxylated, aromatic oxonium cations called anthocyanins provide the red, purple and blue colors of many flowers, fruits and some vegetables. Peonin is one example of this class of natural pigments, which exhibit pronounced pH color dependence. The oxonium moiety is only stable in acidic environments and the color changes or disappears when base is added. The complex changes that occur when wine is fermented and stored are in part associated with glycosides of anthocyanins.

Finally, amino derivatives of ribose, such as cytidine play important roles in biological phosphorylating agents, coenzymes and information transport and storage materials
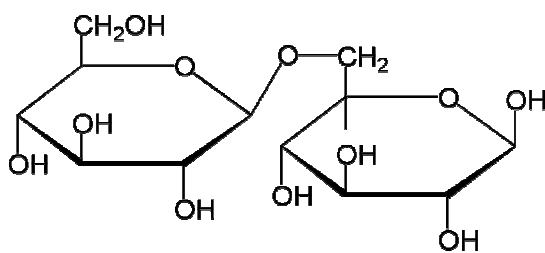
Disaccharides

Two joined monosaccharides are called disaccharides and represent the simplest polysaccharides. They are composed of two monosaccharide units bound together by a covalent bond known as a glycosidic linkage formed via a dehydration reaction, resulting in the loss of a hydrogen atom from one monosaccharide and a hydroxyl group from the other. Some examples of disaccharides are;
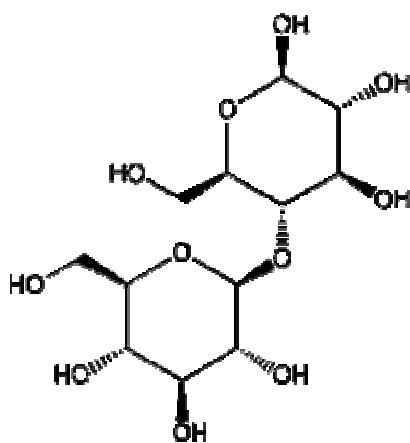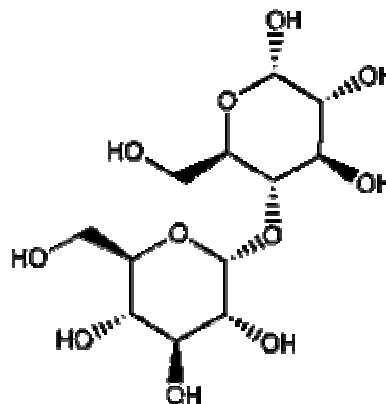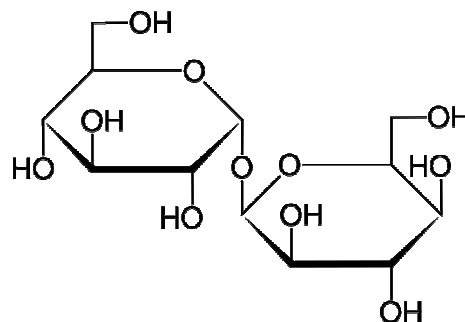
Cellobiose: 4-O-β-D-Glucopyranosyl-D-glucose   **Maltose** : 4-O-α-D-Glucopyranosyl-D-glucose

Gentiobiose : 6-O-β-D-Glucopyranosyl-D-glucose   **Trehalose** : α-D-Glucopyranosyl-α-D-glucopyranoside

Cellobiose, maltose and gentiobiose are hemiacetals they are all reducing sugars (oxidized by Tollen's reagent). Trehalose, a disaccharide found in certain mushrooms, is a bis-acetal, and is therefore a non-reducing sugar. Acid-catalyzed hydrolysis of these disaccharides yields glucose as the only product. Enzyme-catalyzed hydrolysis is selective for a specific

glycoside bond, so an alpha-glycosidase cleaves maltose and trehalose to glucose, but does not cleave cellobiose or gentiobiose. A beta-glycosidase has the opposite activity.

Although all the disaccharides shown here are made up of two glucopyranose rings, their properties differ in interesting ways. Maltose, sometimes called malt sugar, comes from the hydrolysis of starch. It is about one third as sweet as cane sugar (sucrose), is easily digested by humans, and is fermented by yeast. Cellobiose is obtained by the hydrolysis of cellulose. It has virtually no taste, is indigestible by humans, and is not fermented by yeast. Some bacteria have beta-glucosidase enzymes that hydrolyze the glycosidic bonds in cellobiose and cellulose. The presence of such bacteria in the digestive tracts of cows and termites permits these animals to use cellulose as a food. Finally, it may be noted that trehalose has a distinctly sweet taste, but gentiobiose is bitter. Sucrose, or cane sugar, is our most commonly used sweetening agent. It is a non-reducing disaccharide composed of glucose and fructose joined at the anomeric carbon of each by glycoside bonds (one alpha and one beta).

Polysaccharides

 polysaccharides are large high-molecular weight molecules constructed by joining monosaccharide units together by glycosidic bonds. They are sometimes called **glycans**. The most important compounds in this class, cellulose, starch and glycogen are all polymers of glucose. Cotton fibres are essentially pure cellulose, and the wood of bushes and trees is about 50% cellulose.

Cellulose As a polymer of glucose, cellulose has the formula $(C_6H_{10}O_5)_n$ where n ranges from 500 to 5,000, depending on the source of the polymer. The glucose units in cellulose are linked in a linear fashion, as shown below. The beta-glycoside bonds permit these chains to stretch out, and this conformation is stabilized by intramolecular hydrogen bonds. A parallel orientation of adjacent chains is also favored by intermolecular hydrogen bonds. Although an individual hydrogen bond is relatively weak, many such bonds acting together can impart great stability to certain conformations of large molecules. Most animals cannot digest cellulose as a food, and in the diets of humans this part of our vegetable intake functions as roughage and is eliminated largely unchanged.

Some animals (the cow and termites, for example) harbour intestinal microorganisms that breakdown cellulose into monosaccharide nutrients by the use of beta-glycosidase enzymes. Cellulose is commonly accompanied by a lower molecular weight, branched, amorphous

polymer called **hemicellulose**. In contrast to cellulose, hemicellulose is structurally weak and is easily hydrolyzed by dilute acid or base. Also, many enzymes catalyze its hydrolysis. Hemicelluloses are composed of many D-pentose sugars, with xylose being the major component. Mannose and mannuronic acid are often present, as well as galactose and galacturonic acid.
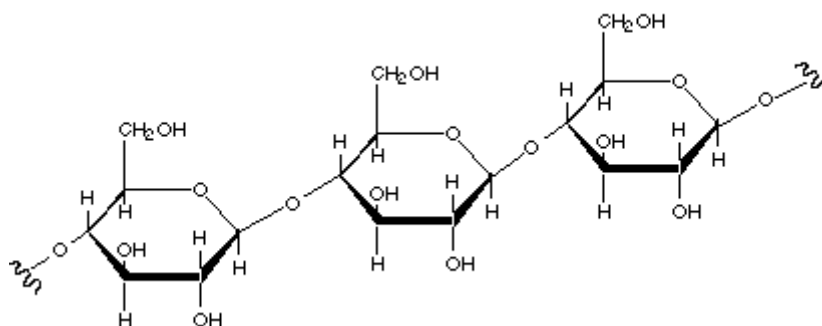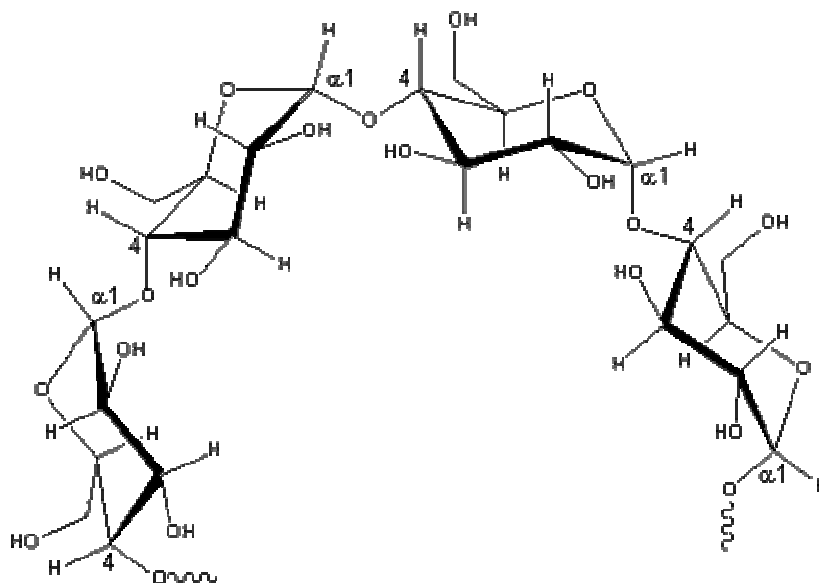

Fig. 15.5. Cellulose structure

Fig. 15.6. Representative partial structure of amylose

Starch is a polymer of glucose, found in roots, rhizomes, seeds, stems, tubers and corms of plants, as microscopic granules having characteristic shapes and sizes. Most animals, including humans, depend on these plant starches for nourishment. The structure of starch is

more complex than that of cellulose. The intact granules are insoluble in cold water, but grinding or swelling them in warm water causes them to burst. The released starch consists of two fractions.

About 20% is a water soluble material called **amylose**. Molecules of amylose are linear chains of several thousand glucose units joined by alpha C-1 to C-4 glycoside bonds. Amylose solutions are actually dispersions of hydrated helical micelles. The majority of the starch is a much higher molecular weight substance, consisting of nearly a million glucose units, and called **amylopectin**. Molecules of amylopectin are branched networks built from C-1 to C-4 and C-1 to C-6 glycoside links, and are essentially water insoluble.
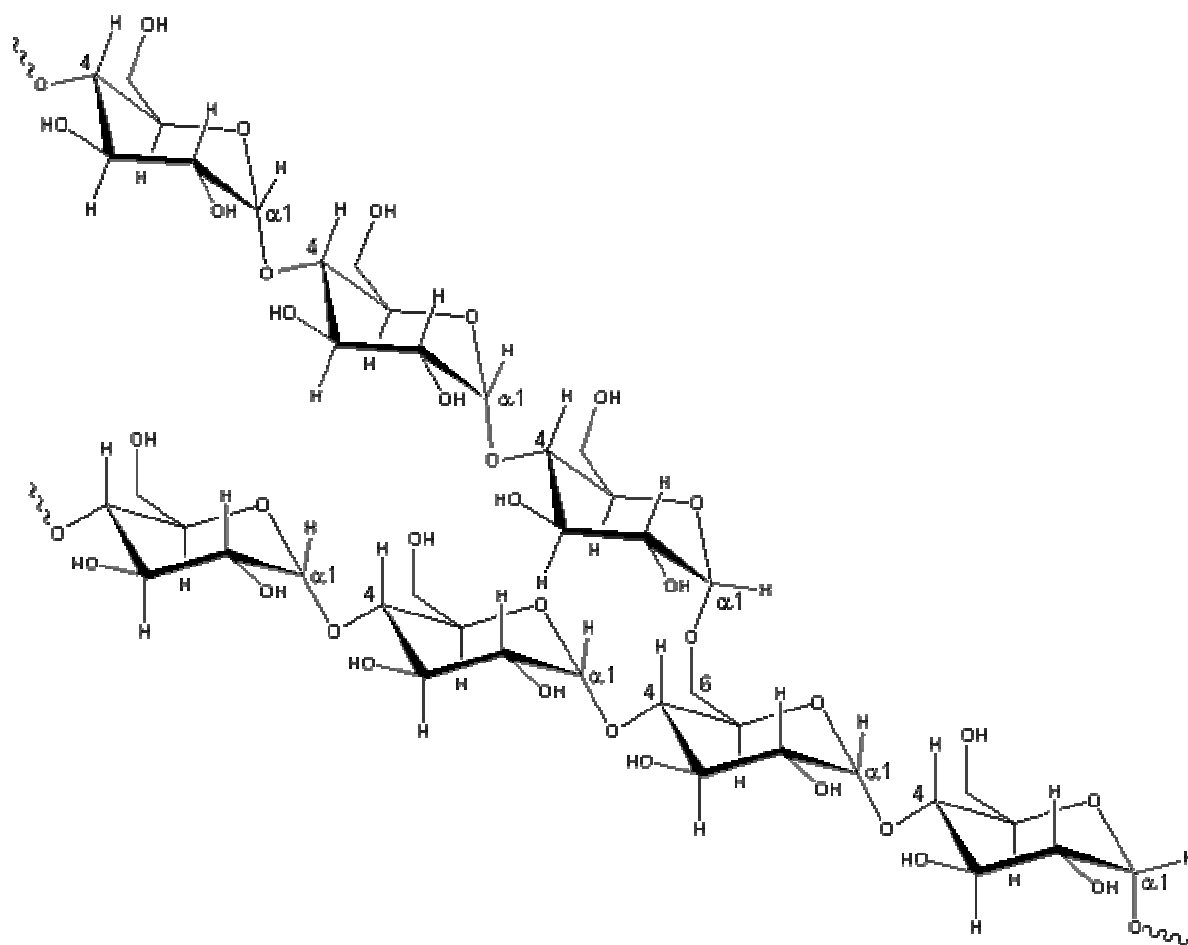

Fig. 15.7.   Representative partial structure of amylopectin

Glycogen is a polysaccharide of glucose (Glc) which functions as the primary short term energy storage in animal cells. Glycogen is the analogue of starch, a less branched glucose

polymer in plants, and is commonly referred to as **animal starch**, having a similar structure to amylopectin. Glycogen forms an energy reserve that can be quickly mobilized to meet a sudden need for glucose, but one that is less compact than the energy reserves of triglycerides (fat). It is made primarily by the liver and the muscles, but can also be made by the brain. The uterus also stores glycogen during pregnancy to nourish the embryo.

Glycogen is a highly branched polymer that is better described as a dendrimer of about 60,000 glucose residues and has a molecular weight between 10^6 and 10^7 daltons (~4.8 million). Most of Glc units are linked by α-1,4 glycosidic bonds, approximately 1 in 12 Glc residues also makes -1,6 glycosidic bond with a **second Glc**, which results in the creation of a branch. Glycogen does not possess a reducing end.
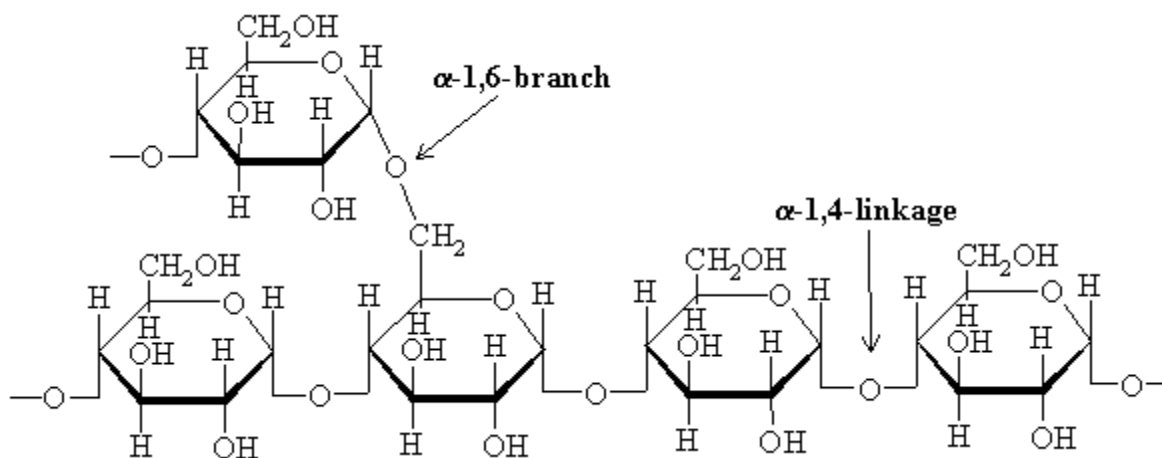
Fig. 15.8. Glycogen

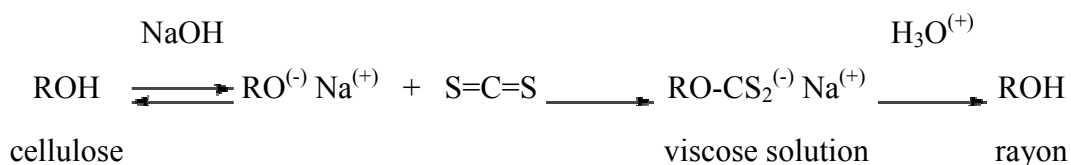**Synthetic Modification of Cellulose**

Cotton, probably the most useful natural fiber, is nearly pure cellulose. Crude cellulose is also available from wood pulp by dissolving the lignan matrix surrounding it. These less desirable cellulose sources are widely used for making paper. In order to expand the ways in which cellulose can be put to practical use, chemists have devised techniques for preparing solutions of cellulose derivatives that can be spun into fibers, spread into a film or cast in various solid forms. A key factor in these transformations are the three free hydroxyl groups on each glucose unit in the cellulose chain, $--[C_6H_7O(OH)_3]_n--$. Esterification of these

functions leads to polymeric products having very different properties compared with cellulose itself.

Cellulose Nitrate, first prepared over 150 years ago by treating cellulose with nitric acid, is the arliest synthetic polymer to see general use. The fully nitrated compound, --[C6H7O(ONO2)3]n--, called guncotton, is explosively flammable and is a component of smokeless powder. Partially nitrated cellulose is called pyroxylin. Pyroxylin is soluble in ether and at one time was used for photographic film and lacquers. The high flammability of pyroxylin caused many tragic cinema fires during its period of use. Furthermore, slow hydrolysis of pyroxylin yields nitric acid, a process that contributes to the deterioration of early motion picture films in storage.

Cellulose Acetate, --[$C_6H_7O(OAc)_3$]$_n$--, is less flammable than pyroxylin, and has replaced it in most applications. It is prepared by reaction of cellulose with acetic anhydride and an acid catalyst. The properties of the product vary with the degree of acetylation. Some chain shortening occurs unavoidably in the preparations. An acetone solution of cellulose acetate may be forced through a spinnerette to generate filaments, called acetate rayon that can be woven into fabrics.

Viscose Rayon , is prepared by formation of an alkali soluble xanthate derivative that can be spun into a fiber that reforms the cellulose polymer by acid quenching. The following general equation illustrates these transformations. The product fiber is called viscose rayon.

$$ROH \xrightleftharpoons{NaOH} RO^{(-)}Na^{(+)} \ + \ S=C=S \longrightarrow RO\text{-}CS_2^{(-)}Na^{(+)} \xrightarrow{H_3O^{(+)}} ROH$$

cellulose   viscose solution   rayon

Catalytic conversion of carbohydrates

Carbohydrates are the main source of renewables used for the production of bio-based products. Sucrose and starch are the major sources. Polysaccharides such as inulin are gaining importance as a source of fructose. Two carbohydrates of animal origin, lactose and chitin are also used commercially.

Multistep reactions carried out by cascade catalysis without intermediate product recovery decrease operating time and may reduce considerably the amount of waste produced. For example, sorbitol can be obtained in one-pot reaction from starch-derived

polysaccharides using ruthenium supported on acidic Y-zeolite. The acidic sites of the zeolite catalyze the polysaccharide hydrolysis yielding transiently glucose, which is hydrogenated to sorbitol on ruthenium. Similarly, 2,5-Furanedicarboxylic acid, a potential substitute for terephtalic acid is obtained in one-pot reaction over a bifunctional acidic and redox catalyst consisting of cobalt acetylacetonate encapsulated in sol–gel silica. In the three former examples, the reactions steps took place on heterogeneous catalysts. However, cascade catalysis without recovery of intermediate products may involve enzymatic catalysis, homogeneous catalysis and heterogeneous catalysis. Combination of enzymatic and chemical steps can give a better yield.

Hydrogenation of glucose and derivatives

Glucose issued from starch or sucrose hydrolysis is hydrogenated to sorbitol , a commodity product used in food, pharmaceutical and chemical industries as well as an additive in many end-products.Mannitol and gluconic acid are the main by-products of this reaction.

Fig.
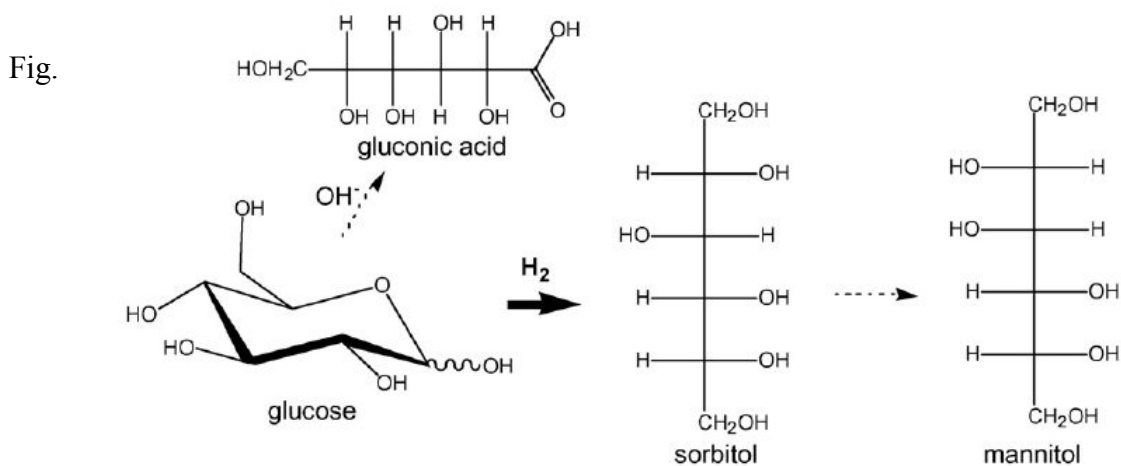
15.9. Hydrogenation of glucose

Catalysts allowing a 100% conversion and 99% selectivity are required. Also, they should be stable after many recycling operations or for extended period of time on stream in continuous reactor. Most of the industrial production is still conducted batch-wise on Raney nickel catalysts promoted with electropositive metal atoms such as molybdenum and chromium ,but because of the risk of nickel or metallic promoter leaching, they tend to be replaced by carbon supported ruthenium catalysts which are also more active. However, active carbon

powders are difficult to handle and recycle in batch operation, therefore a continuous process with formed carbon support are desirable.

Hydrogenation of glucose to sorbitol was achieved on ruthenium catalysts supported on activated carbon cloths (ACC) obtained by carbonization and CO_2 activation of woven rayon .Catalyst 0.9 wt.% Ru/ACC was loaded with ruthenium by cationic exchange or anionic adsorption both giving an homogeneous distribution of 2 nm ruthenium particles in carbon fibers. The ACC was clamped on a support fitting along the autoclave walls thus allowing an easy recycling of the catalyst since, unlike catalysts in powder form, no filtration are required and there is no attrition or leaching.

There is a great interest to convert C6 carbohydrates available in large supply from starch or sucrose into C5 and C4 polyols that are little present in biomass and find many applications in food and non-food products. Glucose can be converted to arabitol by an oxidative decarboxylation of glucose to arabinonic acid followed by hydrogenation to arabitol.The main drawback of this reaction is the formation of deoxy products. Aqueous solutions (20 wt. %) of arabinonic acid were hydrogenated on Rucatalysts in batch reactor. The selectivity was enhanced by adding small amounts of anthraquinone-2-sulfonate (A2S), which decreased the formation of deoxy by-products.
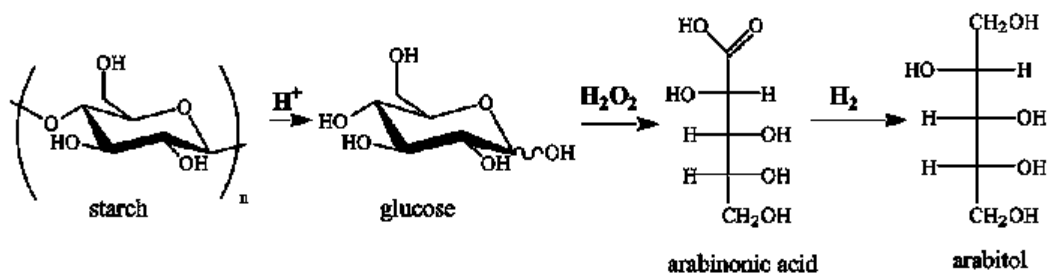

Fig. 15.10.   Oxidative decarboxylation of glucose

Dehydroxylation of carbohydrates

Deoxyhexitols consisting of C6 diols, triols, and tetrols are well suited to replace polyols derived from petrochemistry for applications in polyester and polyurethane manufacture. Sorbitol was taken as model molecule to study the hydrogenolysis to C4–C6 products. To improve the selectivity to deoxyhexitols, catalysts and reaction temperature were optimized to favor the rupture of C–OH bonds (dehydroxylation reactions) rather than C–C bond

rupture. Copper-based catalysts, which have a low activity for hydrogenolysis of C–C bonds, were employed to treat 20 wt.% aqueous sorbitol solutions in the temperature range of 180–240 8C. In contrast, operating in the presence of palladium catalysts at 250 ^{0}C under 80 bar of hydrogen pressure, cyclodehydration reactions of sorbitol and mannitol occurred with formation of cyclic ethers: isosorbide, 2,5-anhydromannitol, 2,5-anhydroiditol, and 1,4-anhydrosorbitol .

Catalytic oxidation of mono- and di-saccharides

Oxidation reactions are widely used for upgrading carbohydrates to varieties of high added value chemicals used in detergents or pharmaceuticals (Vitamin C). To replace the non-green hypochlorite agent by environmentaly friendly reagents, the catalytic system was improved. Oxidation reactions with H_2O_2 mediated by metal phthalocyanine catalysts have also proved very efficient to oxidize various carbohydrates including the oxidation of insoluble substrates such as native starch.
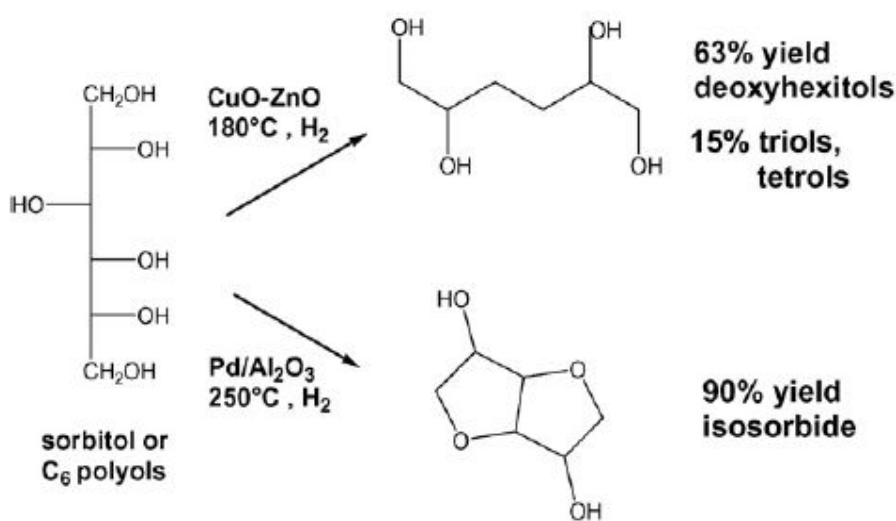

Fig. 15.11.   Hydrogenolysis of sorbitol to C_6 polyols

Glucose oxidation to gluconic acid, a biodegradable chelating agent and an intermediate in food and pharmaceutical industry, was achieved with air oxidation in the presence of palladium catalysts. Unpromoted palladium catalysts were active in glucose oxidation, but the rate of reaction was low because of the over-oxidation of Pd-surface, and side oxidation reactions decreased the selectivity. Using Pd–Bi/C catalysts (5 wt.% Pd, Bi/Pd = 0.1)

prepared by deposition of bismuth on the surface of 1–2 nm palladium particles, the rate of glucose oxidation to gluconate was 20 times higher and the selectivity at near total conversion was high on the fresh and recycled catalysts. Bismuth was assumed to act as a cocatalyst protecting palladium from over-oxidation because of its stronger affinity for oxygen. The metal-catalyzed oxidation gave comparable selectivity and higher productivity than enzymatic glucose oxidation.

Catalytic Conversion of Polysaccharides

Polysaccharides are widely available renewable polymers but it is difficult to find cost effective process to convert them to valuable end-products. Due to its large availability and low cost, native starch has been used for a long time in the preparation of different end-products.

To meet specific hydrophilic properties native starch has been either modified by oxidation or by grafting hydrocarbon chains .Hydrophilic starch obtained by partial oxidation is widely used in paper and textile industries and can be potentially applied in a variety of applications, e.g., for the preparation of paints, cosmetics, and super absorbents. The oxidation occurs at the C6 primary hydroxyl group or at the vicinal diols on C2 and C3 involving a cleavage of the C2–C3 bond to give carbonyl and carboxyl functions.
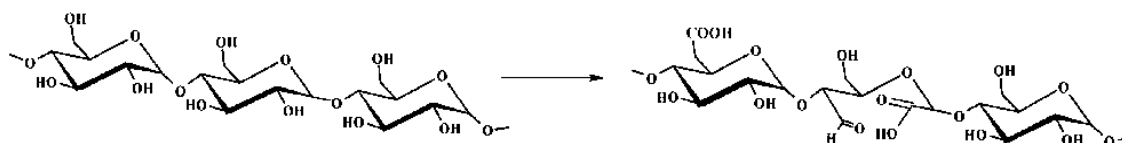

Fig. 15.12. Hydrophilic starch obtained by partial oxidation

Several transition metal catalysts based on Fe, Cu or W salts (0.01–0.1 mol%) have been proposed to activate H_2O_2, which is a well-suited oxidant from an environmental and economical point of view. However, the concentration of metal ions was quite high and heavy metals were retained by the carboxyl functions of oxidized starch, which has good complexing properties. Efficient catalytic methods for native starch oxidation withH_2O_2 in the presence of iron tetrasulfophthalocyanine (FePcS) were proposed .Oxidation of starch aqueous suspension in the presence of iron phthalocyanine gives both carboxylic and carbonyl groups.

To prepare more hydrophobic starches for specific applications, partial substitution of starch with acetate, hydroxypropyl, alkylsiliconate or fatty-acid ester groups were described in the literature. This can also be achieved by grafting octadienyl chains by butadiene telomerization.
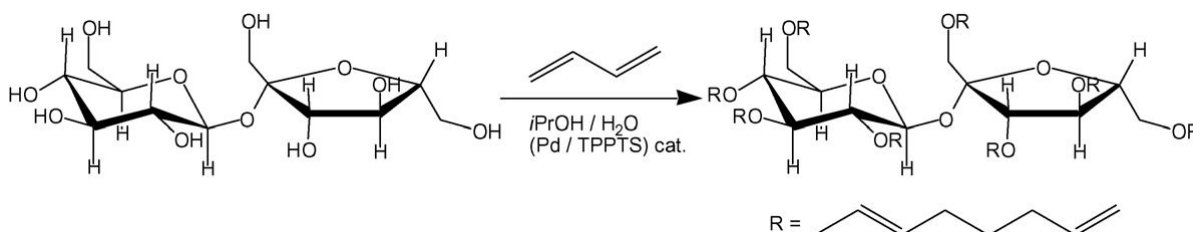

Fig. 15.13. Grafting of octadienyl chains on sucrose through butadiene telomerization

The reaction was first conducted with success on sucrose. The degree of substitution (DS) obtained was controlled by the reaction time. Thus under standard conditions (0.05% Pd(OAc)2/TPPTS, NaOH (1N)/iPrOH (5/1), 50 8C) the DS was 0.5 and 5 after 14 and 64 h reaction time, respectively. The octadienyl chains were hydrogenated quantitatively in the presence of 0.8 wt.% [RhCl(TPPTS)3] catalyst in H2O/EtOH (50/10) mixture yielding a very good biodegradable surfactant.

REFERENCES:

1. www.wikipedia.org

2. www. users.rcn.com/jkimball.ma.ultranet/BiologyPages/C/Carbohydrates

3. www.biochemweb.org/fenteany/teaching/452/Carbohydrates.pdf

4. P.A. Jacobs, H. Hinnekens, EP 0 329 923 for Synfina-Oleofina

5. M.L. Ribeiro, U. Schuchardt, *Catal. Commun.*, 4 (2003) 83

6. A. Perrard, P. Gallezot, in: J. Sowa (Ed.), *Catalysis of Organic Reactions*, Taylor & Francis, New York, 2005, p. 53.

7. L. Fabre, P. Gallezot, A. Perrard, *J. Catal.,* 208 (2002) 247

8. B. Blanc, A. Bourrel, P. Gallezot, T. Haas, P. Taylor, *Green Chem.,* 89 (2000)

9. M. Besson, F. Lahmer, P. Gallezot, P. Fuertes, G. Fle`che, *J. Catal.* , 152 (1999) 116

10. A. Sorokin, S. Kachkarova-Sorokina, C. Donze´, C. Pinel, P. Gallezot, *Top. Catal.*, 27 (2004) 67

11. A. Sorokin, S. Sorokina, P. Gallezot, *Chem. Commun.*, 2004, 2844

12. C. Donze´, C. Pinel, P. Gallezot, P. Taylor, *Adv. Synth. Catal.,* 344 (2002) 906

Chapter - 16

SOME CONCEPTUAL DEVELOPMENTS IN SYNTHESIS IN CHEMISTRY

Joyce DSouza

INTRODUCTION

Synthesis of materials play a crucial role in designing and discovering new materials and also in providing better and less cumbersome methods for preparing known chemicals. Most of the ten million or so chemical compounds that are known today, can be classified into a relatively small number of subgroups or families.

More than 90 percent of the compounds are organic compounds. In turn, organic compounds can be further subdivided into a few dozen major families such as the alkanes, alkenes, alkynes, alcohols, aldehydes, ketones, carboxylic acids, and amines. An important subset of organic compounds include biochemical compounds with four major families: carbohydrates, proteins, nucleic acids, and lipids.

Because of their unique properties, multi-carbon compounds exhibit extremely large variety and the range of application of organic compounds is enormous. They form the basis of important constituents of many products and apart from a very few exceptions, they form the basis of all earthly life processes. The different shapes and chemical reactivities of organic molecules provide an astonishing variety of functions, like those of enzyme catalysts in biochemical reactions of live systems. The autopropagating nature of these organic chemicals is what life is all about. Products such as plastics, synthetic fibres,food, explosives, paints and pigments, pharmaceuticals and pesticides and many others have become readily available through the dynamic development of organic synthesis.

Inorganic compounds are typically classified into one of five major groups: acids, bases, salts, oxides, and others. A large class of compounds discussed in inorganic chemistry textbooks are coordination compounds. Examples range from species that are strictly inorganic, such as $[Co(NH_3)_6]Cl_3$, to organometallic compounds such as $Fe(C_5H_5)_2$ (ferrocene)and extending to bioinorganic compounds, such as the hydrogenase enzymes. Major classes of inorganic compounds that are studied under materials science tend to be polymeric (non-molecular) and refractory, and often are of commercial interest

such as a)alloys: brass, bronze, stainless steel; b)semiconductors : silicon , gallium arsenide; c)superconductors : yttrium barium copper oxide .

SYNTHETIC ORGANIC CHEMISTRY

Synthetic organic chemistry is an applied science as it borders engineering involving design, analysis, and/or construction of work for practical purposes. Organic synthesis of a novel compound is a problem solving task, where a synthesis is designed for a target molecule by selecting optimal reactions from optimal starting materials. Complex compounds can have several reaction steps that sequentially build the desired molecule. The synthesis proceeds by utilizing the reactivity of the functional groups in the molecule. For example, a carbonyl compound can be used as a nucleophile by converting it into an enolate, or as an electrophile, and the combination of the two is called the aldol reaction. Designing practically useful syntheses always requires conducting the actual synthesis in the laboratory. The scientific practice of creating novel synthetic routes for complex molecules is called total synthesis.

There are several strategies to design a synthesis. The modern method of retrosynthesis, developed by E.J. Corey, starts with the target molecule and splices it to pieces according to known reactions. The pieces, or the proposed precursors, are further spliced until   ideally inexpensive and available starting materials are reached. Then, the retrosynthesis is written in the opposite direction to give the synthesis. A "synthetic tree" can be constructed, because each compound and also each precursor have multiple syntheses.

Retrosynthetic Analysis

Disconnection: A retrosynthetic step involving the breaking of a bond to form two (or more) synthons.

Synthon   Synthetic equivalent
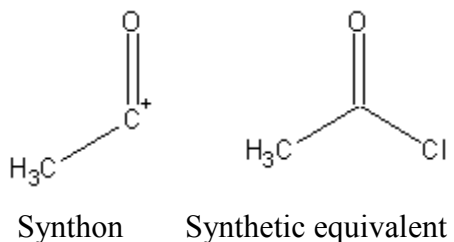
Retron: A minimal molecular substructure that enables certain transformations.

Retrosynthetic tree: A directed acyclic graph of several (or all) possible retrosyntheses of a single target.

Synthon: An idealized molecular fragment. A synthon and the corresponding commercially available synthetic equivalent are shown below:

Target: The desired final compound.

Transform: The exact reverse of a synthetic reaction; the formation of starting materials from a single product.

An example will allow the concept of retrosynthetic analysis to be easily understood.
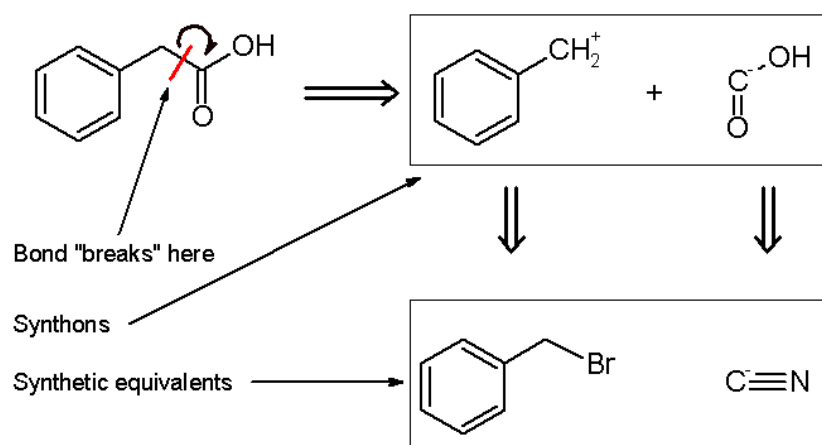
In planning the synthesis of phenylacetic acid, two synthons are identified. A nucleophilic "-COOH" group, and an electrophilic "$PhCH_2^+$" group. Of course, both synthons do not exist per se; synthetic equivalents corresponding to the synthons are reacted to produce the desired product. In this case, the cyanide anion is the synthetic equivalent for the $^-$COOH synthon, while benzyl bromide is the synthetic equivalent for the benzyl synthon.

The synthesis of phenylacetylene determined by retrosynthetic analysis is thus:

1. $PhCH_2Br + NaCN \rightarrow PhCH_2CN + NaBr$

2. $PhCH_2CN + 2\ H2O \rightarrow PhCH_2COOH + NH_3$
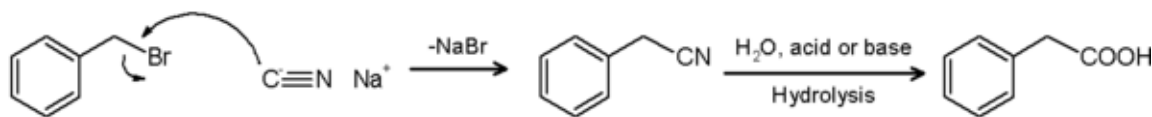
STRATEGIES

Functional Group Strategies: Manipulation of functional groups can lead to significant reductions in molecular complexity.

Stereochemical Strategies: Numerous chemical targets have distinct stereochemical demands. Stereochemical transformations (such as the Claisen rearrangement and Mitsunobu reaction) can remove or transfer the desired chirality thus simplifying the target.

Structure-Goal Strategies: Directing a synthesis towards a desirable intermediate can greatly narrow the focus of an analysis. This allows bidirectional search techniques.

Transform-based Strategies: The application of transformations to retrosynthetic analysis can lead to powerful reductions in molecular complexity. Unfortunately, powerful transform-based retrons are rarely present in complex molecules, and additional synthetic steps are often needed to establish their presence.

Topological Strategies: The identification of one or more key bond disconnections may lead to the identification of key substructures : Disconnections that preserve ring structures are encouraged; Disconnections that create rings larger than 7 members are discouraged.

SYNTHETIC INORGANIC CHEMISTRY

Advances in inorganic chemistry have made significant contributions to modern living. For instance, synthetic fertilizers manufactured from inorganic chemicals have increased worldwide crop production. Inorganic substances used to fabricate silicon chips help power the global information age. Metal alloys are used in automobiles and aircraft to make them lighter and stronger. Companies use inorganic compounds to fabricate concrete, steel, and glass—materials used to construct buildings, infrastructure, and other public works around the world. In the United States, 10 of the 11 most commonly produced chemicals are derived from inorganic elements. These 10 inorganic chemicals (presented below in descending order of production) are used in a wide variety of applications. Sulfuric acid is used to make fertilizers, synthetic fibers, and metals.

Nitrogen is used in recovering underground petroleum deposits, in the production of ammonia, and as a blanketing material for shipping perishables such as fruits and vegetables. Oxygen is used in the production of steel and plastics, in medical applications, and in rocketry. Lime is used in the manufacture of steel and cement. Ammonia is combined with sulfuric acid to make ammonium sulfate the most important of the synthetic fertilizers. Sodium hydroxide is used in the manufacture of paper, soap, detergents, and synthetic fibers, and is also a caustic material used as a drain cleaner. Chlorine is used to manufacture vinyl chloride plastic, to disinfect drinking water, and to bleach paper during manufacturing. Phosphoric acid is used to give soft drinks a tart flavor and to make fertilizers. Sodium carbonate is used in the production of glass, paper, and textiles. Nitric acid is used to make synthetic fibers, such as nylon; explosives, such as nitroglycerin and TNT (trinitrotoluene); and is also combined with ammonia to make fertilizer.

Because of its direct relevance to products of commerce, solid state inorganic chemistry has been strongly driven by technology. Applications discovered in the 20th century include zeolite and platinum-based catalysts for petroleum processing in the 1950's, high-purity silicon as a core component of microelectronic devices in the 1960's, and "high temperature" superconductivity in the 1980's. The invention of X-ray crystallography in the early 1900s by William Lawrence Bragg enabled further innovation. Although some inorganic species can be obtained in pure form from nature, most are synthesized in chemical plants and in the laboratory.

There is much chemical ingenuity in the synthesis of solid materials. While tailor-making of materials of the desired structure and properties remains the main goal of solid state chemistry and material science, it is not always possible. However, a rational approach to the synthesis of solids may be evolved which requires an understanding of the principles of crystal chemistry, and of thermodynamics, phase equilibria and reaction kinetics.
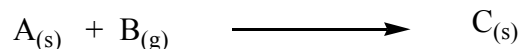
Synthetic Strategies

Various types of chemical reactions have been used for the synthesis of solid materials. Some of common reactions employed for the synthesis inorganic solids are listed below:
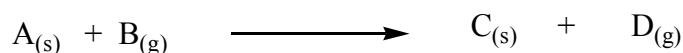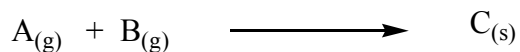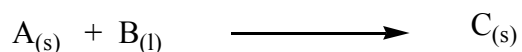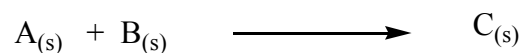
(1) decomposition

$$A_{(s)} \longrightarrow B_{(s)} + C_{(g)}$$

(2) combination

$$A_{(s)} + B_{(g)} \longrightarrow C_{(s)}$$
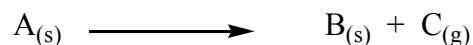
(3) metathetic [combining (1) and (2) above]

$$A_{(s)} + B_{(g)} \longrightarrow C_{(s)} + D_{(g)}$$

(4) addition

$$A_{(s)} + B_{(s)} \longrightarrow C_{(s)}$$

$$A_{(s)} + B_{(l)} \longrightarrow C_{(s)}$$

$$A_{(g)} + B_{(g)} \longrightarrow C_{(s)}$$

(5) exchange

$$AX_{(s)} + BY_{(s)} \longrightarrow AY_{(s)} + BX_{(s)}$$

$$AX_{(s)} + BY_{(g)} \longrightarrow AY_{(s)} + BX_{(g)}$$
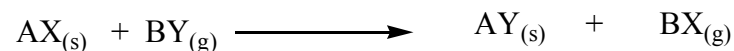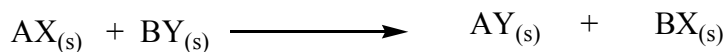
More complex reactions involving more than one type of reaction are also commonly employed in solid state synthesis. For example, in the preparation of complex oxides, it is common to carry out thermal decomposition of a compound followed by oxidation (in air or O_2) essentially in one step:

$$2Ca_{0.5}Mn_{0.5}CO_{(s)} + 1/2\ O_2(g) \longrightarrow CaMnO_3(s) + 2CO_2(g)$$

$$MgO(s) + Cr_2O_3(s) \xrightarrow{\ O_2\ } MgCr_2O_4(s)$$
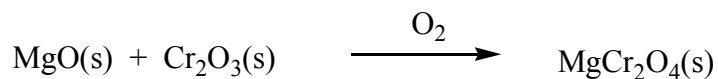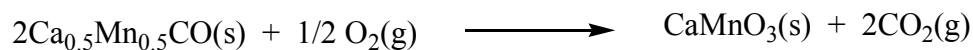
Specific reagents and reaction conditions are employed to carry out various processes such as reduction, oxidation and halogenation in the synthesis of solids.

Reduction of oxides, for instance, may be carried out

- in an atmosphere of (flowing) pure or dilute hydrogen or CO.
- by heating oxides in argon or nitrogen for the purpose of lowering the oxygen content
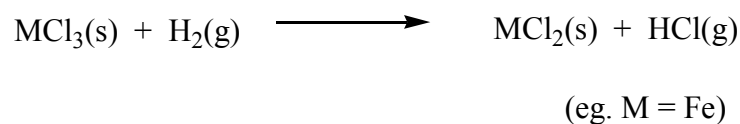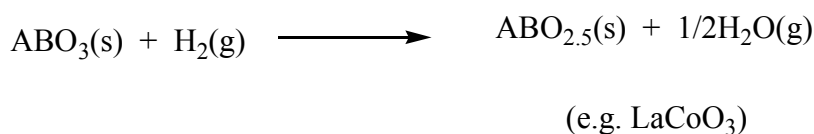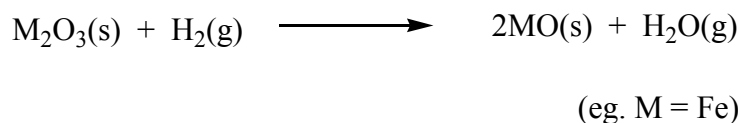- by application of vacuum at an appropriate temperature (vacuum annealing or decomposition at low pressures)

The obvious means of reducing solid compounds by hydrogen is employed not only for reducing oxides, but also halides and other compounds. Thermal decomposition of metal halides also yields lower halides:

$$M_2O_3(s) + H_2(g) \longrightarrow 2MO(s) + H_2O(g)$$

$$(eg. \ M = Fe)$$

$$ABO_3(s) + H_2(g) \longrightarrow ABO_{2.5}(s) + 1/2H_2O(g)$$

$$(e.g. \ LaCoO_3)$$

$$MCl_3(s) + H_2(g) \longrightarrow MCl_2(s) + HCl(g)$$

$$(eg. \ M = Fe)$$

$$MX_3 \xrightarrow{\text{heat}} MX_2 + 1/2X_2 \quad (eg. \ M = Fe)$$

Reduction of oxides and halides can also be accomplished by reacting with elemental carbon or with a metal.

$$2MCl_3 + M \longrightarrow 3MCl_2 \quad (e.g. \ M = Nd, Fe)$$

$$3MCl_4 + M'(s) \longrightarrow 3MCl_3(s) + M'Cl_3(g)$$

$$(e.g. \ M = Hf, M' = Al)$$

$$M_2O_3 + 3M \longrightarrow 5MO \quad (e.g. \ M = Nb)$$
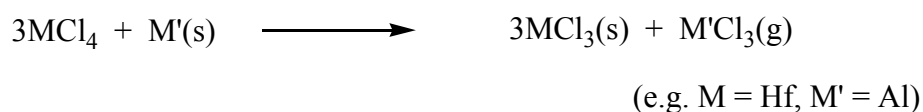
Inorganic Synthetic Methods

Inorganic synthetic methods can be classified roughly according to the volatility or solubility of the component reactants. Soluble inorganic compounds are prepared using the methods of organic synthesis.

Techniques employed in Inorganic synthesis

Oven techniques: For thermally robust materials, high temperature methods are often employed. For example, bulk solids are prepared using tubular furnaces, which allow reactions to be conducted up to ca. 1100 °C. Special equipment e.g. ovens consisting of a tantalum tube through which an electric current is passed, can be used for even higher temperatures up to 2000 °C.

Melt methods: If volatile reactants are involved, the reactants are often put in an ampoule that is evacuated and then sealed. The sealed ampoule is then put in an oven and given a certain heat treatment to melt the reactants together and then later anneal the solidified melt.

Solution methods: Solvents are used to prepare solids by precipitation or by evaporation. At times the solvent is used hydrothermally, i.e. under pressure at temperatures higher than the normal boiling point. A variation on this theme is the use of flux methods, where a salt of relatively low melting point is added to the mixture to act as a high temperature solvent in which the desired reaction can take place.

Gas reactions: Many solids react readily with reactive gases like chlorine, iodine, oxygen etc. Others form adducts with gases like CO or ethylene. Such reactions are often carried out in a tube that is open ended on both sides and through which the gas is passed

A special case of a gas reaction is a chemical transport reaction which entails the reversible conversion of nonvolatile chemical compounds into volatile derivatives. This method may also be used as a process for purification and crystallization of non-volatile solids. These are often carried out in a sealed ampoule to which a small amount of a transport agent, e.g. iodine is added. The ampoule is then placed in a zone oven. This is essentially two tube ovens attached to each other which allows a temperature gradient to be imposed. The volatile derivative migrates through a sealed, evacuated glass tube heated in a tubular furnace. Elsewhere in the tube where the temperature is held at a different value, the volatile derivative reverts to the parent solid and the transport agent is released. The transport agent is thus catalytic. The technique requires that the two ends of

tube be maintained at different temperatures. Such a method can be used to obtain the product in the form of single crystals suitable for structure determination by X-ray diffraction.

Air and moisture sensitive materials: Many solids are hygroscopic and/or oxygen sensitive. Many halides e.g. are very 'thirsty' and can only be studied in their anhydrous form if they are handled in a glove box filled with dry (and/or oxygen-free) gas, usually nitrogen.

Synthetic Methods

A large variety of inorganic solid materials has been prepared in recent years by traditional ceramic method, which involves mixing and grinding powders of the constituent oxides, carbonates and such compounds and heating them at high temperatures with intermediate grinding when necessary. The low-temperature chemical routes, however, are of greater interest so as to have better control of the structure, stoichiometry and phase purity. Noteworthy chemical methods of synthesis include the precursor method, coprecipitation, combustion method, the gel method, topochemical methods and high-pressure methods. Some of the methods are outlined below.

1. Ceramic Method

The most common method of preparing solid materials is by reaction of the component materials in the solid state at elevated temperatures. Several oxides, sulphides, phosphides, have been prepared by this method. Knowledge of the phase diagram is generally helpful in fixing the desired composition and conditions for synthesis. Platinum, silica and alumina containers are generally used for the synthesis of metal oxides, while graphite containers are employed for sulphides and other chalcogenides as well as pnictides. If one of the constituents is volatile or sensitive to the atmosphere, the reaction is carried out in sealed evacuated capsules. Most ceramic preparations require relatively high temperatures which are generally attained by resistance heating. Electric arc and skull techniques give temperatures up to 3300 K while high- power CO_2 lasers give temperatures up to 4300 K.

The ceramic method suffers from several disadvantages. They are:

      1. When no melt is formed during the reaction, the entire reaction has to occur in the solid state, initially by a phase boundary reaction at the points of contact between the

components and later by diffusion of the constituents through the product phase. As the reaction progresses, diffusion paths become increasingly longer and the reaction rate slower. The product interface between the reacting particles acts as a barrier. The reaction can be speeded up to some extent by intermittent grinding between heating cycles.

2. There is no simple way of monitoring the progress of the reaction in the ceramic method. It is only by trial and error (by carrying out X-ray diffraction and other measurements periodically) that one decides on appropriate conditions that lead to completion of the reaction. Because of this difficulty, one frequently ends up with mixtures of reactants and products.

3. Separation of the desired product from these mixtures is generally difficult, if not impossible.

4. It is sometimes difficult to obtain a compositionally homogeneous product by the ceramic technique, even when the reaction proceeds almost to completion.

In spite of such limitations, ceramic techniques have been widely used for the synthesis of solid materials. Mention must be made, among others, of the use of this technique for the synthesis of rare earth mono-chalcogenides such as SmS and SmSe. The method involves heating the elements, first at lower temperatures (870-1170 K) in evacuated silica tubes; the contents are then homogenized, sealed in tantalum tubes and heated to around 2300 K.

Various modifications of the ceramic technique have been employed to overcome some of the limitations. One of these relates to decreasing the diffusion path lengths. In a polycrystalline mixture of reactants, the individual particles are approximately 10 μm in size, representing diffusion distances of roughly 10,000 unit cells. By using freeze-drying, spray-drying, coprecipitation, and sol-gel and other techniques, it is possible to reduce the particle size to a few hundred ångströms and thus effect a more intimate mixing of the reactants.

In spray-drying, suitable constituents dissolved in a solvent are sprayed in the form of fine droplets into a hot chamber. The solvent evaporates instantaneously, leaving behind an intimate mixture of reactants, which on heating at elevated temperatures gives the product.

In freeze-drying, reactants in a common solvent are frozen by immersing in liquid nitrogen and the solvent is removed at low pressures.
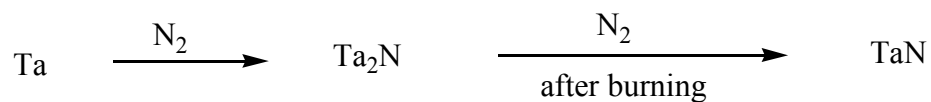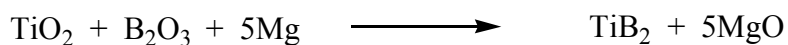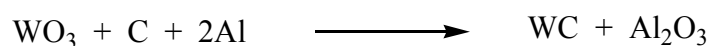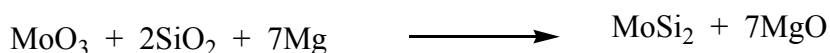
In coprecipitation, the required metal cations taken as soluble salts (e.g. nitrates) are coprecipitated from a common medium, usually as hydroxides, carbonates, oxalates, formats or citrates. In actual practice, one takes oxides or carbonates of the relevant metals, digests them with an acid (usually HNO_3) and then the precipitating reagent is added. After filtering the precipitate and drying, it is heated to the required temperature in a desired atmosphere to produce the final product. For example, tetraethylammonium oxalate has been used to prepare superconducting $YBa_2Cu_4O_8$. The decomposition temperatures of the precipitates are generally lower than the temperatures employed in the ceramic method.

2. Combustion Method

Combustion synthesis or self-propagating high-temperature synthesis makes use of a highly exothermic reaction between the reactants to produce a flame due to spontaneous combustion which then yields the desired product or its precursor in finely divided form. Borides, carbides, oxides, chalcogenides and other metal derivatives have been prepared by this method. In order for combustion to occur, one has to ensure that the initial mixture of reactants is highly dispersed and has high chemical energy. For example, one may add a fuel and an oxidizer when preparing oxides by the combustion method, both these additives being removed during combustion to yield only the product or its precursor. Thus, one can take a mixture of nitrates (oxidizer) of the desired metals along with a fuel (e.g. hydrazine, glycine or urea) in solution, evaporate the solution to dryness and heat the resulting solid to around 423 K to obtain spontaneous combustion, yielding an oxidic product in fine particulate form. Even if the desired product is not formed immediately after combustion, the fine particulate nature of the product facilitates its formation on further heating. In order to carry out combustion synthesis, the powdered mixture of reactants (0.1-100 μm particle size) is generally placed in an appropriate gas medium which favours an exothermic reaction on ignition. The combustion temperature is anywhere between 1500 and 3500 K, depending on the reaction. The advantages of this method are that

- reaction times are very short since the desired product results soon after the combustion.
- a gas medium is not always necessary.

This is so in the synthesis of borides, silicides and carbides where the elements are quite stable at high temperatures. Combustion in a nitrogen atmosphere yields nitrides. Nitrides of various metals have been prepared in this manner. Azides have been used as sources of nitrogen. The following are some typical combustion reactions:

$$MoO_3 + 2SiO_2 + 7Mg \longrightarrow MoSi_2 + 7MgO$$

$$WO_3 + C + 2Al \longrightarrow WC + Al_2O_3$$

$$TiO_2 + B_2O_3 + 5Mg \longrightarrow TiB_2 + 5MgO$$

$$Ta \xrightarrow{N_2} Ta_2N \xrightarrow[\text{after burning}]{N_2} TaN$$

Most of the ternary or quaternary oxides can also be prepared by this method. All the superconducting cuprates have been prepared by this method, although the resulting products in fine particulate form have to be heated to an appropriate high temperature in a desired atmosphere to obtain the final cuprate. Table 16.1 lists typical materials prepared by the combustion method.

Table 1. Typical materials prepared by the Combustion method

Oxides	$BaTiO_3$, $LiNbO_3$, $PbMoO_4$
Carbides	TiC, Mo_2C, NbC
Borides	TiB_2, CrB_2, MoB_2, FeB
Silicides	$MoSi_2$, $TiSi_2$, $ZrSi_2$
Phosphides	NbP, MnP, TiP
Chalcogenides	WS_2, MoS_2, $MoSe_2$, TaS_2
Hydrides	TiH_2, NdH_2

3. Precursor Method

Synthesis of complex oxides by the decomposition of compound precursors has been known for some time. For example, thermal decomposition of $LaCo(CN)_6.5H_2O$ and $LaFe(CN)_6.6H_2O$ in air readily yields $LaCoO_3$ and $LaFeO_3$ respectively. $BaTiO_3$ can be prepared by the thermal decomposition of $Ba[TiO(C_2O_4)_2]$, while $LiCrO_2$ can be prepared from $Li[Cr(C_2O_4)_2(H_2O)_2]$. Ferrite spinels of the general formula MFe_2O_4 (M-Mg, Mn, Ni, Co) are prepared by the thermal decomposition of acetate precursors of the type $M_3Fe_6(CH_3COO)_{17}O_3OH.12C_5H_5N$. Chromites of type MCr_2O_4 are obtained by the decomposition of $(NH_4)2M(CrO_4)_2.6H_2O$. Carbonates of metals such as calcium, magnesium, manganese, iron, cobalt, zinc and cadmium are all iso-structural, possessing the calcite structure. We can therefore prepare a large number of carbonate solid solutions containing two or more cations in different proportions.

Carbonate solid solutions are ideal precursors for the synthesis of monoxide solid solutions of rock-salt structure. The facile formation of rock-salt oxides by the decomposition of carbonates of calcite structure is due to the close (possible topotactic) relationship between the structures of calcite and rock-salt. The monoxide solid solutions can be used as precursors for preparing spinels and other complex oxides. Besides monoxide solid solutions, a number of ternary and quaternary oxides of novel structures

can be prepared by decomposing carbonate precursors containing the different cations in the required proportions. A number of ternary and quaternary metal oxides of perovskite and related structures can be prepared by employing hydroxide, nitrate and cyanide solid solution precursors as well.

4. Topochemical Reactions

A solid state reaction is said to be topochemically controlled when the reactivity is controlled by the crystal structure rather than by the chemical nature of the constituents. The products obtained in many solid state decompositions are determined by topochemical factors, especially when the reaction occurs within the solid without the separation of a new phase. In topotactic solid state reactions, the atomic arrangement in the reactant crystal remains largely unaffected during the course of the reaction, except for changes in dimension in one or more directions. Dehydration of $WO_3.H_2O$ or $MoO_3.H_2O$ to give WO_3 or MoO_3 is one such reaction. Dehydration of many other hydrates such as $VOPO_4.2H_2O$ and $HMoO_2PO_4.H_2O$ is also found to be topotactic. Intercalation reactions are generally topotactic in nature. Decomposition of V_2O_5 to form V_6O_{13} is a similar reaction. The reduction of NiO to nickel metal proceeds topochemically.

a) Dehydration of $Mo_{1-x}W_xO_3.H_2O$

$Mo_{1-x}W_xO_3$ solid solutions can be prepared by the ceramic method (by heating MoO_3 and WO_3 in sealed tubes at around 870 K) or by the thermal decomposition of mixed ammonium metallates. These methods, however, do not always yield monophasic products owing to the difference in volatilities of MoO_3 and WO_3. Therefore, it was sought to prepare $Mo_{1-x}W_xO_3$ by topochemical dehydration of the hydrates, the process being very gentle. $MoO_3.H_2O$ and $WO_3.H_2O$ are isostructural and the solid solutions between the two hydrates are prepared readily by adding a solution of MoO_3 and WO_3 in ammonia to hot 6M HNO_3. The hydrates $Mo_{1-x}W_xO_3.H_2O$ crystallize in the same structure as $MoO_3.H_2O$ and $WO_3.H_2O$ with a monoclinic unit cell. The hydrate solid solutions undergo dehydration under mild conditions (around 500 K) yielding $Mo_{1-x}W_xO_3$ which crystallizes in the ReO_3-related structure of WO_3. The ReO_3 structure of MoO_3 is metastable and is produced only by topotactic dehydration under mild conditions. This preparation of ReO_3-1ike MoO_3 by mild chemical processing is

significant. Bulk quantities of MoO_3 in the ReO_3 structure have been prepared by mild dehydration of the hydrate.

   b)Reduction of perovskite oxides

Reduction of the high temperature superconductor $YBa_2Cu_3O_7$ to YBa_2CuO_6 (Fig. 16.7) is a topochemical process.
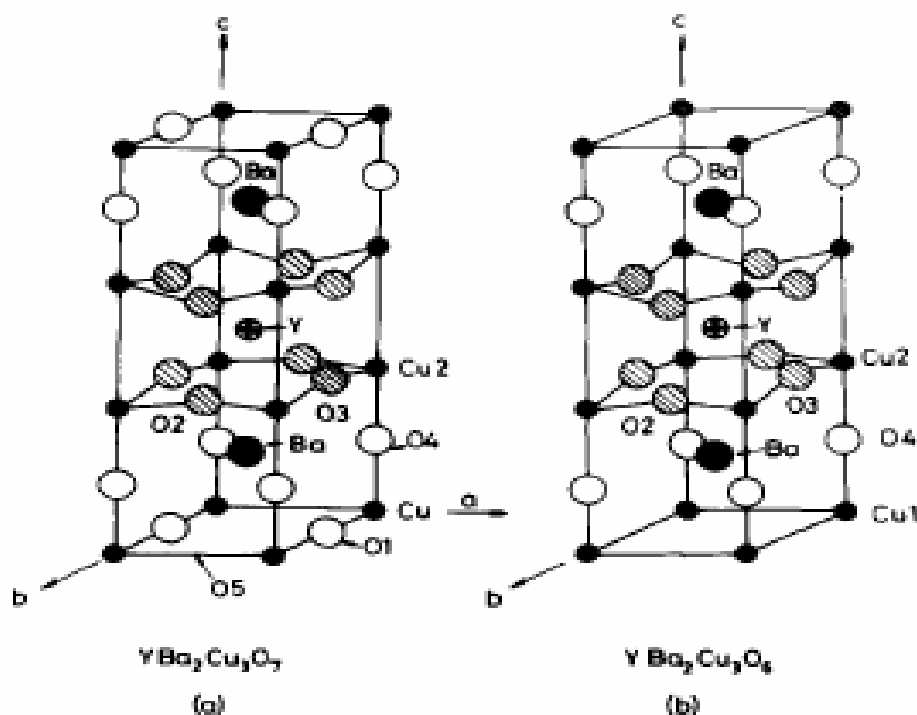
Fig. 7. Structures of $YBa_2Cu_3O_7$ and $YBa_2Cu_3O_6$.

5. Intercalation Compounds

Intercalation reactions of solids involve the insertion of a guest species (ion or molecule) into a solid host lattice without any major rearrangement of the solid structure:

x(guest) + □ $_x$[host] $\rightleftharpoons$ (guest)$_x$[host]
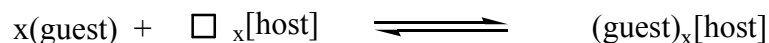
   where   □   stands for a vacant lattice site.

Tungsten and molybdenum bronzes, A_xWO_3 and A_xMoO_3 (A=K, Rb, Cs) are generally prepared by reaction of the alkali metals with the host oxide. Electrochemical methods are also employed for these preparations. A novel reaction that has been employed to prepare bronzes which are otherwise difficult to obtain involves the reaction of oxide host with anhydrous alkali iodides:

$$Mo_{1-x}W_xO_3 \quad + \quad y(AI) \quad \rightarrow \quad A_y.Mo_{1-x}W_xO_3 \quad + \quad y/2 \ I_2$$
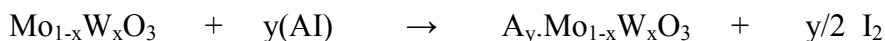
Atomic hydrogen has been inserted into many binary and ternary oxides. Recently, iodine has been intercalated into the superconducting cuprate, $Bi_2CaSr_2Cu_2O_8$, causing an expansion of the c-parameter of the unit cell, without destroying the superconductivity.

6. Sol-gel Method

The sol-gel method is a wet chemical method and a multi-step process involving both chemical and physical processes such as hydrolysis, polymerization, drying and densification. The name "sol-gel" is given to the process because of the distinctive increase in viscosity which occurs at a particular point in the sequence of steps. A sudden increase in viscosity is the common feature in sol-gel processing, indicating the onset of gel formation. In the sol-gel process, synthesis of inorganic oxides is achieved from inorganic or organometallic precursors (generally metal alkoxides). The important features of the sol-gel techniques are better homogeneity compared with the traditional ceramic method, high purity, lower processing temperature, more uniform phase distribution in multicomponent systems, better size and morphological control, the possibility of preparing new crystalline and non-crystalline materials, and lastly easy preparation of thin films and coatings. The sol-gel method is widely used in ceramic technology. The important steps in sol-gel synthesis are:

Hydrolysis. The process of hydrolysis may start with a mixture of a metal alkoxide and water in a solvent (usually alcohol) at the ambient or a slightly elevated temperature. Acid or base catalysts are added to speed up the reaction.

Polymerization. This step involves condensation of adjacent molecules wherein H_2O and ROH are eliminated and metal oxide linkages are formed. Polymeric networks grow to colloidal dimensions in the liquid (sol) state.

Gelation. In this step, the polymeric networks link up to form a three-dimensional network throughout the liquid. The system becomes somewhat rigid, characteristic of a gel. The solvent as well as water and alcohol remain inside the pores of the gel. Aggregation of smaller polymeric units to the main network continues progressively on aging the gel.

<u>Drying.</u> Here, water and alcohol are removed at a moderate temperature (less than 470 K), leaving a hydroxylated metal oxide with residual organic content. If the objective is to prepare a high surface area of aerogel powder with low bulk density, the solvent is removed supercritically.

<u>Dehydration.</u> This step is carried out between 670 and 1070 K to drive off the organic residues and chemically bound water, yielding a metal oxide with up to 20%-30% microporosity.

<u>Densification.</u> Temperatures in excess of 1270 K are used to form the dense oxide product.

Many complex metal oxides are prepared by a modified sol-gel route without actually preparing metal alkoxides. For example, a transition metal salt solution is converted into a gel by the addition of an appropriate organic reagent. In the case of cuprate superconductors, an equimolar proportion of citric acid is added to the solution of metal nitrates, followed by ethylene diamine until the solution attains a pH of 6-6.5. The blue sol is concentrated to obtain the gel. The xerogel is obtained by heating at approximately 420 K. The xerogel is decomposed at an appropriate temperature to obtain the cuprate.

The sol-gel technique has been used to prepare sub-micrometre metal oxide powders with a narrow particle size distribution and unique particle shapes (e.g. Al_2O_3, TiO_2, ZrO_2, Fe_2O_3). Uniform SiO_2 spheres have been grown from aqueous solutions of colloidal SiO_2. Small metal clusters (e.g. nickel, copper, gold) have been prepared by in situ chemical reduction of metal salts. Metal-ceramic composites (e.g.$Ni-Al_2O_3$, $Pt-ZrO_2$) can also be prepared in this manner. By employing several variants of the basic sol-gel technique, a number of multicomponent oxide systems have been prepared. Typical of these are: $SiO_2-B_2O_3$, SiO_2-TiO_2, SiO_2-ZrO_2, $SiO_2-Al_2O_3$, ThO_2-UO_2 . A variety of ternary and still more complex oxides have been prepared by this technique. Different types of cuprate superconductors have also been prepared by this method. These include $YBa_2Cu_3O_7$, $YBa_2Cu_4O_8$, $Bi_2CaSr_2Cu_2O_8$ and $Pb_2Sr_2Ca_{1-x}Y_xCu_3O_8$.

6. Alkali Flux Method

The use of strong alkaline media, either in the form of solid fluxes or molten (or aqueous) solutions, has enabled the synthesis of novel oxides. The alkali flux method stabilizes higher oxidation states of the metal by providing an oxidizing atmosphere. Alkali

carbonate fluxes have traditionally been used to prepare transition metal oxides such as $LaNiO_3$. A good example of an oxide synthesized in a strongly alkaline medium is the pyrochlore, $Pb_2(Ru_{2-x}Pb_x)O_{7-y}$ where Pb is in the 4 + state; this oxide is a bifunctional electrocatalyst. The procedure for preparation involves bubbling oxygen through a solution of lead and rubidium salts in strong KOH at 320 K. The so-called alkaline hypochlorite method is used in many instances. For example, La_4NiO_{10} was prepared by bubbling Cl_2 gas through a NaOH solution of lanthanum and nickel nitrates.

$YBa_2Cu_4O_8$ has been prepared by using a Na_2CO_3-K_2CO_3 flux in a flowing oxygen atmosphere. KOH melt has been used to prepare superconducting $Ba_{1-x}K_xBiO_3$.

7. Electrochemical Method

Electrochemical methods have been employed to advantage for the synthesis of many solid materials. Typical of the materials prepared in this manner are metal borides, carbides, silicides, oxides and sulphides. Vanadate spinels of formula MV_2O_4 as well as tungsten bronzes have been prepared by the electrochemical route. Tungsten bronzes are obtained at the cathode when current is passed through two inert electrodes immersed in a molten solution of the alkali metal tungstate, A_2WO_4 and WO_3; oxygen is liberated at the anode. Blue molybdenum bronzes have been prepared by fused salt electrolysis. Mono-sulphides of uranium, gadolinium, thorium and other metals are obtained from a solution of the normal valent metal sulphide and chloride in an NaC1-KCI eutectic. LaB_6, is prepared by taking La_2O_3 and B_2O_3 in an $LiBO_2$-LiF melt and using gold electrodes. Crystalline transition metal phosphides are prepared from solutions of oxides with alkali metal phosphates and halides. Superconducting $Ba_{1-x}K_xBiO_3$ has been prepared electrochemically.

Although the electrochemical method is old, the processes involved in the synthesis of various solids are not entirely understood. Generally one uses solvents whose decomposition potentials are high (e.g. alkali metal phosphates, borates, fluorides, etc.). Changes in melt composition could cause limitations in certain instances.

8. High Pressure Methods

The use of high pressures for solid state synthesis has become increasingly common in recent years. With the development of high-pressure technology, commercial equipment permitting simultaneous use of both high-pressure and high-temperature conditions has

become available. For the 1-10 kbar pressure range, the hydrothermal method is often employed. In this method, the reaction is carried out either in an open or a closed system. In the open system, the solid is in direct contact with the reacting gas (F_2, O_2 or N_2) which also serves as a pressure intensifier. A gold container is generally used in this type of synthesis. This method has been used for the synthesis of transition metal compounds such as RhO_2, PtO_2 and Na_2NiF_6 where the transition metal is in a higher oxidation state. Hydrothermal high pressure synthesis under closed system conditions has been employed for the preparation of higher-valence metal oxides. An internal oxidant such as $KClO_3$ is added to the reactants, which on decomposition under reaction conditions provides the necessary oxygen pressure. For example, pyrochlores of palladium(IV) and platinum(IV), $Ln_2M_2O_7$, (Ln = rare earth) have been prepared by this method (970 K, 3 kbar). $(H_3O)Zr_2(PO_4)_3$ and a family of zero thermal expansion ceramics (e.g. $Ca_{0.5}Ti_2P_3O_{12}$) have also been prepared hydrothermally. Another good example is the synthesis of borates of aluminium, yttrium and such metals wherein the sesquioxides are reacted with boric acid. Oxyfluorides have been prepared in HF medium [75]. Zeolites are generally prepared under hydrothermal conditions in the presence of alkali. The alkali, the silica component and the source of aluminium are mixed in appropriate proportions and heated. The reactant mixture forms a hydrous gel which is then allowed to crystallize under pressure for several hours to several weeks between 330 and 470 K. In a typical synthesis, $Al_2O_3.3H_2O$ dissolved in concentrated NaOH solution (20 N) is mixed with a 1 N solution of $Na_2SiO_3.9H_2O$ to obtain a gel (of composition $2.1Na_2O \cdot Al_2O_3 \cdot 2.1SiO_2 \cdot 60H_2O$) which is then crystallized to give zeolite A. The Na_2O-SiO_2-Al_2O_3-H_2O system yields a large number of materials with the zeolitic framework. Under alkaline conditions, aluminium is present as $Al(OH)_4$ anions. The OH- ions act as a mineralizing catalyst while the cations present in the reactant mixture determine the kinds of zeolite formed.

Besides water, some inorganic salts are also encapsulated in some zeolites. Several zeolite structures are found in the K_2O-SiO_2-Al_2O_3-H_2O system as well. Li_2O, however, does not give rise to many microporous materials. Group IIA cations yield several zeolitic products.

Zeolitization in the presence of organic bases is useful for synthesizing silica-rich zeolites. Silicalite with a tetrahedral framework enclosing a three-dimensional system of channels (defined by 10 rings wide enough to absorb molecules up to 0.6 nm in diameter) has been synthesized by the reaction of tetrapropylammonium (TPA) hydroxide and a reactive form of silica between 370 and 470 K. The precursor crystals have the composition $(TPA)_2 0.48SiO_2 . H_2O$ and the organic cation is removed by chemical reaction or thermal decomposition to yield microporous silicalite which may be considered to be a new polymorph of SiO_2. The clathrasil (silica analogue of a gas hydrate), dodecasil-1H, is prepared from an aqueous solution of tetramethoxysilane and $N(CH_3)_4OH$; after the addition of aminoadamantane, the solution is treated hydrothermally under nitrogen for four days at 470 K. The use of template cations has enabled the synthesis of a variety of zeolite materials. Cations such as $(NMe_4)+$ fit snugly into the cages (e.g. sodalite cages of sodalite and SAPO or gmelinite cages of zeolites omega). Neutral organic amines have also been used (e.g. in the synthesis of ZSM-5). Many new microporous materials, including those based on $AlPO_4$ (analogue of SiO_2), gallosilicates and aluminogerminates (analogues of aluminosilicates), have been prepared. $AlPO_4$-based materials are prepared by the crystallization of gels formed by adding an organic template to a mixture of active alumina, H_3PO_4 and water at a pH of 5-8 around 470 K. Pressures in the range 10-150 kbar are commonly used for solid-state synthesis. In the piston-cylinder apparatus consisting of a tungsten carbide chamber and a piston assembly, the sample is contained in a suitable metal capsule surrounded by a pressure-transducer (pyrophyllite). Pressure is generated by moving the piston through the blind hole in the cylinder. A microfurnace made of graphite or molybdenum is incorporated in the design. Pressures up to 50 kbar and temperatures up to 1800 K are readily reached in a volume of 0.1 cm^3 using this design. In the anvil apparatus, first designed by Bridgman, the sample is subjected to pressure by simply squeezing it between two opposed anvils. Although pressures of around 200 kbar and temperatures up to 1300 K are reached in this technique, it is not popular for solid-state synthesis since only milligram quantities can be handled. An extension of the opposed anvil principle is the tetrahedral anvil design, where four massively supported anvils disposed tetrahedrally ram towards the centre where the sample is located in a pyrophyllite medium together with a heating arrangement. The

multi-anvil design has been extended to cubic geometry, where six anvils act on the faces of a pyrophyllite cube located at the centre. The belt apparatus provides the best high-pressure-high-temperature combination for solid-state synthesis. This apparatus, which was used for the synthesis of diamonds some years ago is a combination of the piston-cylinder and the opposed anvil designs. The apparatus consists of two conical pistons made of tungsten carbide, which ram through a specially shaped chamber from opposite directions. The chamber and pistons are laterally supported by several steel rings making it possible routinely to reach fairly high pressures (around 150 kbar) and high temperatures (approximately 2300 K). In the belt apparatus, the sample is contained in a noble metal capsule (a BN or MgO container is used for chalcogenides) and surrounded by pyrophyllite and a graphite sleeve, the latter serving as an internal heater. In a typical high-pressure run, the sample is loaded, the pressure raised to the desired value and then the temperature increased. After holding the pressure for about 30 min, the sample is quenched (400 Ks^{-1}) while still under pressure. The pressure is released after the sample has cooled at room temperature.

High-pressure methods have been used for the synthesis of several materials that cannot possibly be made otherwise. In general, the formation of a new compound from its components requires that the new composition have a lower free energy than the sum of the free energies of the components. Pressure can aid in the lowering of free energy in different ways.

(a)Pressure delocalizes outer d electrons in transition-metal compounds by increasing the magnitude of coupling between the d electrons on neighbouring cations, thereby lowering the free energy. A typical example is the synthesis of $ACrO_3$ (A = Ca, Sr, Pb) perovskites and CrO_2.

(b) Pressure stabilizes higher-valence states of transition metals, thus promoting the formation of a new phase. For example, in the Ca-Fe-O system only $CaFeO_{2.5}$ (brown-millerite) is stable under ambient pressures. Under high oxygen pressures, iron is oxidized to the 4^+ state and hence $CaFeO_3$ with the perovskite structure is formed.

(c) Pressure can suppress the ferroelectric displacement of cations, thereby adding the synthesis of new phases. The synthesis of A~MoO3 bronzes, for example, requires

populating the empty d orbitals centred on molybdenum; at ambient pressures, MoO_3 is stabilized by a ferroelectric distortion of MoO_6 octahedra up to the melting point.

(d) Pressure alters site-preference energies of cations, and facilitates the formation of new phases. For example, it is not possible to synthesize $A^{2+}Mn^{4+}O_3$ (A = Mg, Co, Zn) ilmenites because of the strong tetrahedral site preference of the divalent cations. One therefore obtains a mixture of $A[AMn]O_4$(spinel) + MnO_2(rutile) under atmospheric pressure instead of monophasic $AMnO_3$. However, the latter is formed at high pressures with a corundum-type structure in which both the A and Mn ions are in octahedral coordination.

(e) Pressure can suppress the $6s^2$ core polarization in oxides containing isoelectronic Tl^+, Pb^{2+}, Bi^{3+} cations. For example, perovskite-type $PbSnO_3$ cannot be made at atmospheric pressure because the mixture of PbO + SnO_2 is more stable than the perovskite.

Thus, solid-state reactions are generally slow under ordinary pressures even when the product is thermodynamically stable. Pressure has a marked effect on the kinetics of the reaction, reducing the reaction times considerably, and at the same time giving more homogeneous and crystalline products. For instance, $LnFeO_3$, $LnRhO_3$ and $LnNiO_3$ (Ln = rare earth) are prepared in a matter of hours under high-pressure-high-temperatue conditions, whereas at ambient pressure the reactions require several days ($LnFeO_3$ and $LnRhO_3$) or they do not occur at all ($LnNiO_3$). Thus $LnFeO_3$ is formed in 30 min at 50 kbar.

In several $(AX)(ABX_3)_n$ series of compounds, the end members ABX_3 and A_2BX_4, having the perovskite and K_2NiF_4 structures respectively, are formed at atmospheric pressures, but not the intermediate phases such as $A_3B_2X_7$ and $A_4B_3X_{10}$. Pressure facilitates the synthesis of such solids. $Sr_3Ru_2O_7$ and $Sr_4Ru_3O_{10}$ are formed in 15 min at 20 kbar and 1300 K.

High-pressure methods have been employed in the synthesis of novel superconducting cuprates. A rudimentary example is the preparation of oxygen-excess La_2CuO_4 under high oxygen pressure. A more interesting example is the synthesis of the next homologue with two CuO_2 layers. $La_2Ca_{1-x}Sr_xCu_2O_6$ which had earlier been found to be an insulator was rendered superconducting by heating it under oxygen pressure.

$YBa_2Cu_4O_8$ was first prepared under high oxygen pressure, but this was soon found unnecessary. However, superconducting cuprates with infinite CuO_2 layers of the type $Ca_{1-x}Sr_xCuO_2$ or $Sr_{1-x}Nd_xCuO_2$ can only be prepared under high hydrostatic pressures which help to give materials with shorter Cu-O bonds. It should be noted that $Ca_{1-x}Sr_xCuO_2$ prepared at ambient pressure is insulating.

9. The pyrosol Process: a novel chemical method for depositing films

Pyrolysis of sprays is a well known method for depositing films. Thus, one can obtain films of oxidic materials such as CoO, ZnO and $YBa_2Cu_3O_7$ by the spray pyrolysis of solutions containing salts (e.g. nitrates) of the cations. A novel improvement in this technique is the pyrosol process involving the transport and subsequent pyrolysis of a spray generated by an ultrasonic atomizer. When a high frequency (100 kHz-10 MHz range) ultrasonic beam is directed at a gas-liquid interface, a geyser is formed and the height of the geyser is proportional to the acoustic intensity. Its formation is accompanied by the generation of a spray, resulting from the vibrations at the liquid surface and cavitation at the liquid-gas interface. The quantity of spray is a function of the intensity. Ultrasonic atomization is accomplished using an appropriate transducer made of PZT located at the bottom of the liquid container. A 500-1000 kHz transducer is generally adequate. The atomized spray which goes up in a column fixed to the liquid container is deposited onto a suitable solid substrate and then heat treated to obtain the film of the material concerned. The flow rate of the spray is controlled by the flow rate of air or any other gas. The liquid is heated to some extent, but its vaporization should be avoided. The source liquid contains the relevant cations in the form of salts dissolved in an organic solvent. Organometallic compounds are often used (e.g. acetates, alkoxides, acetylacetonates, etc.). Proper gas flow is crucial to obtain satisfactory conditions for a good liquid spray.

The pyrosol process is in some way between chemical vapour deposition and spray pyrolysis, but the choice of source compounds for the pyrosol process is larger than that available for chemical vapour deposition. Films of a variety of materials have been obtained by the pyrosol method. The thickness of the films can be anywhere between a few hundred angstroms to a few micrometres. Films of superconducting cuprates such as

$YBa_2Cu_3O_7$ have also been prepared by the pyrosol process. Epitaxy has been observed in films deposited onto single-crystal substrates.

10. Czochralski Process for Semiconductor Materials

Semiconductors with predictable, reliable electronic properties are necessary for mass production. The level of chemical purity needed is extremely high because the presence of impurities even in very small proportions can have large effects on the properties of the material. A high degree of crystalline perfection is also required, since faults in crystal structure (such as dislocations, twins, and stacking faults) interfere with the semiconducting properties of the material. Crystalline faults are a major cause of defective semiconductor devices. The larger the crystal, the more difficult it is to achieve the necessary perfection. Current mass production processes use crystal ingots between four and twelve inches (300 mm) in diameter which are grown as cylinders and sliced into wafers.

Because of the required level of chemical purity and the perfection of the crystal structure which are needed to make semiconductor devices, special methods have been developed to produce the initial semiconductor material. A technique for achieving high purity includes growing the crystal using the Czochralski process. An additional step that can be used to further increase purity is known as zone refining. In zone refining, part of a solid crystal is melted. The impurities tend to concentrate in the melted region, while the desired material recrystalizes leaving the solid material more pure and with fewer crystalline faults. In manufacturing semiconductor devices involving heterojunctions between different semiconductor materials, the lattice constant, which is the length of the repeating element of the crystal structure, is important for determining the compatibility of materials.

The Czochralski process is a method of crystal growth used to obtain single crystals of semiconductors (e.g. silicon, germanium and gallium arsenide), metals (e.g. palladium, platinum, silver, gold), salts and some man-made (or lab) gemstones. The most important application may be the growth of large cylindrical ingots, or boules, of single crystal silicon. Other semiconductors, such as gallium arsenide, can also be grown by this method, although lower defect densities in this case can be obtained using variants of the Bridgeman technique.

High-purity, semiconductor-grade silicon (only a few parts per million of impurities) is melted down in a crucible , which is usually made of quartz. Dopant impurity atoms such as boron or phosphorus can be added to the molten intrinsic silicon in precise amounts in order to dope the silicon, thus changing it into n-type or p-type extrinsic silicon. This influences the electrical conductivity of the silicon. A seed crystal, mounted on a rod, is dipped into the molten silicon. The seed crystal's rod is pulled upwards and rotated at the same time. By precisely controlling the temperature gradients, rate of pulling and speed of rotation, it is possible to extract a large, single-crystal, cylindrical ingot from the melt. Occurrence of unwanted instabilities in the melt can be avoided by investigating and visualizing the temperature and velocity fields during the crystal growth process [1]. This process is normally performed in an inert atmosphere, such as argon, and in an inert chamber, such as quartz.

Size of Crystals: While the largest silicon ingots produced today are 400 mm in diameter and 1 to 2 metres in length, 200 mm and 300 mm diameter crystals are standard industrial processes. Thin silicon wafers are cut from these ingots (typically about 0.2 - 0.75 mm thick) and can be polished to a very high flatness for making integrated circuits, or textured for making solar cells.

Impurity Incorporation: When silicon is grown by the Czochralski method the melt is contained in a silica (quartz) crucible. During growth the walls of the crucible dissolve into the melt and Czochralski silicon therefore contains oxygen impurities with a typical concentration of 10^{18} cm^{-3}. Perhaps surprisingly, oxygen impurities can have beneficial effects. Carefully chosen annealing conditions can allow the formation of oxygen precipitates. These have the effect of trapping unwanted transition metal impurities in a process known as gettering. Additionally, oxygen impurities can improve the mechanical strength of silicon wafers by immobilising any dislocations which may be introduced during device processing. It has experimentally been proved in the 1990s that the high oxygen concentration is also beneficial for radiation hardness of silicon particle detectors used in harsh radiation environment (eg. CERN's LHC/S-LHC projects) [2, 3, 4]. Therefore, radiation detectors made of Czochralski- and Magnetic Czochralski-silicon are considered to be promising candidates for many future high-energy physics experiments.[5][6] However, oxygen impurities can react with boron in an illuminated

environment, such as experienced by solar cells. This results in the formation of an electrically active boron–oxygen complex that detracts from cell performance. Module output drops by approximately 3% during the first few hours of light exposure [7].

The **Bridgman technique** is a method of growing single crystal ingots or boules. The method involves heating polycrystalline material in a container above its melting point and slowly cooling it from one end where a seed crystal is located. Single crystal material is progressively formed along the length of the container. The process can be carried out in a horizontal or vertical geometry. It is a popular method of producing certain semiconductor crystals, such as gallium arsenide where the Czochralski process is more difficult.

Purification process: Zone melting is a method of separation by melting in which a molten zone traverses a long ingot of impure metal or chemical.

Zone refining: In zone refining, solutes are segregated at one end of the ingot in order to purify the remainder. The molten region melts impure solid at its forward edge and leaves a wake of purer material solidified behind it as it moves through the ingot. The impurities concentrate in the melt, and are moved to one end of the ingot. Zone refining was developed in Bell Telephone Laboratories as a method to prepare high purity materials for manufacturing transistors. Its early use was on germanium for this purpose, but it can be extended to virtually any solute-solvent system having an appreciable concentration difference between solid and liquid phases at equilibrium. This process is also known as the **Float zone process**, particularly in semiconductor materials processing.

Zone leveling : Zone melting is also used to concentrate the impurities for analytical or other purposes. In zone leveling, the objective is to distribute solute evenly throughout the purified material, which may be sought in the form of a single crystal. For example, in the preparation of a transistor or diode semiconductor, an ingot of germanium is first purified by zone refining. Then a small amount of antimony is placed in the molten zone, which is passed through the pure germanium. With the proper choice of rate of heating and other variables, the antimony can be spread evenly through the germanium. This technique is also used for the preparation of silicon for use in computer chips.

Heaters: A variety of heaters can be used for zone melting, with their most important characteristic being the ability to form short molten zones that move slowly and

uniformly through the ingot. Induction coils, ring-wound resistance heaters, or gas flames are common methods. Another method is to pass an electric current directly through the ingot while it is in a magnetic field, with the resulting magnetomotive force carefully set to be just equal to the weight in order to hold the liquid suspended. Zone melting can be done as a batch process, or it can be done continuously, with fresh impure material being continually added at one end and purer material being removed from the other, with impure zone melt being removed at whatever rate is dictated by the impurity of the feed stock.

Zone Remelting: Another related process is zone remelting, in which two solutes are distributed through a pure metal. This is important in the manufacture of semiconductors, where two solutes of opposite conductivity type are used. For example, in germanium, pentavalent elements of group V such as antimony and arsenic produce negative (n-type) conduction and the trivalent elements of group III such as aluminium and boron produce positive (p-type) conduction. By melting a portion of such an ingot and slowly refreezing it, solutes in the molten region become distributed to form the desired n-p and p-n junctions.
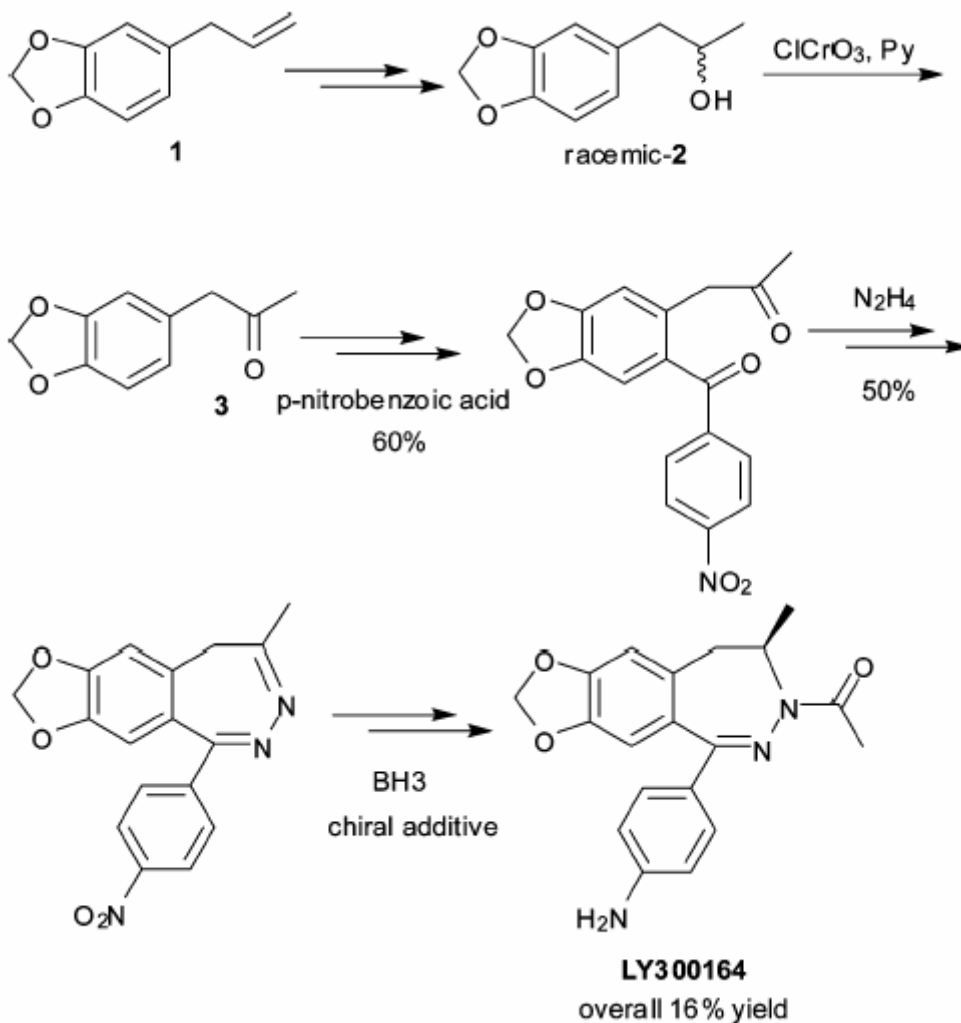
Biocatalysis

Pharmaceutical industry has been a rapidly growing field. About 54% of drug molecules are chiral, and resolution remains an important and cost-effective approach to chiral molecules. In order to achieve a typical enantiomeric purity of 99.5%, resolution is often accomplished at the price of restricting the overall maximum yield of a process to 50% at most. While metal catalyzed reactions have become prevalent in recent years, their use in manufacturing requires great effort to identify appropriate catalysts, solvents and reaction conditions. Reproducibility and robustness can remain a problem, especially with regard to sensitivity to substrate quality and small variation in reaction parameters. There is a clear need for new methodologies to produce chiral molecules. Enzymes are highly efficient with excellent regioselectivity and stereoselectivity. By conducting reactions in water under ambient reaction conditions, both the use of organic solvents and energy input are minimized. Furthermore, one can design processes with high energy efficiency and safe chemistry by conducting reactions at ambient temperature under ambient

atmosphere, and atom economy can be increased by avoiding extensive protection and deprotection sequences.

Biocatalysis is emerging as one of the greenest technologies as a result of recent advances in genomics, proteomics and pathway engineering (large scale DNA sequencing, structural biology, protein expression, high throughput screening, directed enzyme evolution and metabolic engineering). Application of the twelve principles of green chemistry can deliver higher efficiency and reduce the environmental burden during chemical synthesis.

As the green chemistry movement gains momentum, fresh opportunities of research and development have been opened up to improve the efficiency of chemical processes while simultaneously reducing production costs. The attention is focused on reducing the use and generation of large quantities of hazardous substances which frequently accompanies the synthesis of a pharmaceutical agent, at each of the numerous steps, each of which involve feedstocks, reagents, solvents, and separation. The following case studies depict the developments and improvements in the synthetic strategies of various chemicals.

CASE STUDY 1: Production of LY300164 (Talampanol) : An example of the reduction of hazardous materials is the use of a chemoenzymatic synthesis for the production of LY300164 (Talampanol) for treating epilepsy and neurodegenerative diseases. The first generation synthesis, which starts from 5-allyl-1,3-benzodioxole **1**, suffers from a low yield of 16%, and requires the use of a large amount of organic solvents and chromium oxide, a cancer-suspect agent, to oxidize racemic alcohol **2** to ketone **3** (Scheme 16.1).

Scheme 16.1.

In order to improve its synthesis, a second generation route was developed involving a biocatalytic ketone reduction of **3** by Zygosaccharomyces rouxii to give (S)-**2** with a yield of 96% and >99.9% ee (enantiomeric excess) (Scheme 16.2). Acid-catalyzed reaction with 4-nitrobenzaldehyde led to 1-arylisochroman **4**, which was subsequently oxidized to ketal **5** in the presence of oxygen. The final product LY300164 was obtained after formation of hydrazone **6**, and cyclization via mesylate **7** to give **8** followed by Pd-catalyzed nitro group reduction.
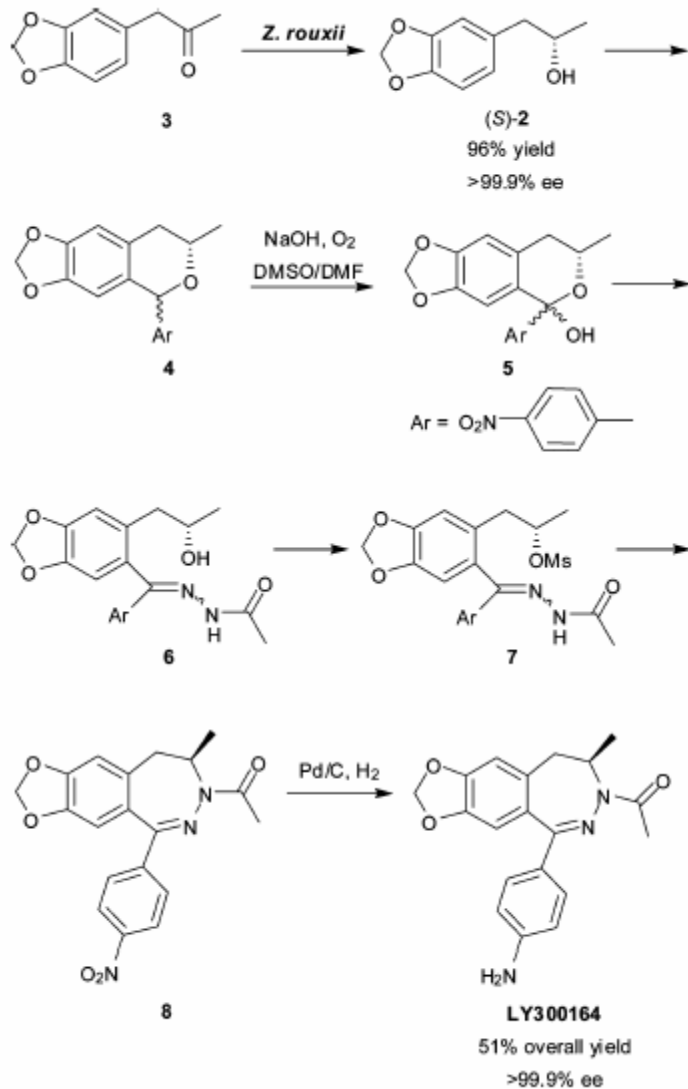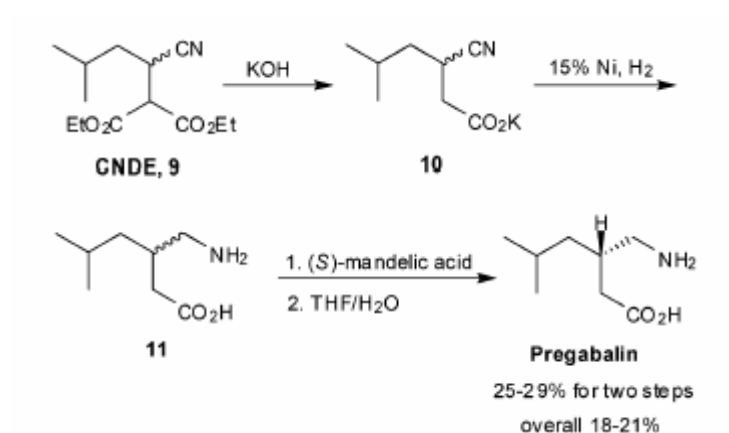
Scheme 16.2.

By using a chemoenzymatic approach, not only was the overall yield improved to 51% from 16% in the old route, the new synthetic pathway eliminated the use of transition metal oxidants and a large volume of organic solvents by judicious adjustment of oxidation states and integration of a biotransformation. For example, using the biocatalytic process, approximately 340000 L of solvents and 3000 kg of chromium waste were eliminated for the production of every 1000 kg of LY300164.

CASE STUDY 2: Production of Pregabalin

Most enzymatic catalysis achieves high regio- and stereoselectivity under mild conditions, allowing new and more efficient processes to be designed with significant advantages over chemical approaches. For example, in the first generation route for the production of pregabalin, chemical resolution of the racemic γ-amino acid **11**, which was prepared from the racemic cyanodiester **9** (CNDE) after hydrolysis and decarboxylation, took place at the end of the process (Scheme 3). To obtain a high optical purity (99.5%) of the final API, (S)-mandelic acid resolution was followed by another step of recrystallization in THF/H_2O with a combined two-step yield of 25–29%. As a result, the overall yield for the route is only 18–21% and over 70% of all process materials before the resolution step including nickel were ultimately turned into wastes. Since the undesired enantiomer could not be recycled, this modest efficiency leads to a large amount of wastes and excessive reactor capacity requirements.

To overcome these issues, a second generation process using a fungal lipase was developed, where enzymatic resolution occurred at the first step and the undesired enantiomer **13** could be easily recycled (Scheme 4). Regio- and stereospecific hydrolysis of **9** led to the mono acid **12** with 45% conversion and >98% ee. After decarboxylation of **12** and phase splitting, mono ester **14** was telescopically subjected to basic hydrolysis and hydrogenation to give the final product. Simple operation as a result of using water as the solvent significantly improved process efficiency. Comparing with the first generation synthesis, not only are a large amount of (S)-mandelic acid completely eliminated, the biocatalytic process also rendered it unnecessary to use most organic solvents. This stands in contrast to a typical process for the production of an API, where 80% of all wastes are solvents. If spent solvents are incinerated instead of being recovered, the life-cycle profile and impacts are considerably increased. Moreover, recycling of the undesired enantiomer **13** doubled both the yield (40% vs. <21%) and throughput. Overall, it was projected that at the peak of manufacturing, the biocatalytic aqueous process would annually eliminate the usage of over thousands of metric tons of rawmaterials including mandelic acid, CNDE and nickel, and tens millions of gallons of alcoholic solvents and THF associated with the classic resolution route.
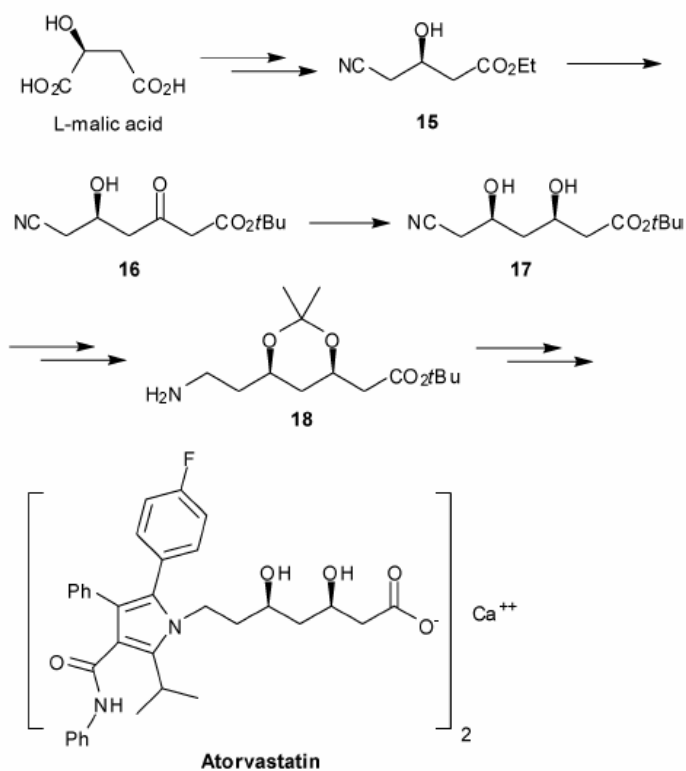
Scheme 16.3.
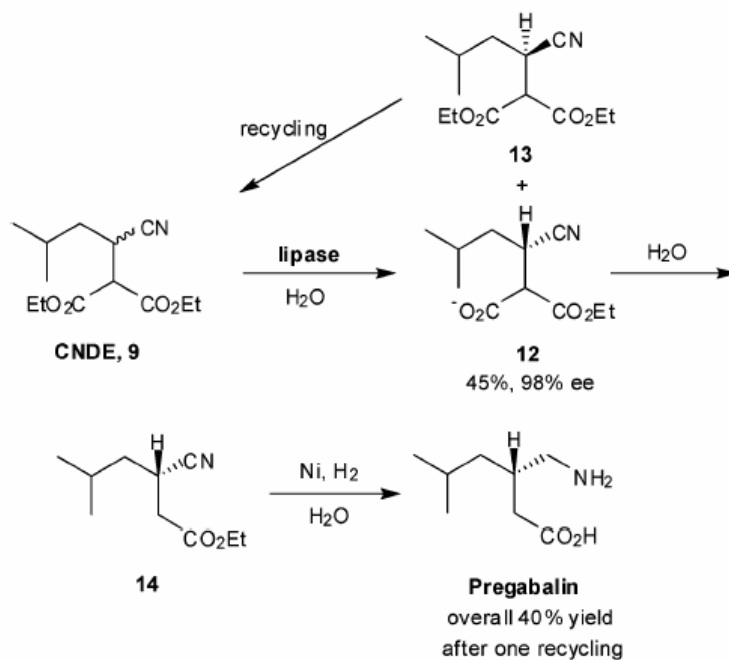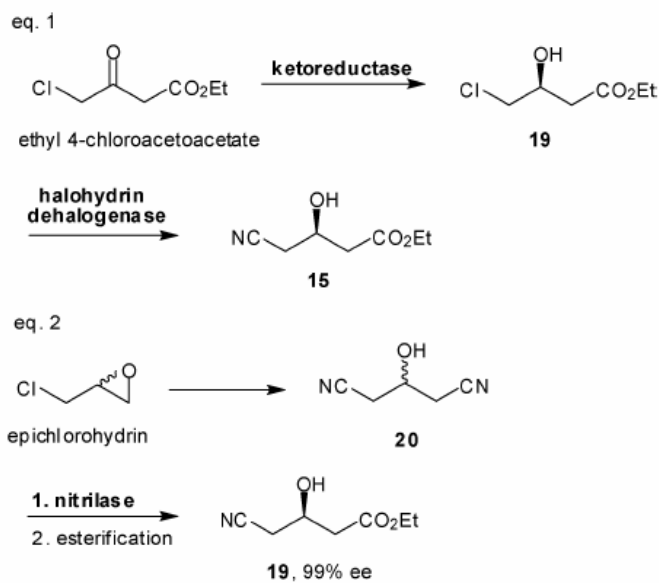

Scheme 16.4.

CASE STUDY 3: Atorvastatin Calcium

Atorvastatin calcium is the active ingredient of Lipitor R, the first drug with annual sales exceeding $10B. In the current process, the key chiral building block in the synthesis of atorvastatin is ethyl (R)-4-cyano-3-hydroxybutyrate (**15**) with an annual demand estimated to be about £440 000, which was then converted to atorvastatin side chain **18** upon Claisen condensation, borane-chelation controlled reduction, both under cryogenic

conditions, followed by protection of the two hydroxy groups and Ni-catalyzed nitrile group hydrogenation. The final API atorvastatin was produced after Paal–Knorr condensation of **18** with a diketone (Scheme 5). A number of biocatalytic approaches have been reported for the synthesis of (R)-4-cyano-3-hydroxybutyrate **15**. For example, a green process has recently been reported using a two-enzyme system under neutral conditions in water (eq. 1, Scheme 16.6). In this process, the first step involves enantioselective enzymatic reduction of ethyl 4-chloroacetoacetate to give **19** followed by a biocatalytic cyanation of the chlorohydrin to produce **15**.

Alternatively, **15** was synthesized from inexpensive racemic epichlorohydrin via nitrilase-catalyzed desymmetrization of meso-3-hydroxyglutaronitrile **20** (eq. 2, Scheme 6). By applying gene site saturation mutagenesis to improve the stereoselectivity of the biocatalyst, the ee of the desired product reached 99% under a 3M loading of the substrate. The synthesis is short and utilizes an inexpensive starting material. Both the ketoreductase (eq. 1, Scheme 6) and nitrilase processes (eq. 2, Scheme 6) led to significant reduction of byproducts, wastes and organic solvents associated with existing chemical routes. Recently, a more concise approach to install the atorvastatin side chain was reported by using a microbial deoxyribose-5-phosphate aldolase (DERA). This enzyme catalyzes the sequential aldol condensation between one equivalent of amino aldehye **21** and two equivalents of acetaldehyde to form lactol **22** with excellent ee (98%) and de (97%), which was then converted to the statin side chain **18** upon oxidation, protection and esterification. Using this method, the overall process to atorvastatin was shortened significantly and two cryogenic steps in the existing process were eliminated (Scheme 7). It is estimated that hundreds of metric tons of raw materials and solvents will be reduced each year by using the chemoenzymatic route in concomitant with significant reduction in energy consumption.
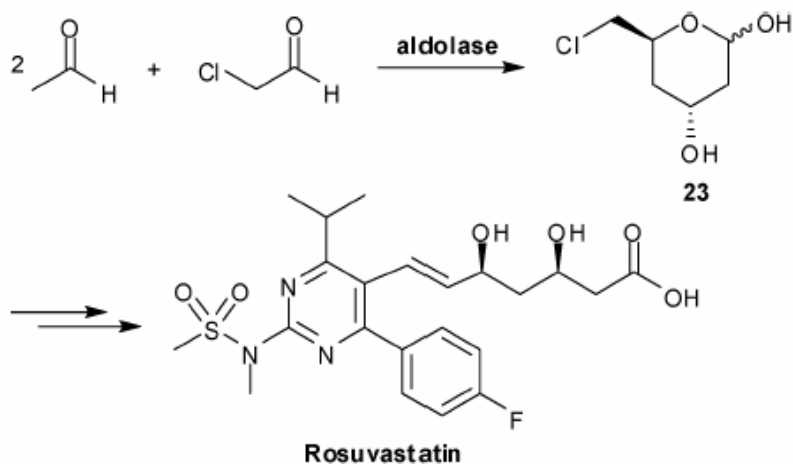
Scheme 5

eq. 1

ethyl 4-chloroacetoacetate

eq. 2

epichlorohydrin
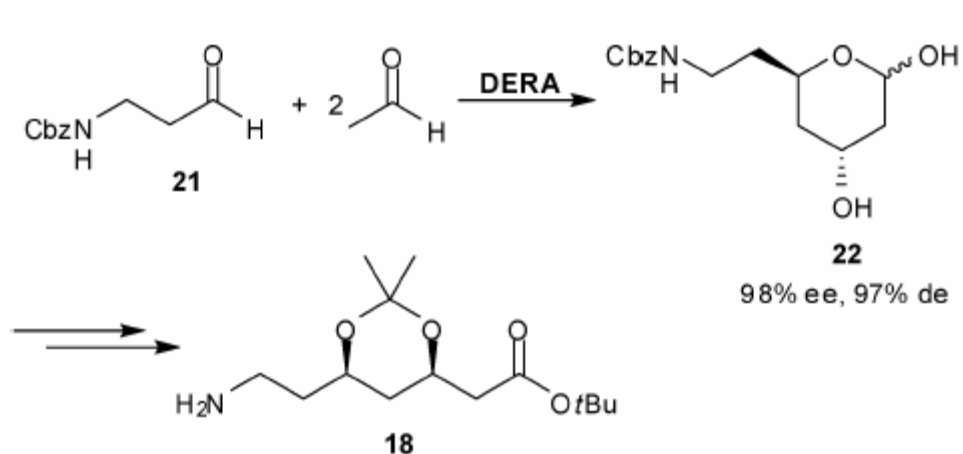
Scheme 16.6.

Scheme 16.7.

Rosuvastatin :

Similar approaches have been applied to the synthesis of the side chain of rosuvastatin, the API of Crestor(R) (Scheme 8). By a combination of activity- and sequence-based screening, a Novel DERA was discovered from environmental DNA libraries leading to an enzymatic process to obtain lactol **23** with volumetric productivity of 720 g L^{-1} day^{-1} under an enzyme loading of 2% wt/wt.
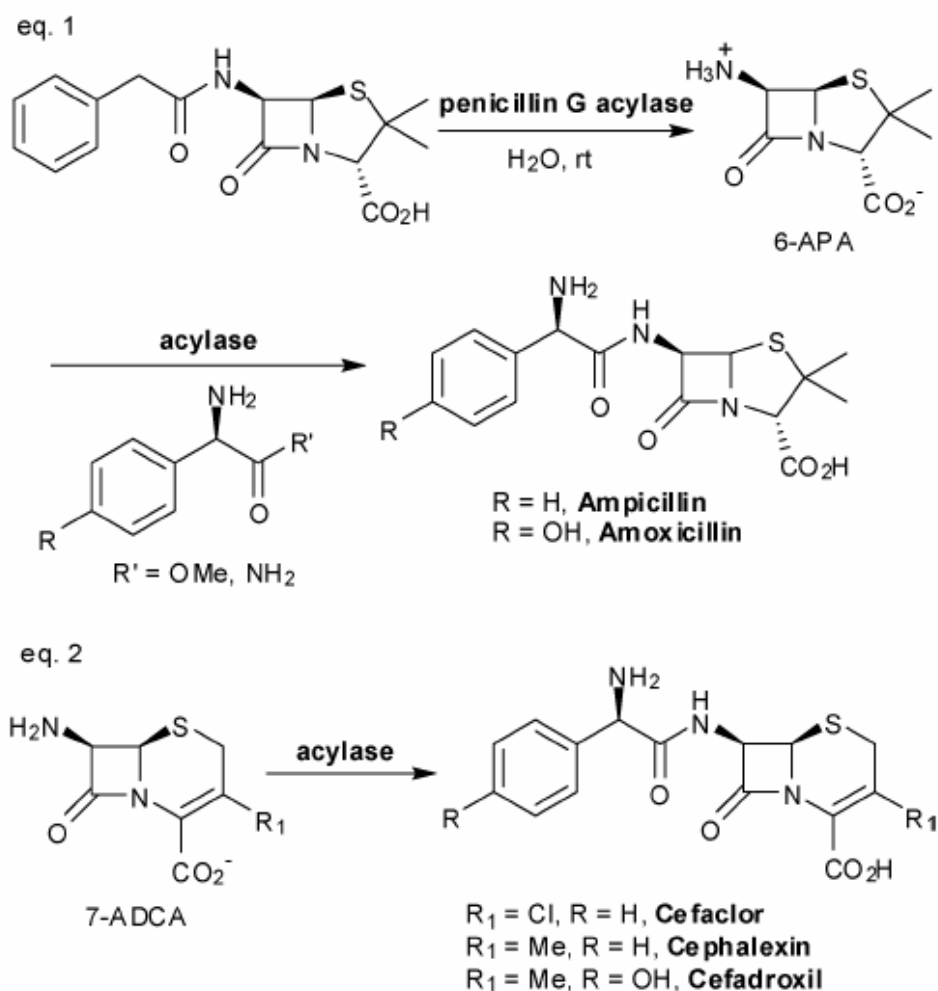

Scheme 16.8.

CASE STUDY 4: Industrial Production of b-lactam Antibiotics :

Biocatalysis is uniquely suited to the development of green chemistry routes for complex molecules, which are often labile and densely functionalized. As a result of high selectivity and mild conditions, enzymatic catalysis has been applied to the industrial production of b-lactam antibiotics, which are mostly derived from 6-aminopenicillanic acid (6-APA) or 7-aminodesacetoxycephalosporanic acid (7-ADCA). The annual world production of 6-APA and 7-ADCA were estimated to be over 8000 and 600 t, respectively. Until recently, they were prepared from penicillin G, a fermentation product derived from non-ribosomal peptide synthase (NRPS), by chemical deacylation, where the carboxy group of the penicillin G is first protected by silylation, followed by selective deacylation via the imidoyl chloride (**25**), and removal of the protecting group (Scheme 9). The method uses stoichiometric amounts of the silylating agent, and a large amount of hazardous chemicals and solvents such as phosphorus pentachloride and dichloromethane.
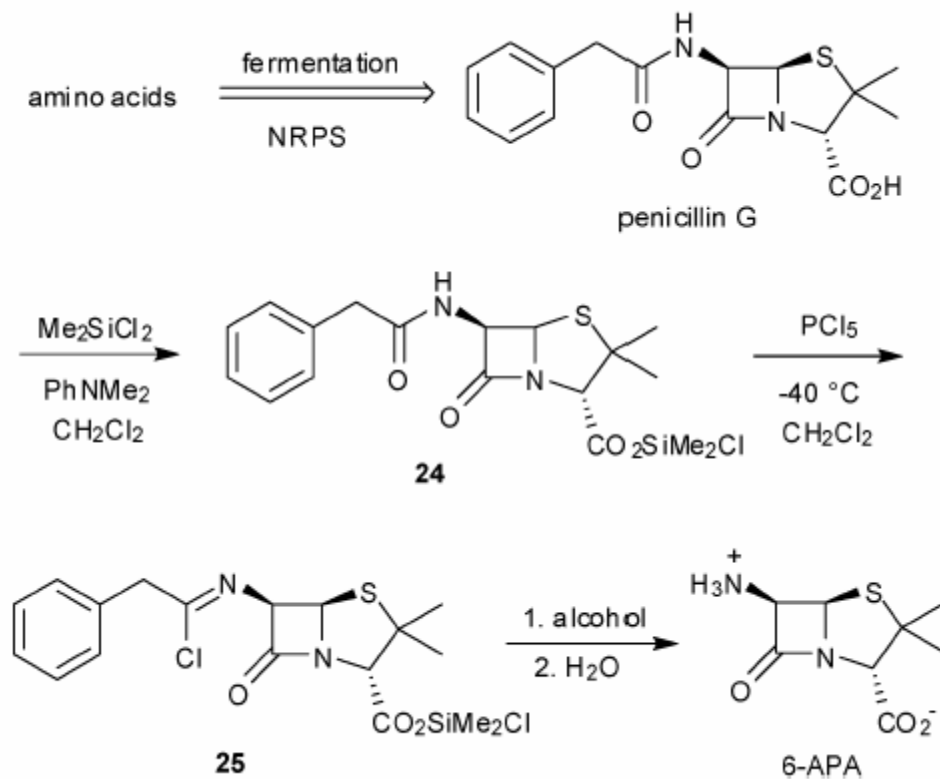
Scheme 16.9

In contrast, enzymatic deacylation of penicillinGby penicillin G acylase was accomplished in water at room temperature requiring no protection and deprotection of other functional groups (Scheme 10). Moreover, under kinetic control, an immobilized penicillin aclyase was also able to catalyze the acylation of 6-APA and 7-ADCA with either D-phenylglycine methyl ester (PGA), D-phenylglycine amides (PGA) or their parahydroxylated analogs to produce a wide range of semi-synthetic b-lactam antibiotics such as ampicillin, amoxicillin, cefaclor, cephalexin and cefadroxil (Scheme 16.10). As a result of the biotransformation, raw material efficiency and E-factor were significantly improved from the first generation of chemical processes.

Scheme 16.10.

CASE STUDY 5: Paclitaxel (Taxol R_)

Plant secondary metabolites have provided a rich and renewable resource of natural products for drug development. However, establishing a stable supply of the active compounds from plants is often difficult. A prominent example is Paclitaxel (Taxol R_), a complex diterpenoid alkaloid originally isolated from the bark of the pacific yew tree Taxus brevifolia with a yield of 0.014%. In addition, isolating Paclitaxel required stripping the bark from the yew trees, thus killing a slow growing tree in the process, which takes about 200 years to mature.
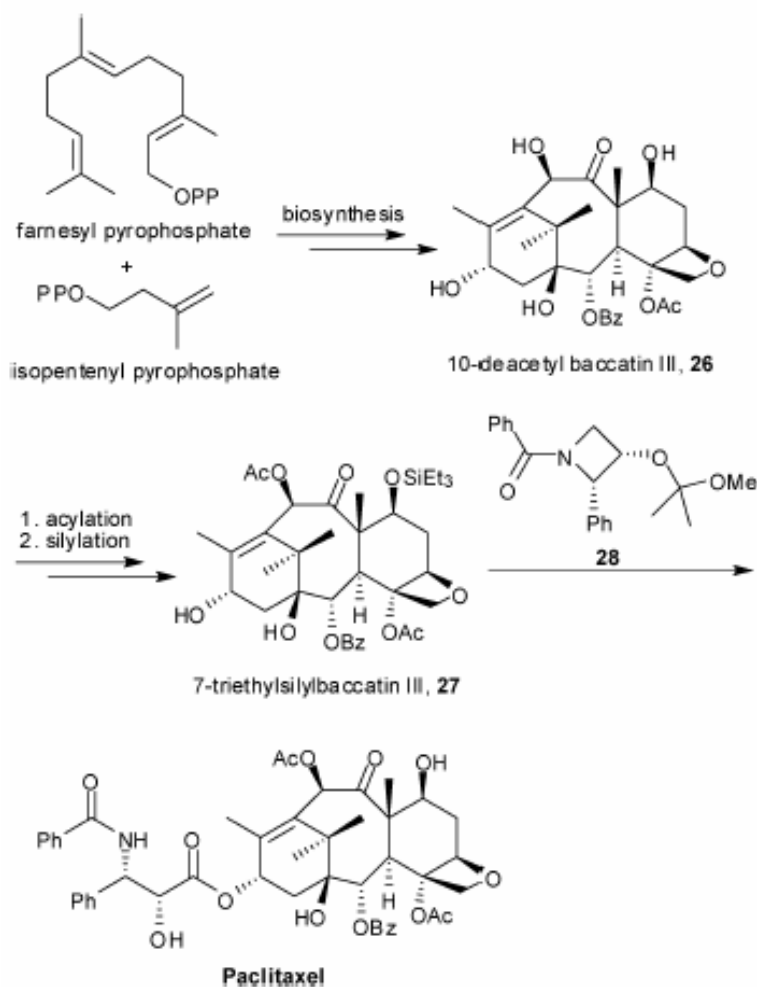
Scheme 16.11

On the other hand, the complexity of the Paclitaxel molecule makes commercial production by chemical synthesis from simple compounds impractical. As a result, a

semisynthetic process was developed starting from 10-deacetylbaccatin III (Scheme 16.11),
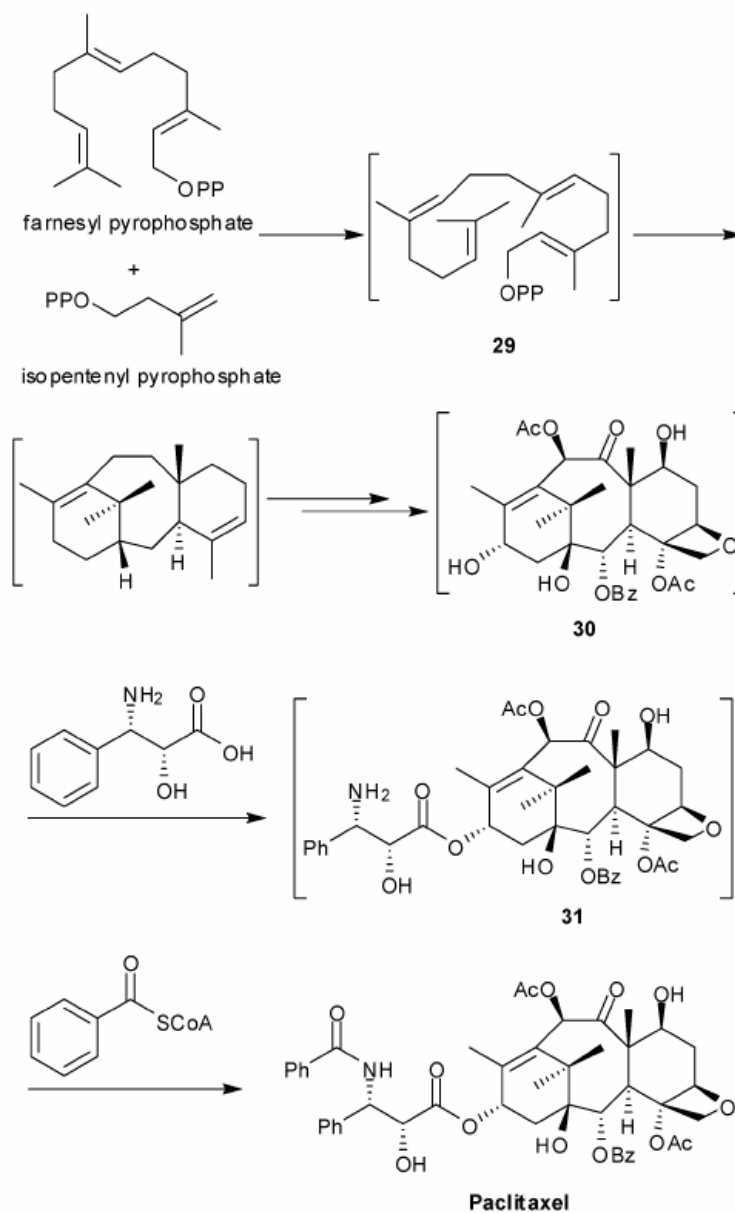
Scheme 16.12.

a more abundant taxoid biosynthesized from isoprenyl diphosphate and farnesyl diphosphate in the needles of the European yew tree Taxus baccata, which could be isolated with a yield of 0.1% without harm to the trees. In this route, 10-deacetylbaccatin

III was first acetylated and silylated. The resulting 7-triethylsilyl baccatin III (**27**) was then coupled to an N-acyl-b–lactam (**28**) to install a phenylisoserine side chain at the C-13 position followed by deprotection to afford Paclitaxel. Overall, however, the semisynthetic process is still complex requiring eleven chemical transformations including the preparation of **28** and seven isolations. Consequently, an alternative process to Paclitaxel was developed using Taxus cell fermentation and extraction from culture medium, followed by recrystallization.

Starting from the two isoprenoid precursors, isoprenyl diphosphate and farnesyl diphosphate (Scheme 12), geranylgeranyl pyrophosphate synthetase catalyzes the coupling to give geranylgeranyl pyrophosphate, **29**, which is then cyclized and then converted to baccatin III **30** through a series of enzymatic transformationsincluding hydroxylation, acylation, oxidation and generation of the oxetane ring. The side chain in **31** was installed by enzymatic transfer of phenylisoserine. To achieve a high titer of Paclitaxel production, cell cultures from various species of Taxus and different elicitors to induce Paclitaxel production have been examined. For example, methyl jasmonate was able to enhance Paclitaxel production to 110 mg L^{-1} every 2 weeks in cell suspension culture of T. media. The plant cell fermentation process led to an elimination of the eleven chemical transformations and a large amount of hazardous solvents and wastes, which came with the semi-synthesis route. Recent advances in metabolic engineering have created another opportunity to develop green processes for relatively complex molecules. An example is the production of shikimic acid for the synthesis of oseltamivir phosphate (Tamiflu) for treatment and prevention of in.uenza virus infections. In the current ten-step commercial synthesis (Scheme 16.13), the key intermediate is shikimic acid **32**, which was produced by a genetically engineered E. coli strain deficient in both shikimate kinase isozymes or isolated from the star anise.

The metabolic engineering efforts have led to the development of an E. coli strain capable of producing the molecule with a titer of 84 g L^{-1} and a yield of 33% from glucose. This acid was subsequently converted into a diethyl ketal **33**, which was then transformed to the oseltamivir phosphate after side chain installation, reductive opening of the ketal, base-catalyzed epoxide ring closure (**34**) followed by aziridination (**35**). One drawback of the above process is the use of the hazardous azide reagent to prepare the

aziridine intermediate **35**. To eliminate the use of azides, an azide-free chemoenzymatic synthesis of oseltamivir phosphate was recently reported that comprised fewer synthetic steps than the commercial process.
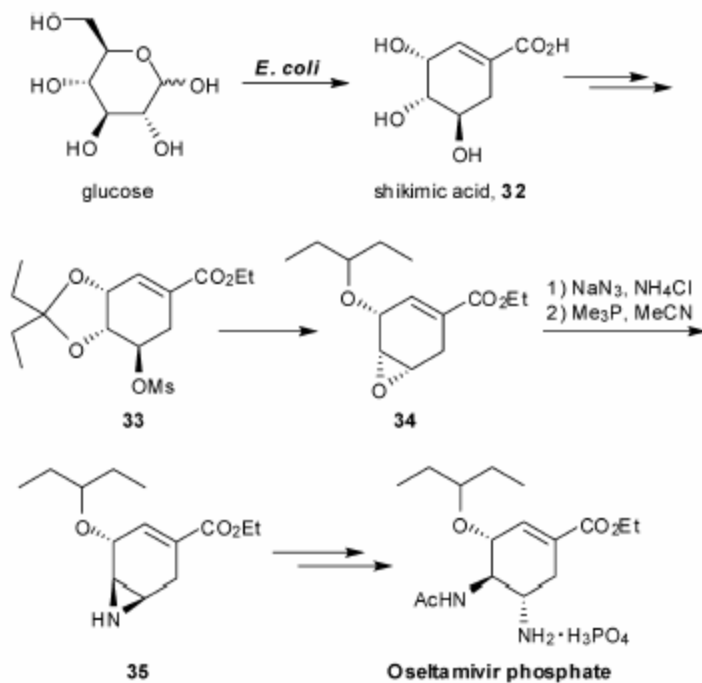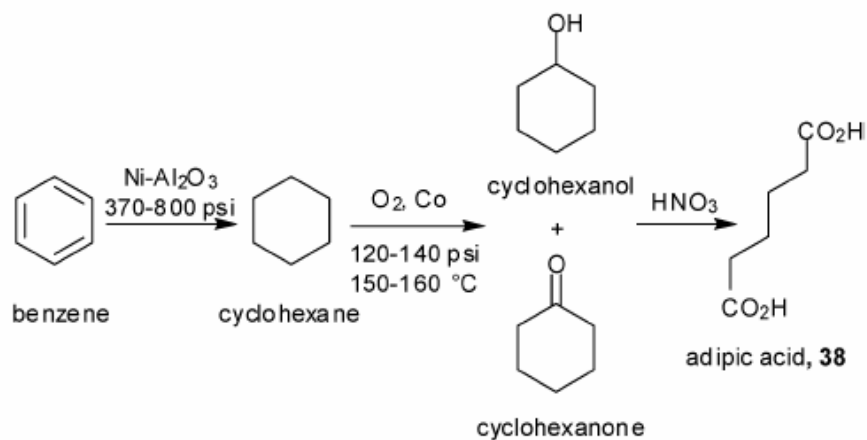

Scheme 16.13.
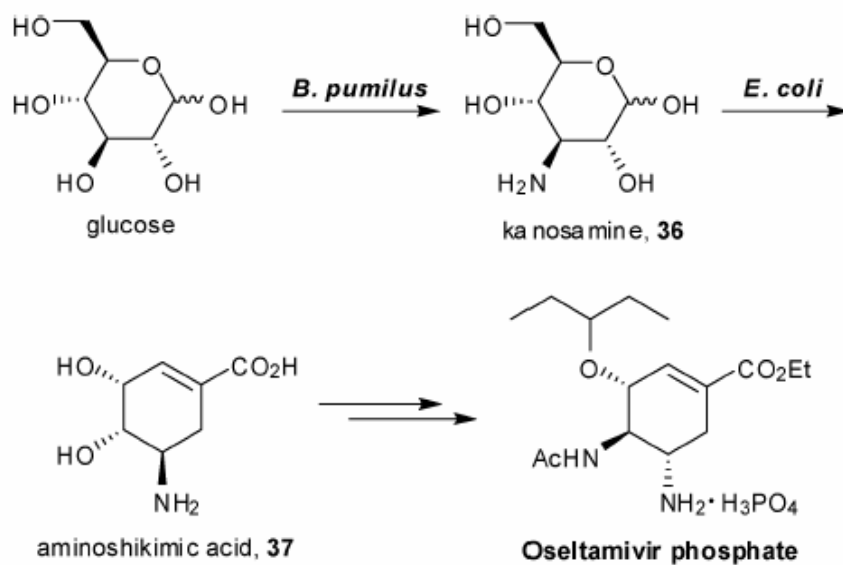
Scheme 16.14.

In this method, the key intermediate is aminoshikimic acid (**37**) that was produced from glucose by a two-step microbial process using Bacillus pumilus to generate kanosamine **36** followed by an engineered E. coli to give **37** (Scheme 16.14). The new route has an overall yield of 22% from aminoshikimic acid and holds great potential if the biosynthesis of aminoshikimic acid can be further improved.

CASE STUDY 6: Fine Chemicals

Due to the exquisite regioselectivity under mild conditions, biotransformations often offer great advantages over chemical synthesis in large-scale production of fine chemicals, which is usually energy intensive and generates a large amount of wastes and gas emissions. The first example of enzymatic manufacture of a bulk chemical involves the conversion of acrylonitrile to acrylamide, which is the monomer of widely used polyacrylamide. The chemical manufacturing process involves hydration of acrylonitrile at 70–120°C by Raney copper resulting in a large volume of toxic wastes and HCN. In addition, the acrylamide produced by this fashion requires considerable purification as it tends to polymerize under the harsh reaction conditions. Acrylic acid is also a byproduct of chemical hydration. Many nitrile hydratases catalyze the conversion of acrylonitrile into acrylamide.For example, immobilized Rhodococcus rhodochrous J1 was able to produce acrylamide at a concentration of 400 g L^{-1} in a fed batch process under 10 .C. There is no need to recover residual acrylonitrile because the yield of the enzymatic conversion is almost 100%. Currently the microbial process is operated at a scale of >40 000 t year^{-1}. It is much greener and more economical than the chemical process. In addition to acrylamide, Rhodococcus rhodochrous J1 was also used to prepare a variety of amides in high concentration and throughput in water (Fig. 16.1). The drive toward environmentally benign synthesis and sustainable development in the chemical industry is contributing to a growing interest in the use of renewable feed stocks and reduction of hazardous wastes in manufacturing. Consequently, carbohydrates such as glucose derived from corn starch or cellulosic biomass provide an intriguing alternative to the current use of nonrenewable petroleum as starting materials. The keys to the success of this transition are the elaboration of new synthetic routes, as well as the design and engineering of robust microbial biocatalysts. Two examples are the development of biocatalytic syntheses of adipic acid and catechol from glucose. Adipic acid , one of the monomers

used in the manufacture of nylon 6,6, is currently produced at 2.2 million metric tons per year. The existing route to adipic acid first entails oxidation of cyclohexane, mostly derived from benzene, to a mixture of cyclohexanol and cyclohexanone by oxygen with a cobalt catalyst at a temperature of 150–160 °C. This mixture was then converted to adipic acid by oxidation in nitric acid (Scheme 16.15).
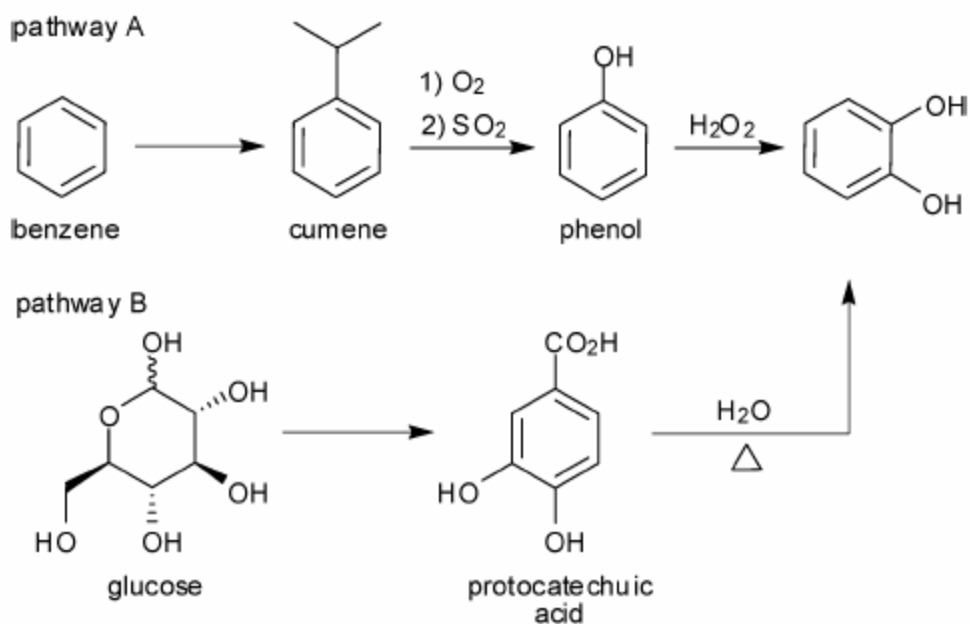

Scheme 16.15
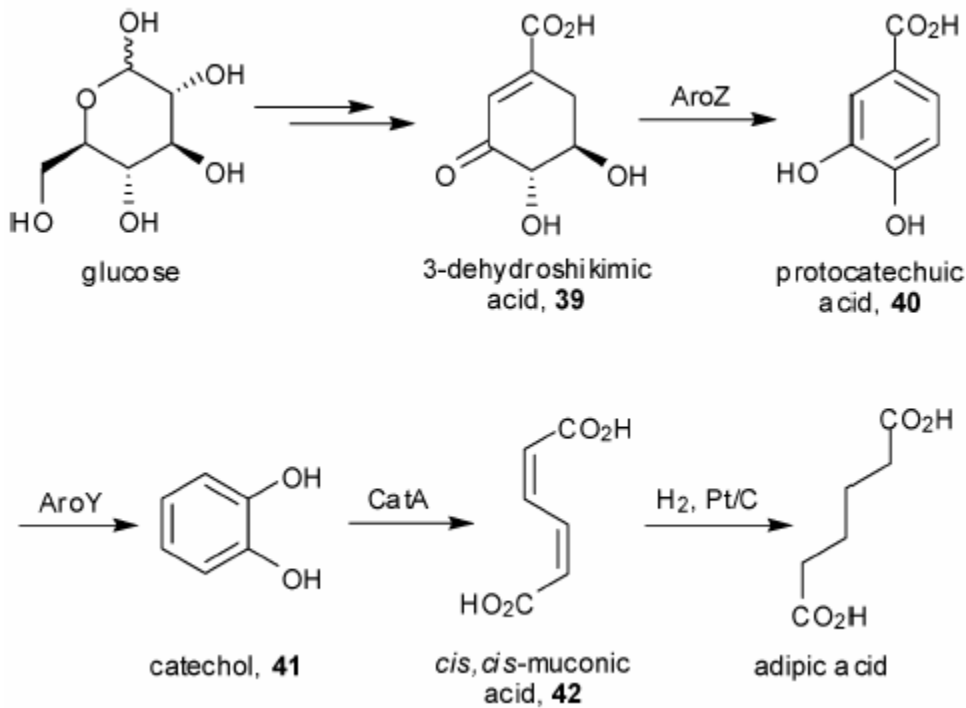
Scheme 16.16

Due to its massive scale, adipic acid manufacture has been estimated to account for some 10% of the annual increase in atmospheric nitrous oxide levels.

Benzene is a carcinogen and volatile chemical and is derived from nonrenewable fossil fuels. Biocatalytic routes to adipic acid have been reported in which glucose was converted to cic,cis-muconic acid followed by hydrogenation (Scheme 16.16). The biosynthetic pathway leading to the production of cic,cis-muconic acid was assembled by expressing Klebsiella pneumoniae aro Z-encoded 3-dehydroshikimate dehydratase, aroY-encoded protocatechuate decarboxylase,**44c** and Acinetobacter calcoaceticus catA-encoded catechol 1,2-dioxygenase in a 3-dehydroshikimate-syntheszing E. coli strain. The resulting heterologous biocatalyst E. coli WN1/pWN2.248 was able to produce 37 gL^{-1} of cic,cis-muconic acid (**42**) in 22% yield from glucose in one-pot via intermediates **39**, **40** and **41** (Scheme 16.16). Catalytic hydrogenation of cic,cis-muconic acid affords adipic acid in 97% yield.
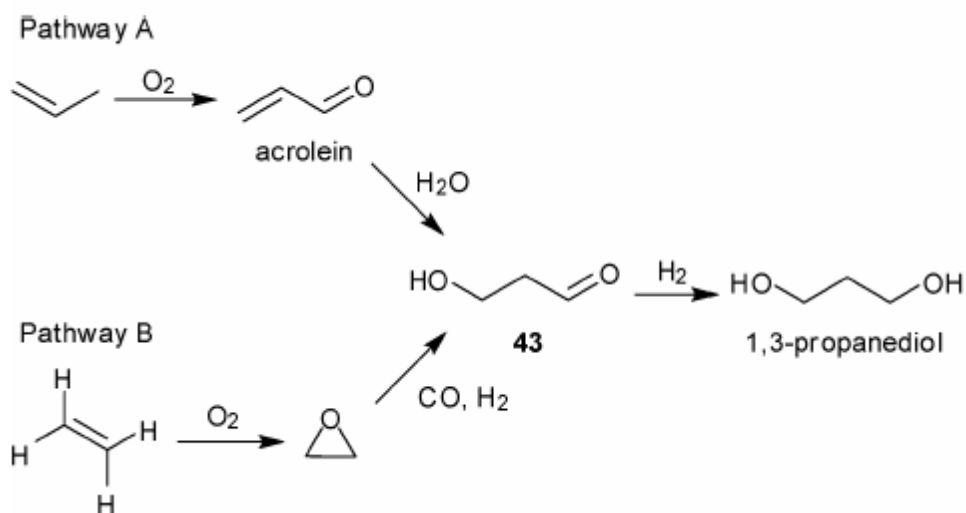

Scheme 16.17.

In the above metabolic pathway, catechol is an intermediate in the route to cic,cis-muconic acid. As a result, this technology may also be applied to the production of catechol, which is manufactured at an annual volume of 25000 metric tons as an important chemical building block for flavors, pharmaceuticals, agrochemicals,

polymerization inhibitors and antioxidants. Although some catechol is distilled from coal tar, phenol is the starting material for the production of the majority of catechol, and was obtained by Hock-type air oxidation of benzene-derived cumene (pathway A, Scheme 17).**47** Direct microbial synthesis of catechol from glucose resulted in only 5% yield due to its high toxicity to the production host. The issue was circumvented by microbial production of a less toxic intermediate protocatechuate using E. coli KL3/pWL2.46B followed by chemical decarboxylation in water (pathway B, Scheme 16.17).

By this strategy, the overall yield of catechol from glucose was improved to 43%. As illustrated in microbial syntheses of adipic acid and catechol, manufacture of chemicals of major industrial importance from renewable feedstocks offer significant environmental advantages and economic opportunities. A single genetically engineered microbe is able to catalyze the conversion of glucose in water at near-ambient pressure and temperature. The spectrum of chemicals that could be synthesized from glucose can be further expanded by the construction of heterologous biocatalysts and integration of microbial and chemical transformations.

Scheme 16.18.

Research aimed at increasing synthetic efficiency and overcoming product toxicity and isolation problems are critical to move biocatalytic syntheses from proof-of-concept into practical routes to compete with existing chemical routes based on petroleum. Another example using metabolic engineering is microbial production of 1,3-propanediol. The emergence of a new 1,3-propanediol (PDO)-based polyester has dramatically increased the demand for PDO in recent years. Once a fine chemical, PDO is now becoming a bulk chemical as its production volume will increase to a level of one million tons annually. Historically, PDO was produced from petroleum chemicals from two different chemical processes. One uses propylene as the starting material, which was catalytically oxidized to acrolein, followed by hydration to 3-hydroxypropionaldehyde (pathway A, Scheme 18). An alternative process starts from ethylene oxide obtained from oxidation of ethylene (pathway B, Scheme 18). Ethylene oxide was then converted to 3-hydroxypropionaldehyde by hydroformylation under high pressure. The conversion of **43** to PDO requires hydrogenation over a rubidium or nickel catalyst under high-pressure.

To lower the cost of PDO and reduce the negative environmental impact of its production, a recombinant E. coli strain was developed to produce PDO from glucose. The E. coli strain was modified to contain genes from Saccharomyces cerevisiae, which is capable of producing glycerol from glucose, and Klebsiella pneumoniae, which contains the metabolic pathway of glycerol to PDO (Scheme 19).

a) glycerol 3-phosphate dehydrogenase   c) glycerol dehydratase
b) glycerol 3-phosphate phosphatase   d) propanediol oxidoreductase
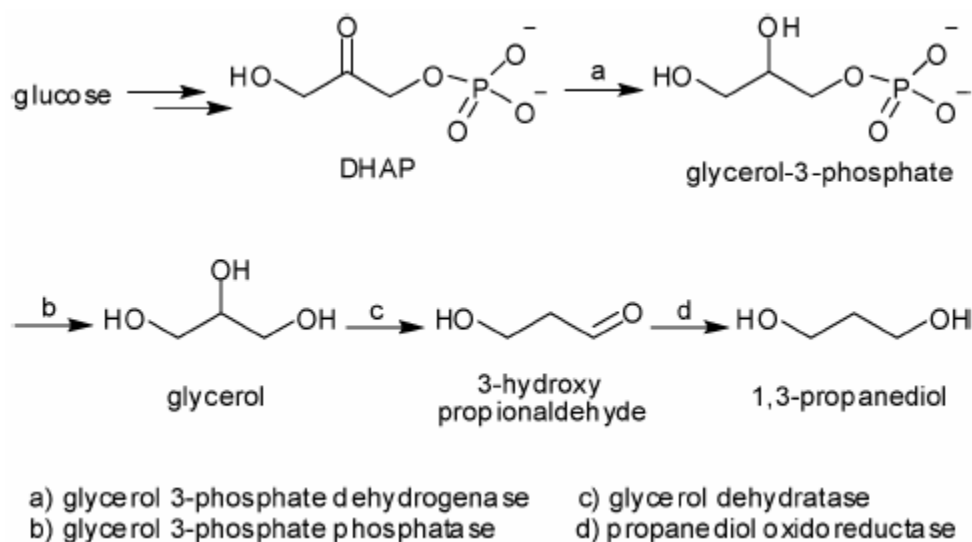
Scheme 16.19.

The engineered strain relies on a predominantly heterologous carbon pathway that diverts carbon from dihydroxyactone phosphate (DHAP) to PDO. Two genes from yeast encoding glycerol 3-phosphate dehydrogenase (dar1) and glycerol 3-phosphate phosphatase (gpp2) directs glycolysis pathway to glycerol. Two genes from K. pneumoniae encoding glycerol dehydratase (dhaB1-3) and 1,3-propanediol oxidoreductase (dhaT) then transform glycerol to PDO. Significant modifications were then made to the base strain by extensive metabolic engineering to improve the fermentation productivity. Additional genes from dha operon were incorporated into the engineered strain to stabilize glycerol dehydratase via reactivation. Moreover, an E. coli endogenous oxidoreductase (yqhD) was found to be superior to dhaT in providing high PDO titer (¡«130 g L-1). As a result, the yield of PDO production in one-pot from glucose was eventually improved to 51% (g g-1).

In contrast to the chemical processes to PDO, the biocatalytic process uses a renewable resource and was run at close to room temperature without added pressure. The bioprocess to PDO also reduces the energy consumption by 40% and green gas emissions by 20%. As of December 2006, shipments of corn sugar-derived PDO have been initiated from a 100 million-lb per- year plant. The successful development of a bio-based PDO process showed that it is possible to produce bulk chemicals in a more cost-effective way than the chemical processes while adhering to the principles of green chemistry.

CASE STUDY 7: Polymers

Another recent application of biocatalysis for green chemistry development is the production of polymeric materials. Enzymatic polymerization, i.e., in vitro synthesis of polymers using isolated enzymes, offers a number of advantages over conventional chemical methods that often require harsh conditions and the use of toxic reagents. Benefiting from high regio and enantioselectivities under mild conditions, an enzymatic approach provides a new synthetic strategy for the production of novel polymers, which are otherwise dif.cult to get by chemical transformations. Enzymatic polymerization has been applied to the synthesis of a number of polymers such as polyesters, polycarbonates, polysaccharides, polyurethanes, polyaromatics and vinyl polymers using oxidoreductases, transferases and hydrolases.

For example, a simple, environmentally-friendly, and versatile method was recently developed to produce polyol-containing polyesters through selective lipase-catalyzed condensation polymerization between diacids and reduced sugar polyols such as sorbitol (Scheme 20). Instead of using organic solvents, the monomers adipic acid, glycerol and sorbitol were solubilized within binary or ternary mixtures, and no preactivation of adipic acid was needed. The direct condensation of adipic acid and sorbitol was performed in bulk at 90 °C for 48 h using immobilized lipase B from Candida Antartica (Scheme 20). The product, poly(sorbityl adipate), had an average molecular weight of 10880 (M_n) and 17030 (M_w) respectively.
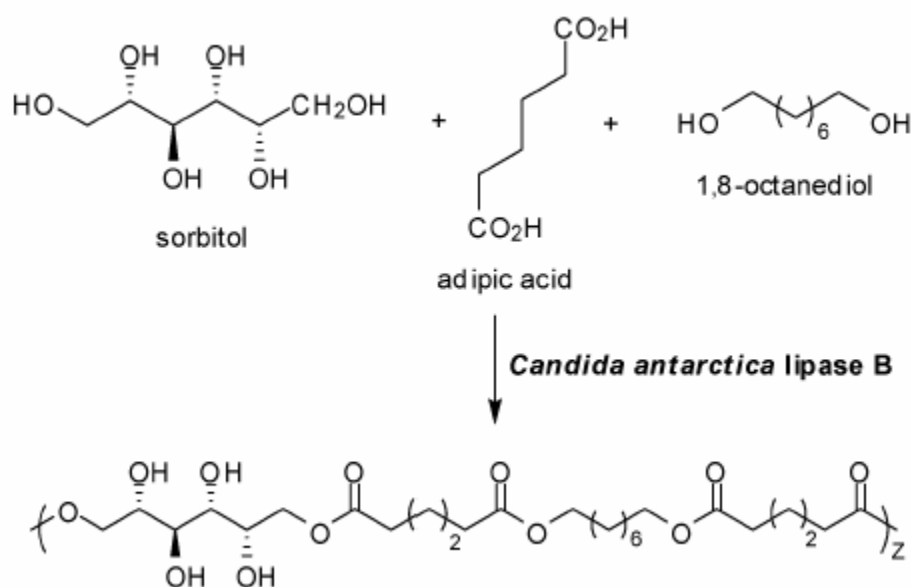
Scheme 16.20

By replacing a fraction of sorbitol with 1,8-octanediol, copolyesters of adipic acid, 1,8-octanediol, and sorbitol were obtained in the molar ratio of 50 : 35 : 15 with an Mw of >100 000. Similar results were also obtained with glycerol in place of sorbitol as the natural polyol (not shown). The condensation reactions with gycerol and sorbitol building blocks proceeded with high regioselectivity without protection–deprotection of functional groups. Although the polyol monomers contain three or more hydroxy groups, only two are highly reactive in enzymatic polymerization. Therefore instead of obtaining highly cross-linked products, the high regioselectivity leads to lightly branched polymers where

the degree of branching varies with the reaction time and monomer stoichiometry. The mild reaction conditions also facilitate the polymerization of chemically and thermally sensitive molecules. Alternative chemical polymerization would necessitate the use of stoichiometric amount of coupling agents. The biocatalytic approach is also versatile for simultaneous polymerization of lactones, hydroxyacids, cyclic carbonates, cyclic anhydrides, amino alcohols, and hydroxythiols as a result of high regioselectivity. Another example is enzyme-catalyzed ring-opening polymerizations of lactones and cyclic carbonates, which offer number of advantages over chemical methods including mild reaction conditions and improved propagation kinetics and/or molecular weights.

The ring-opening polymerization of pentadecalactone and trimethylene carbonate catalyzed by the lipase PS-30 and Novozyme-435 in bulk at 70 ^{o}C afforded high average molecular weight and moderate dispersity products (not shown). Enzymatic polymerization also allows structural control by regioselective incorporation of multifunctional initiators such as carbohydrates. In the ring-opening polymerization of e-caprolactone or trimethylene carbonate with ethyl glucopyranoside as an initiator catalyzed by porcine pancreatic lipase, the polymerization occurred selectively from the 6-hydroxyl position (Scheme 21). Since both ethyl glucopyranoside and the monomers are liquids, the reaction could be carried out in the absence of solvents. The novel amphiphilic product was prepared in one-pot without the need of protection and deprotection chemistry. Hydrolases were also able to catalyze transesterification reactions between a monomer and a polymer or between two homopolyesters that differ in main chain structure. For example, Novozym-435 catalyzed transesterification between polypentadecalactone (4300 g mol-1) and polycaprolactone (9200 g mol-1) resulted in random copolymers within one hour. In addition to catalyzing metal-free transesterification under mild conditions, lipases endow transesterfication reactions with remarkable selectivity, allowing the preparation of block copolymers that have selected block lengths. Recent advances in biocatalysis have also made an in road in the manufacture of biodegradable plastics such as polyhydroxyalkanoates (PHA) and polylactides (PLA). Polyhydroxyalkanoates are a class of natural polyesters produced by many bacteria in the form of intracellular granulates as a carbon and energy reserve. Since the initial discovery of poly-3-hydroxybutyrate (PHB), more than 130 hydroxyacid

monomer compositions have been identified that have been classified as short-chain and medium-chain hydroxyalkanoates. Once extracted from bacterial cells, the biobased polymers display diverse material properties that range from thermoplastics to elastomers depending upon their monomer unit composition. The environmental benefit of using biodegradable PHA and the utilization of abundant, renewable starch as a starting material for its synthesis provide an appealing alternative to the commonly used petroleum-derived plastics. Of all the PHAs, PHB copolymers are the most extensively studied. The biosynthetic pathway of polyhydroxybutyrate consists of three enzymatic reactions (Scheme 22).Thiolase catalyzes the condensation of two molecules of acetyl-CoA to form one molecule of acetoacetyl-CoA, which is then reduced to (R)-3-hydroxybutyryl-CoA by aNADPH-dependent acetoacetyl-CoA dehydrogenase. The crucial polymerization of **44** is catalyzed by a PHB synthase with concomitant regeneration of coenzyme A (Scheme 16.22).
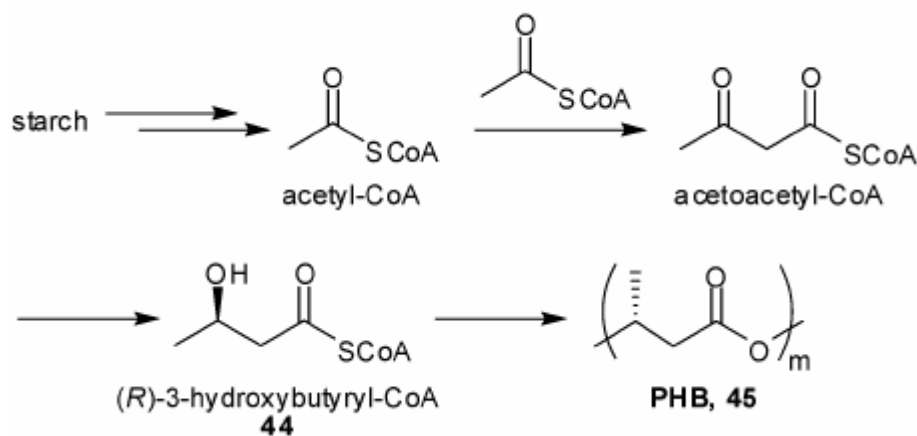
Scheme 16.22.

PHB homopolymer is a stiff and brittle material. The high melting temperature of PHB limits the ability to process the biopolymer. Incorporation of 3-hydroxyvalerate into PHB renders a poly(3-hydroxybutyrate-co-3-hydroxyvalerate) block copolymer **48**, which can be processed at a lower temperature while still retaining excellent mechanical properties. The monomer (R)-3-hydroxyvaleryl-CoA **47** is produced from condensation of acetyl-CoA and propionyl-CoA to 3-ketovaleryl-CoA (**46**) followed by reduction catalyzed by acetoacetyl-CoAdehydrogenase (Scheme 23). With the advances in genome sequencing projects, novel PHA synthases with different activities and substrate specificities have

been identified. Together with metabolic engineering of diverse, heterologous pathways for efficient biosynthesis of the monomer substrates from renewable starting materials, high yielding production of polyhydroxyalkanoates has been achieved via microbial fermentation. Accumulation of PHA in genetically engineered Pseudomonas reached 90% of the cell weight. Typical molecular weight of the polymer ranges from 50 000 to 1 000 000 Da. Recent research efforts have been devoted to the production of PHA in transgenic plants. Direct production of PHA in plants has the potential to dramatically lower the manufacturing cost, and reduce the burden of plastic wastes as a result of biodegradability to environmentally friendly products.
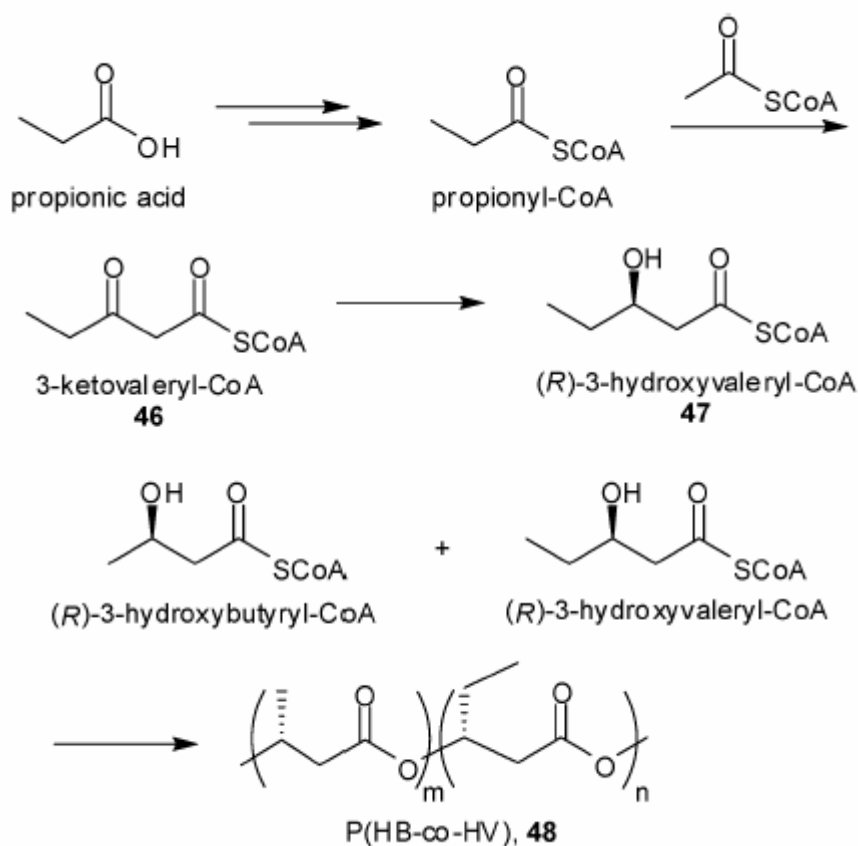
Scheme 16.23.

CONCLUSIONS

The new development in synthetic chemistry is green chemistry, and the principles involved have created newer opportunities to develop new technologies to improve chemical processes. A recent study shows that among the 1039 chemical transformations

analyzed for the synthesis of 128 drug molecules, chemical acylations are one of the most common transformations which, however, are generally inefficient. Development of catalytic, low waste acylation methods would significantly improve the environmental performance of many syntheses. The discovery of new regioselective and catalytic oxidations would greatly increase flexibility in synthetic design, as illustrated in the green and biocatalytic synthesis of pharmaceuticals and fine chemicals. Biotransformations are uniquely suited to deliver high stereo- and regioselectivity in water at ambient temperature and atmosphere, and are able to catalyze reactions that are challenging for traditional chemistry. The key is to integrate synthetic chemistry, biological transformations and process development and biocatalysis is positioned to be a transformational technology for chemical production with improved synthetic efficiency.

REFERENCES

1. James A. Schwarz, Cristian Contescu & Adriana Contescu, Chem.Rev., (1995) 95477

2. Ningqing Ran, Lishan Zhao, Zhenming Chenb & Junhua Tao, Green Chem., 10 (2008) 361.

3. C. N. R. Rao, Materials Science and Engineering, BI8 (1993) 1.

4. Abraham Szöke, William G. Scott & János Hajdu, FEBS Letters 553 (2003) 18.

5. The Way of Synthesis: Evolution of Design and Methods for Natural Products Tomas Hudlicky, Josephine W. Reed, 2007, Wiley-VCH.

6. Synthesis of Inorganic Materials, Ulrich Schubert, Nicola Hüsing, 2005,Wiley-VCH.

7. Härkönen et al., Nucl. Instr. and Meth. A 541 (2005) 202.

8. leksic et al., Ann. of NY Academy of Sci. 972 (2002) 158.

9. Lindström et al., Nucl. Instr. and Meth. A 466 (2001) 308 and cited literature therein.

10. C. N. R. Rao Materials Science and Engineering B,Volume 18, Issue 1, 1993, 1.

11. Insights into Speciality Inorganic Chemicals, David Thompson, 1995, Wiley-VCH.

12. Organic Chemistry Principles and Industrial Practice, Mark M Green, Harold A Wittcoff, 2003, Wiley-VCH.

Chapter - 17

COMPUTATIONAL BASICS UNDERLYING SYNTHETIC STRATEGIES

S. Sabiah

KEY WORDS: Computation, Synthetic strategy, Synthesis design, Computer-assisted synthesis

INTRODUCTION:

Synthetic strategy is an important stepping stone for scientific community. It has been found so crucial and innovative in the four mainstream of research namely,

1. Observational Science
2. Experimental Science
3. Theoretical Science
4. Computational Science

Since the topic of choice is on computational, I would like to draw few lines about the computational science. **Computational science** (or **scientific computing**) is the field of study concerned with constructing mathematical models and numerical solution techniques and using computers to analyze and solve scientific, social scientific and engineering problems. In practical use, it is typically the application of computer simulation and other forms of computation to problems in various scientific disciplines. It uses everything that scientists already know about a problem and incorporates it into a mathematical problem which can be solved. The mathematical model which then develops gives scientists more information about the problem. Computational Science is beneficial for two main reasons:

1. It is a cheaper method of conducting experiments.
2. It provides scientists with extra information which helps them to better plan and hypothesizes about experiments.

Due to these reasons, computation has gained much attention in almost all fields of science which are listed below under computational disciplines.

COMPUTATIONAL DISCIPLINES

- Bioinformatics
- Cheminformatics
- Chemometrics
- Computational biology

- Computational chemistry
- Computational economics
- Computational electromagnetics
- Computational engineering
- Computational fluid dynamics
- Computational mathematics
- Computational mechanics
- Computational physics
- Computational statistics
- Environmental simulation
- Financial modeling
- Geographic information system (GIS)
- High performance computing
- Machine learning
- Network analysis
- Numerical weather prediction
- Pattern recognition

Since the main focus of the chapter is on **synthetic strategies in chemistry**, it is likely to be elaborated towards chemical aspects. In the field of chemistry, we all know that the beginning of the organic synthesis is started with the preparation of urea by Wohler in 1828. It is only in 1967 that a systematic analysis of synthesis towards the direction of computer-assisted synthesis design (CASD) was reported by E. J. Corey [1]. Since then the computational methods in chemistry has been growing in many dimensions and every scientific paper pays attention to computational support in addition to the experimental evidences. It has also become a useful way to investigate materials that are too difficult to find or too expensive to purchase. It helps chemists to make predictions before running the actual experiments so that they can be better prepared for making observations. Hence, we can say that computational chemistry is partly assisting the basic chemical problems deal with synthesis, structure and spectroscopy of materials and indeed important to discuss further.

Computational Chemistry

Computational chemistry is a branch of chemistry that generates data, which complements experimental data on the structures, properties and reactions of substances. It can in some cases predict hitherto unobserved chemical phenomena. It

is widely used in the design of new drugs and materials. The calculations are based primarily on Schrödinger's equation (eqn. 1).

$$\{\frac{-h^2}{8\pi^2 m}\nabla^2 + V\}\Psi(r,t) = \frac{ih}{2\pi}\frac{\partial\Psi(r,t)}{\partial t}$$ ....**eqn 1**

The symbol ψ is a mathematical function that calculates the strength of the deBroglie wave at various positions in space. The rest of the components are as follows:

h = Planck's constant

m = the mass of the particle

Δ = a partial differential operator called the Laplacian operator

V=the potential energy

Ψ=psi, the wave function

i =the square root of -1

The final form of equation **1** is $H\psi = E\psi$

Where H = Hamiltonian Operator; E = total energy of the system

- Computational chemistry is particularly useful for determining molecular properties which are inaccessible experimentally and for interpreting experimental data

- With computational chemistry, one can calculate:
    - electronic structure determinations
    - geometry optimizations
    - frequency calculations
    - transition structures
    - protein calculations, i.e. docking
    - electron and charge distributions
    - potential energy surfaces (PES)
    - rate constants for chemical reactions (kinetics)
    - thermodynamic calculations- heat of reactions, energy of activation

- There are three main types of calculations:
    1. Ab Initio: (Latin for "from scratch") a group of methods in which molecular structures can be calculated using nothing but the Schroedinger equation, the values of the fundamental constants and the atomic numbers of the atoms present

2. Semi-empirical: techniques use approximations from empirical (experimental) data to provide the input into the mathematical models

3. Molecular mechanics: uses classical physics to explain and interpret the behavior of atoms and molecules

Currently, there are two ways to approach chemistry problems: **computational quantum chemistry** and **non-computational quantum chemistry.** Computational quantum chemistry is primarily concerned with the numerical computation of molecular electronic structures by *ab initio* and semi-empirical techniques and non-computational quantum chemistry deals with the formulation of analytical expressions for the properties of molecules and their reactions. Examples of such properties are structure (i.e. the expected positions of the constituent atoms), absolute and relative (interaction) energies, electronic charge distributions, dipoles and higher multipole moments, vibrational frequencies, reactivity or other spectroscopic quantities, and cross sections for collision with other particles.

The methods employed cover both static and dynamic situations. In all cases the computer time increases rapidly with the size of the system being studied. That system can be a single molecule, a group of molecules or a solid. The methods are thus based on theories which range from highly accurate, but are suitable only for small systems, to very approximate, but suitable for very large systems. The accurate methods used are called ab initio methods, as they are based entirely on theory from first principles. The less accurate methods are called empirical or semi-empirical because some experimental results, often from atoms or related molecules, are used along with theory.

There are two different aspects to computational chemistry:

- Computational studies can be carried out in order to find a starting point for a laboratory synthesis, or to assist in understanding experimental data, such as the position and source of spectroscopic peaks.

- Computational studies can be used to predict the possibility of so far entirely unknown molecules or to explore reaction mechanisms that are not readily studied by experimental means.

To perform these computational simulations or calculations, super computers with high performance computing facility is needed.

Impact of High Performance Computing

The amount of chemical information is quite large and calls for computer as the main source for storage. With presently

- 17 million known compounds
- 500000 new compounds each year
- 600 000 chemistry-related publications annually

An overview and access to all this information can only be maintained by electronic means.

Thus, databases on chemical information play a major role in present day research and development. Databases provide access to

- literature on 17 million compounds
- factual data on 7 million organic compounds
- several million reactions
- 140000 experimental 3D structures
- 250 000 spectra

SOFTWARES

The use of computers as tools in chemistry dates back to late 1950s. The adoption of FORTRAN as a scientific programming language is the beginning of these studies[2]. Only from around 1980 – 1990, the user had access to a variety of network based resources from a single point of use. A more sophisticated example is the use of Java to display digital spectral information derived from an NMR spectrometer, [3] and Java is a computer language developed by Sun Microsystems for writing programs to run on the web within a browser. It is used to link regions of the spectrum to specific atoms or residues in a 3D molecular object. The links can be bi-directional, i.e. clicking on a specified atom will highlight the spectral region containing peaks associated with that atom.

Chemists have been some of the most active and innovative participants in this rapid expansion of computational science. Some common computer software used for computational chemistry includes:

- Gaussian 03
- GAMESS
- MOPAC
- Spartan

- Sybyl

Now let us move towards the use of these computational basics for synthetic strategy especially in basic organic chemistry. Once we know how it works, it can be extendable to other materials.

1. IN ORGANIC SYNTHESIS

When a chemist wants to synthesize a compound of interest, it is called *target molecule* and he looks in to the target to identify any known fragment called *substructure* is present whose synthesis is already available. For example, in the synthesis of the Ibogamine, chemist perceives the presence of an indole nucleus, whose synthesis is known (Chemical structures are shown inside the box). So, he may plan the synthesis similar to Indole as outlined in Scheme 1.
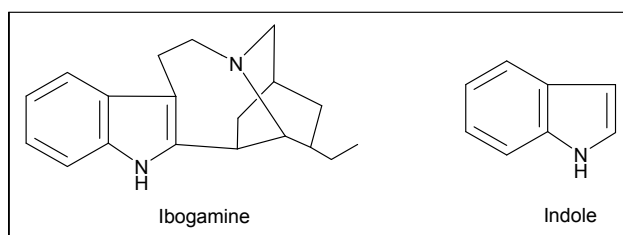
Scheme 1
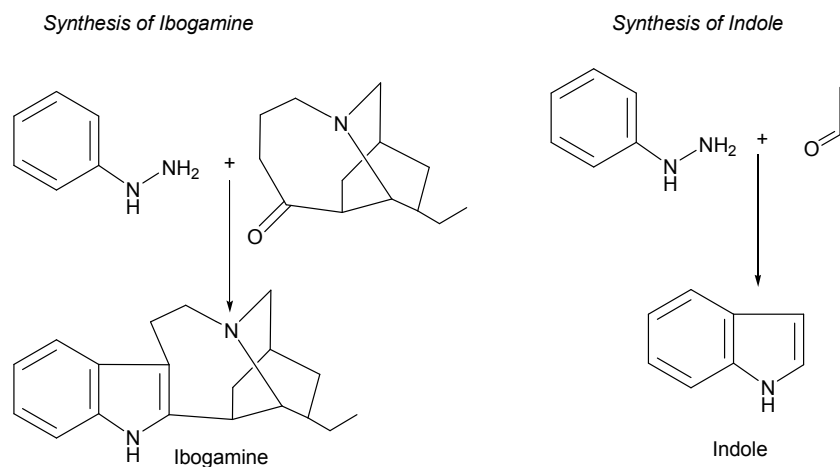
A known *starting material* is very similar to the target and the problem is 'reduced' to find the reactions which will convert it to the target. Despite the similarity of the starting material and the target, the number of steps to obtain the target may be high in certain cases which triggered the venture of using a computer to solve synthesis problems [4]. The number of reactions being very high (several thousands), the computer should be able to store all these reactions. It would never forget them and it

could generate all the possibilities. For this purpose, Corey proposed a general approach which is discussed.

Corey's Approach

Starting from the target, the program finds its *precursors,* then each precursor becomes a target and new precursors are generated; the process is then repeated until commercial or simple products are generated. This approach is called *retro-synthetic* or antithetic, since it is the reverse of the synthesis as practiced at the bench. This approach may be visualized by a *'synthesis tree'* (Scheme 2). This approach should, formally, be 'easily' programmed: it necessitates 'only' writing a program able to generate the precursors of a target and this program is repeated again and again. Numerous programs have been written after this initial report and several reviews on this subject have been published [5].

Scheme 2

Target

P1   P2   P3   First level
                              of precursors

P4   P5 P6   P7   P8   Second level
                              of precursors
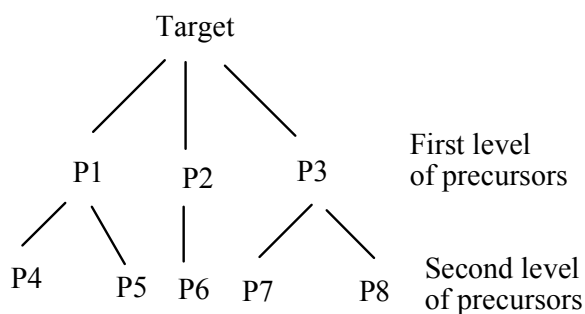
The above *tree* points outline the essential problems like how to describe a molecule and how to describe a reaction, that is, how to generate a precursor. Let us consider the classical Diels-Alder reaction,

Scheme 3

diene   dienophile   cyclohexene

  1   2   3
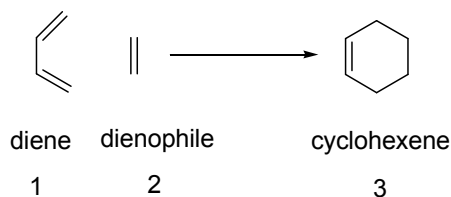
The above equation corresponds to writing of the reaction in the synthetic (or forward) direction: reacting **1** with **2,** under appropriate conditions, generates **3**. In the approach proposed by Corey, the program works backward, from the target to the precursor: in the retro-synthetic or antithetic direction. So the program has to search the *substructure* **3** in the target and, if it is present, it replaces it by the precursor(s)

substructure(s), here 1 + 2. To describe the reaction in the retro-synthetic direction, the term of *'transform'* has been proposed [6] and the use of a double lined arrow indicates this operation (Scheme 4):

Scheme 4

cyclohexene   diene   dienophile
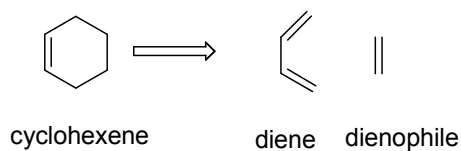
This description may look simple for a computer, but fails for certain circumstances. For example,

Scheme 5

4   5
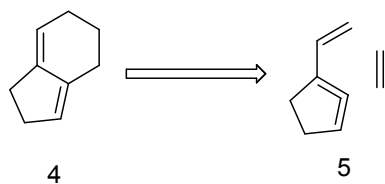
If 4 is the target then the precursor would be 5, which is an impossible solution due to the allenic function in a five-membered ring. But, computer predicts scheme 5 as a retro-synthetic approach which is not applicable to laboratory synthesis. Similarly, if the computer is taught the reduction of a keto group (7) to form an alcohol (6), described in scheme 6, the backward mode by the transform of scheme it will generate 7 as a possible precursor for 6. This is again a wrong solution, indeed there is another keto group which will generally be reduced, so that, in the laboratory the result would not be 6 but 8 (Scheme 6).

Scheme 6

6   7   8
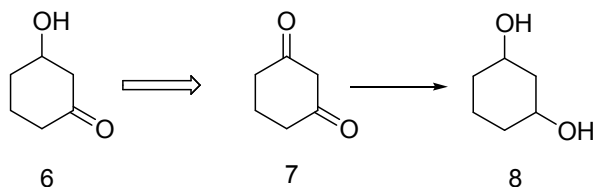
These two examples clearly indicate that the computer should know to discard wrong solutions for a synthetic strategy. Hence there should be a way to settle communication between the computer and the chemist for the following aspects:

I.   Description of molecules

II.   Description of reactions

III. Pruning the synthesis tree

These aspects are discussed in the upcoming section.

I. Description of Molecules

(a) Use of Connectivity Table

The molecules of interest are first described by *connectivity tables* which list in several arrays the atoms and the bonds of the target. An example is given with atom labeling (bold) and nature of bonds (normal numbers) for compound A.
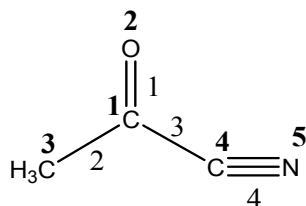
compund A

Then the connectivity is given by atomic table and bond table as described in Tables 17.1 and 17.2. These tables are not given in this form to the computer. Actually the chemist draws the structure on the screen using a mouse [7], and a program takes care of transforming this graphic structure into a connectivity table.

Table 17.1. Atomic table for compound A

Atom number	Atom type	Neighbors number			Bonds number			Number of hydrogen atoms
1	C	2	3	4	1	2	3	0
2	O	1			1			0
3	C	1			2			3
4	C	1	5		3	4		0
5	N	4			4			0

This description is a *topological* one, but when a chemist looks at a target he does not only see a succession of atoms and bonds. He automatically perceives structural features, such as functional groups, rings, stereo-centers, and their relative positions. The information is central to finding the solutions of the problem. The computer also needs to be taught this chemical perception of the target. So, when the drawing of the target is done and the connectivity tables have been established, before starting the retro-synthetic process, the program searches for these characteristics and stores them

in a binary array which is a kind of identity card of the target. An example of a partial binary array for structure A is given in Table 17.3.

Table 17.2. Bond table for compound A

Bond number	Atom 1	Atom 2	Bond type
1	1	2	2
2	1	3	1
3	1	4	1
4	4	5	3

Table 17.3. Binary array for compound A

Groups atom number	C	N	O	CH	CH_2	CH_3	Ketone	Nitrile	Cyclic atom
1	1	0	0	0	0	0	1	0	0
2	0	0	1	0	0	0	0	0	0
3	1	0	0	0	0	1	0	0	0
4	1	0	0	0	0	0	0	1	0
5	0	1	0	0	0	0	0	0	0

With the topological tables and this analytical one, the program gains a chemical perception of the target.

(b) Use of Matrices

In 1971 Ugi and Gillespie [8] proposed the concept of 'BE' (for bond-electron) matrices to describe molecules. 'BE' matrices were then transformed into connection tables. In this model the element (i, *j)* of the matrix corresponds to the bond order between atoms i and *j* (l = single bond, 2 = double bond, ...) and the diagonal elements (i, i) describe the free valence electrons of atom i. Compound A is described by the matrix of equation (1):

	1	2	3	4	5
1	0	2	1	1	0
2	2	2	0	0	0
3	1	0	0	0	0
4	1	0	0	0	3
5	0	0	0	3	1

------------ (1)

(c) Use of Numerical Linear Notation

In 1971, Hendrickson proposed a logical description of structures and reactions by a simple mathematical model [9] which has been developed and used in the program SYNGEN. This mainly focuses on carbon skeleton as shown for a three carbon system of compound B. In the original system four kinds of attachments to any carbon are described and counted: H for attachment of hydrogen, or electropositive atoms; R for σ-bond to another carbon; Π for π-bond to another carbon and Z for a bond $(\sigma$ or $\pi)$ to an electronegative heteroatom (N, O, S, X). The H, R, Π and Z are notations used in the program. How many numbers of such attachments is described by h, σ, π, z, respectively. The functionality (f) at a carbon site is defined as the sum of z and π, and the character (c) of a carbon site is $c = 10\,\sigma + f$.

In SYNGEN the functional groups on each carbon atom are abstracted with the two digits z and π; for atom 2 of Scheme 7, the $z\pi$ list is 11, for atom 3 it is 30.

Scheme 7

Compound B
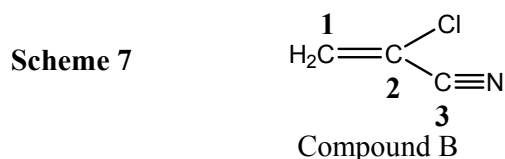
atom	σ	z	π	f	c
1	1	0	1	1	11
2	2	1	1	2	22
3	1	3	0	3	13

II. Coding of a Particular Reaction

The three main systems described above lead to three main methods for coding reactions in CASD programs. The description of reactions leads also to two families of CASD programs: empirical and non-empirical. The empirical programs are based

on known reaction libraries. The advantage of such an approach is that the programs predict syntheses which have great chances of feasibility provided that specific structural features do not strongly interfere with one of the proposed reactions. On the other hand, these programs cannot suggest totally new synthesis reactions. Further, the number of reactions to code is very large; theoretically, all known reactions should be coded in the reaction files.

In the non-empirical programs reactions are coded in a logical, mathematical or general way, in order to describe the maximum of reactions with a minimum of principles. The aim is also to have a system able to propose new syntheses, even new reactions if they have not yet been described in the literature

(a) The Transform Approach

As indicated above, the word 'transform' is employed to describe a reaction in the retro-synthetic direction. The aim of a CASD program is to generate the precursors of a target. To do this, a program has three main tasks to perform:

- Search for a substructure which describes the transform (called synthon or retron)

- Generation of the precursors

- Evaluation of the validity of the solutions.

The main differences between the various programs come from the evaluation step, which may be more or less accurate. In SOS program, a full graphic interface has been developed to input transform and evaluation tests. For example, the user draws the retron and its precursor with the mouse (Fig. 17.1). Let us consider the example of the Diels-Alder reaction. Symbol A stands for any atom in order to generalize the reaction. Since the diene may react with a double or a triple bond, one may use the simple/double bond in the target and double/triple bond in the precursor (bonds with dotted lines).
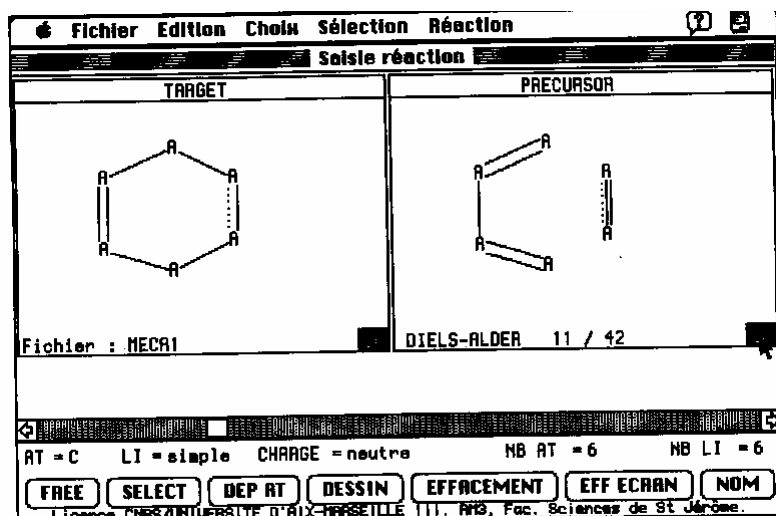
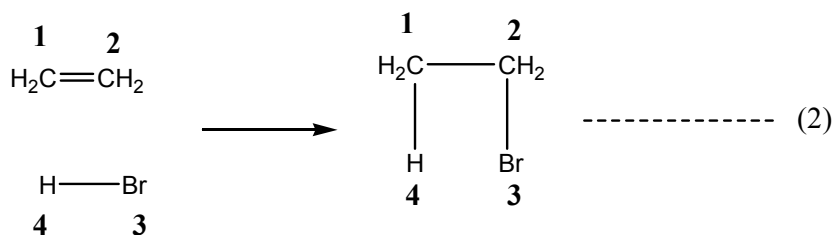Fig. 17.1. Representation of an active window from SOS program

To enter a test, the chemist selects this option in the reaction menu and indicates that the test must be applied on the target. The atoms and the bonds are numbered and the user may enter the test by clicking on the buttons at the bottom of the screen. The test allows for a solution such as that if atom 4 is sp^2 and bond 3 is a fused bond then the reaction is impossible. This program also allows graphical tests: the user draws a substructure and the action to perform if it is present in the scrutinized target.

In SOS, coding of reactions by means of mechanisms (i.e., elimination, nucleophilic addition, nucleophilic substitution, etc.) allowed chemists to generalize reactions, to reduce the number of reactions in the files, and to extend a scheme to a new case even if it has not been described in the literature.

(b) Be-matrices Approach.

Ugi and Dugundji developed a mathematical model of constitutional chemistry [10]. This model is based on the concept of isomerism of molecules which has been extended to ensembles of molecules. For example, a theoretical reaction: A + B → C + D can be seen as the conversion of an ensemble of molecules (A + B) into an isomeric ensemble (C + D). As an extension, the discovering of a synthesis: Target ⇨ Precursor 1 ⇨ Precursor 2⇨ ⇨::::⇨Starting materials, may be done by generation of isomers.

The description of molecules by means of matrices allows one to describe reactions by additions of matrices; let us take the addition of H-Br on a double bond (equation 2).
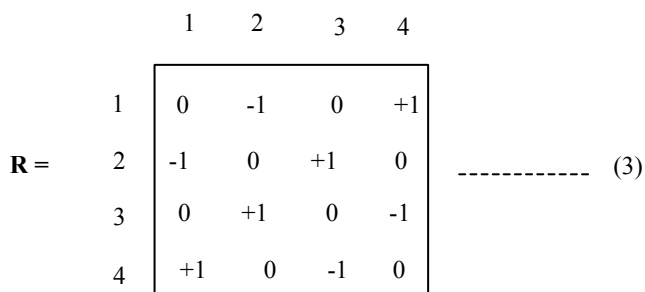
$$
\begin{array}{cc}
\overset{1}{}\quad\overset{2}{} \\
H_2C = CH_2
\end{array}
\qquad\longrightarrow\qquad
\begin{array}{cc}
\overset{1}{H_2C}\!-\!\!-\!\!-\!\overset{2}{CH_2} \\
\big| \qquad\ \big| \\
\underset{4}{H} \qquad \underset{3}{Br}
\end{array}
\qquad\text{-------------- (2)}
$$

$$
\begin{array}{cc}
\overset{}{H}\!-\!\!-\!\!-\!Br \\
4 \qquad\ 3
\end{array}
$$

Let B be the be-matrix for the starting materials and E the be-matrix for the end products (Scheme 8).

Scheme 8

	1	2	3	4
1	0	2	0	0
2	2	0	0	0
3	0	0	0	1
4	0	0	1	0

B

|	1	2	3	4
1	0	1	0	1
2	1	0	1	0
3	0	1	0	0
4	1	0	0	0

E
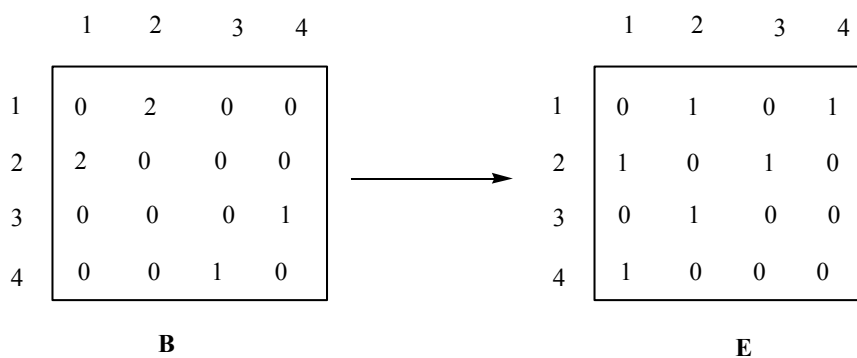
The transformation of B into E is defined by the reaction matrix R of equation (3) such that: B + R = E where off-diagonal entries $R_{ij} = R_{ji} = 0, \pm1, \pm2, \pm3$, indicate the bonds made or broken. This method is conceptually attractive because the retro-synthesis is simply: B = E - R.

$$
R =
\begin{array}{c|cccc}
 & 1 & 2 & 3 & 4 \\
\hline
1 & 0 & -1 & 0 & +1 \\
2 & -1 & 0 & +1 & 0 \\
3 & 0 & +1 & 0 & -1 \\
4 & +1 & 0 & -1 & 0 \\
\end{array}
\qquad\text{----------- (3)}
$$

(c) The Numerical Approach

The numerical approach is dealt by different ways by different programs. The SYNGEN program is based upon the concept of half-reactions; the formation of a bond may be seen as two linked half-reactions on each side of the bond (Scheme 9).

Scheme 9

C——C——C══C——C——C
γ   β   α   α   β   γ

C——C——C⁻   ⁺C——C——C
γ   β   α   α   β   γ
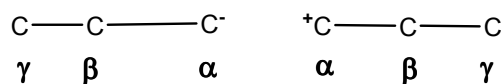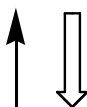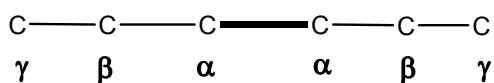
Nucleophilic   Electrophilic
Half-reaction   Half-reaction

Only three atoms are considered around the bond which is formed, because more than three carbons which change in a half-reaction are virtually never found [11]. The nucleophilic centers are given in Scheme 10, and the electrophilic ones in Scheme 11.

Scheme 10

α   β   γ

C⁻ ⟶ ══C——C——C

Z   C══C ⟶ ══C——C——Z

H——C——C══C ⟶ ══C——C══C
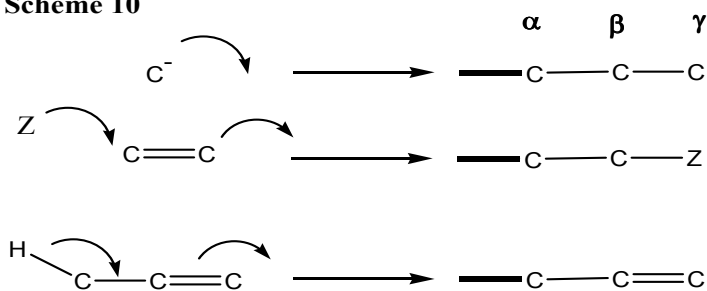
Thus, combining these three nucleophilic half-reactions with the three electrophilic half-reactions produces nine possible full construction reactions. A reaction may also be described by two letters, the first for the bond made, second for that broken.

Scheme 11

α   β   γ

C——Z ⟶ ══C

C══C H ⟶ ══C——CH

C══C——C——Z ⟶ ══C——C══C
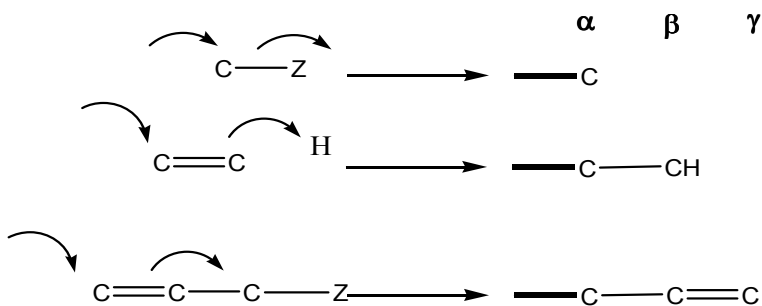
For the Michael reaction (Scheme 12), this concept yields for atom 2: formation of an σ bond (+ R) and loss of hydrogen (- H), the reaction on this carbon is designated by RH; for atom 3: formation of an σ bond and loss of a π bond: R Π and for atom 4: H Π.

Scheme 12
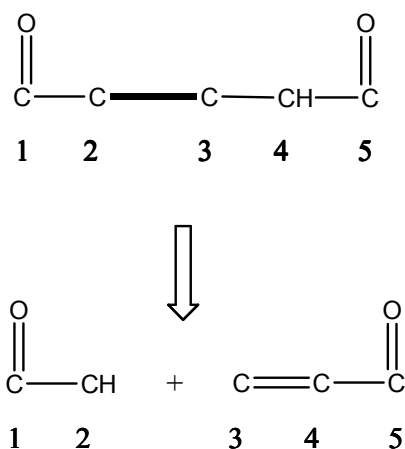
Since there are four kinds of bond (H, R, П, Z), there are 16 possible unit exchanges per carbon. This code allows a simple classification of reactions, for example ZH represents oxidation reactions (CH →C-OH), HZ represents reduction, the opposite of the previous one; addition reactions on a carbon-carbon double bond are: HП, RП, ZП, etc. This systematic definition of organic reactions provided a basis for developing COGNOS, a program for organizing and retrieving reactions in a large database [12].

III. Pruning the Synthesis Tree

The descriptions which are given above concern the coding of one reaction and how a precursor may be generated. In a basic retro-synthesis program, each reaction of the file (or of the files) is applied in turn for generating precursors and building, step by step, the synthesis tree. As indicated, the number of solutions found may be large and it is necessary to develop methods that are strategies, in order to reduce this tree and to try to select the best solutions.

The search of the key-step in a synthesis is, rather, a fundamental step. When it has been found, one may say that a general plan of the synthesis has been found. This search has been done in a very simple way in the SAS program: this program simply deleted one or several bonds in the target, suggesting ideas of synthesis. For example, in the case of ellipticine (Compound D), it suggested that several internal Diels-Alder reactions are involved. Solutions similar to **E** and **F** have been subsequently and independently found experimentally by others groups of researchers [13] (Scheme 13).

Scheme 13
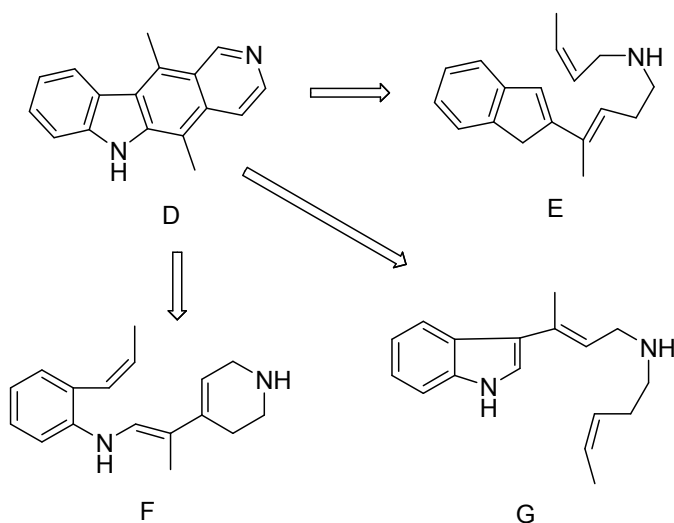
The other Strategies also include starting material oriented strategy, topological Strategies, stereo-chemical Strategies and Tactical Combinations of Transforms Strategy for pruning the synthesis tree for organic compounds. The idea derived from this is also applicable to synthesis of *Inorganic metal complexes, Energetic materials, Bio-molecules and drug design* which are briefly described in the following section.

2. INORGANIC MATERIALS

(a) Structure Identification:

In principle, systems for representing organic compounds can be applied to inorganic substances, as far as compounds are concerned in which the atoms are connected by covalent bonds. The Chemical Abstracts Service (CAS) registry system uses the notion of a mixture to accommodate substances without structure, e.g., alloys, whereas covalently bonded inorganic compounds represented by the connection table (CT) based system of CAS. Salts are represented as mixtures of the possibly structured ions constituting the salt.

In organic compounds an atom is generally connected to at most four neighbouring atoms where as in inorganic compounds larger coordination numbers is found and, consequently, a more involved stereochemistry is encountered. Furthermore, one has to deal with more complicated types of chemical bonds and sometimes there are well defined substances for which it is not obvious how to draw a structure at all. Whereas the subjects of organic chemistry are exclusively covalently bonded compounds of carbon, inorganic compounds furthermore comprise ionically

bonded substances like salts, alloys and glasses, different kinds of solutions, minerals, etc. Therefore a representation of inorganic compounds must provide some means to deal not only with covalently bonded compounds but also with substances which belong to those other types [14].Thus, the generalization leads the concept of multi-component systems in which each component consists of one or several fragments. The fragments turn may be structured or not, i.e., it may be possible to draw a structure diagram for them or not. In the structure storage system of the Gmelin Database, compounds without a structure are taken into account by a tabular representation, the inorganic structure tables (1ST). The hierarchy is shown in Fig. 17.4.

Figure 4
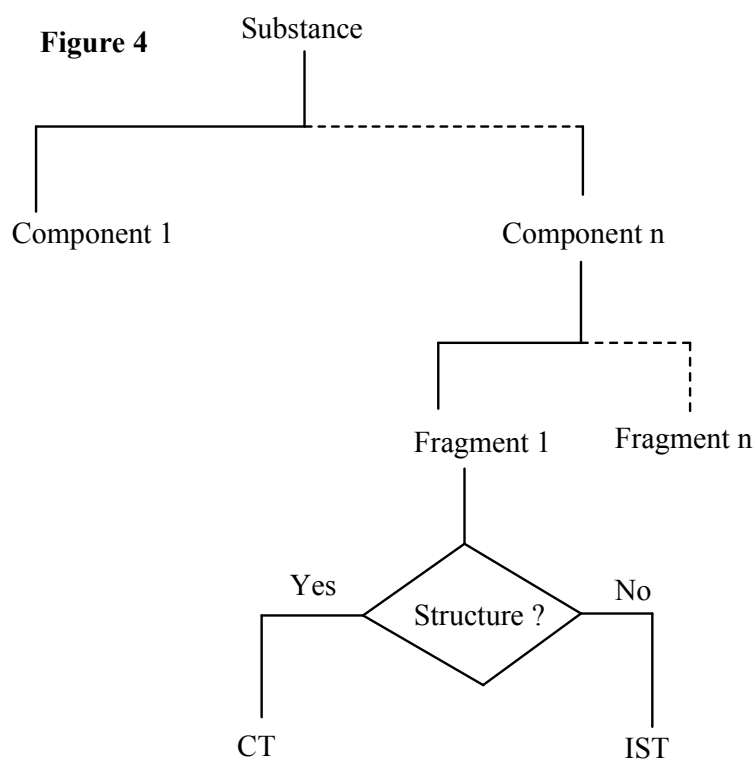
(b) Methodology

Molecular mechanics (MM) calculations have become increasingly important in understanding the structures and steric interactions that occur in inorganic, bioinorganic, and organo-metallic compounds. Since 1984, the growing use of the MM model in inorganic chemistry has been documented in a number of reviews [15]. Metal complexes that have been treated with MM typically involve one metal and multidentate organic ligands. The common functional groups found in these ligands include amines, imines, pyridines, amino acids, alcohols, ethers, carboxylic acids, thiols, sulfides, and phosphines. Many MM models, developed originally for

application to organic molecules, have the capability to treat the ligand part of the metal complex. These organic MM models have been extended to include metal-ligand interactions with the addition of relatively few terms. Various approaches are distinguished by the types of metal-dependent interaction that are used.

The two bonded methods in common use are the valence force field (VFF) method and the points-on-a-sphere (POS) method. In both methods the metal ion, M, is formally connected to the ligand donor atoms, L. In a normal organic MM program, this connection will create M - L bonds, M - L- X and L-M-L bond angles, M-L-X-X and X-M-L-X torsions, and M - X non-bonded interactions. The user decides which of these interactions will be used in the calculation through a choice of parameters. The VFF and POS methods differ only in the treatment of L- M - L angles. In the VFF method, L- M - L bond angle interactions are used to define a geometry prefer-ence about the metal center. In the POS method, L- M - L bond angle interactions are not used and geometry preference about the metal center derives primarily from 1, 3 van der Waals interactions between the donor atoms. The third method is non-bonded method where the metal ion is not formally connected to the ligand donors; the metal-ligand complex is modeled with a collection of pair-wise electrostatic and van der Waals interactions. The three methods which are commonly used for denoting these interactions are summarized in Table 17.4.

Table 17.4. Methods to extend MM models for metal complexes

No	Interaction	Bonded		Non-bonded
		VFF	POS	Ionic
1	M-L stretch	yes	yes	no
2	M-L-X bend	yes	yes	no
3	L-M-L bend	yes	no	no
4	L-L non-bonded	no	yes	yes
5	M-L-X-X torsion	yes	yes	no
6	L-M-L-X torsion	no	no	no
7	M-L non-bonded	no	no	yes
8	M-X non-bonded	no	no	yes

Apart from this, the geometry optimization and frequency analysis will give an idea about the stability of the molecules for laboratory synthesis. It is also possible to get structure-reactivity relationship for metal complexes. The concept of structure-

reactivity relationship implies that changes in structure should be quantitatively reflected in some measurable reactivity parameters associated with the molecule. For metal complexes, the capacity of the ligand structure to influence chemical properties is measurable in terms of reactivity parameters such as stability constants, rates of ligand dissociation, and reduction potentials. The influence of structure on chemical reactivity can often be rationalized in terms of steric and electronic components which module the synthesis of a particular compound. Same way, the structure-reactivity plays important role in constructing energetic materials which is outlined below.

3. ENERGETIC MATERIALS

Energetic materials encompass different classes of chemical compositions of fuel and oxidant that react rapidly upon initiation and release large quantities of force (through the generation of high-velocity product species) or energy (in the form of heat and light). These particular features have been advantageously employed in a wide variety of industrial and military applications, but often these utilizations have not been fully optimized, mainly due to the inability to identify and understand the individual fundamental chemical and physical steps that control the conversion of the material to its final products. The conversion of the material is usually not the result of a single-step reaction, or even a set of a few simple consecutive chemical reactions. Rather, it is an extremely complex process in which numerous chemical and physical events occur in a concerted and synergistic fashion, and whose reaction mechanisms are strongly dependent on a wide variety of factors.

Also, these processes often occur under extreme conditions of temperature and pressures, making experimental measurement difficult. These are but a few of the complexities associated with studies of reactions of energetic materials that make resolving the individual details so difficult. These difficulties have required the development of a variety of innovative theoretical methods, models and experiments designed to probe details of the various phenomena associated with the conversion of energetic materials to products [16].

The high time and pecuniary costs associated with the synthesis or formulation, testing and fielding of a new energetic material has called for the inclusion of modeling and simulation into the energetic materials design process. This has resulted in growing demands for accurate models to predict properties and behavior of notional energetic materials before committing resources for their development. For example, in earlier times, extensive testing and modification of proposed candidate

materials for military applications could take decades before the material was actually fielded, in order to assure the quality and consistent performance of the Predictive models that will allow for the screening and elimination of poor candidates before the expenditure of time and resources on synthesis and testing of advanced materials promise significant economic benefit in the development of a new material.

4. BIO-MOLECULES

Computational bio-modeling refers to a type of artificial life research concerned with building computer simulations of biological systems (bio-modeling). The immediate goal is to understand how biological entities such as cells or whole organisms, develop, work collectively, and survive in changing environments using a purely computational model. In order to meet this challenge we need to establish the methodologies and techniques that will enable us to gain a system-level understanding of biological processes. These kinds of models hold great promise for new discoveries in a wide variety of biological systems. Once an executable model has been built of a particular system, it can be used to get a global dynamic picture of how the system responds to various perturbations. In addition, preliminary studies can be quickly performed using executable models, saving valuable laboratory time and resources for only the most promising avenues.

One way of approaching this problem is to use ideas and methods originally developed in computer science, mainly in software and systems engineering (and in particular visual languages and formal verification) to construct, simulate and analyze biological models. The benefit of molecular modeling is that it reduces the complexity of the system, allowing many more particles (atoms) to be considered during simulations. The types of biological activity that have been investigated using molecular modeling include protein folding, enzyme catalysis, protein stability, conformational changes associated with bio-molecular function, and molecular recognition of proteins, DNA, and membrane complexes.

Softwares for bio-models

❖ **SPiM**

The Stochastic Pi Machine (SPiM) is a simulator for the stochastic pi-calculus that can be used to simulate models of Biological systems. The machine has been formally specified, and the specification has been proved correct with respect to the calculus.

❖ **ScatterWeb.NET SDK**

ScatterWeb.NET SDK is a new approach to working with wireless sensor networks. It hides the complexity of embedded programming and makes it easy to handle objects representing wireless sensors.

5. DRUG DESIGN

Drug design is presently the most prominent and visible application of information processing in chemistry. Clearly this is due to the large scientific and economic investment necessary for the development of a new drug. Efforts are made to combine all possible means for developing an understanding of the relationships between structure and biological activity. Consequently, this is an area where quantum mechanical and molecular mechanics calculations are effectively employed.

CONCLUSIONS

The collected examples explain the use of computational methods in synthesis of organic compounds and also extendable to inorganic and energetic materials. Researchers are focusing on creating the computational tools that will enable biologists and others working in the life sciences to better understand and predict complex processes in biological systems, which could revolutionize our understanding of disease, and lead to new and faster insights into entirely novel therapies and better vaccines.

REFERENCES

1. E. J. Corey, *Pure Appl. Chern.,* 14 (1967) 19.

2. S.1. Salley, *J. Am. Chem. Soc.,* 89 (1967) 6762.

3. H. S. Rzepa, "Chemistry and the World-Wide-Web", chapter in "The Internet: A Guide for Chemists", Ed. S. Bachrach, American Chemical Society, 1995. See http:// www.ch.ic.ac.uk/ java/HyperSpec

4. E. J. Corey and W. T. Wipke, *Science,* 166 (1969) 178.

5. M. Bersohn and A. Esack, *Chern. Rev.,* 76 (1976) 269.

6. E. J. Corey, R. D. Cramer, III, and W. J. Howe, *J. Am. Chem. Soc.,* 94 (1972) 440

7. S. Hanessian, J. Franco, G. Gagnon, D. Laramee, and B. Laruche, *J. Chem. Inf. Cornput. Sci.,* 30 (1990) 413.

8. I. Ugi and P. Gillespie, *Angew. Chem., Int. Ed. Engl.,* 10 (1971) 914.

9. J. B. Hendrickson, *J. Am. Chem. Soc.*, 93 (1971) 6847.

10. I. Dugundji and I. Ugi, *Top. Curr. Chem.,* 39 (1973) 19.

11. J. B. Hendrickson, D. L. Grier, and A. G. Toczko, *J. Am. Chem. Soc.,* 107 (1985) 5228.

12. J. B. Hendrickson and T. L. Sander, *Chen. Eur. J.,* 1 (1995) 449.

13. E. Differding and L. Ghosez, *Tetrahedron Lett.,* 26 (1985) 1647.

14. N. Allinger, Encyclopedia of Computational Chemistry, 1-5 (1997) 1320.

15. N. Allinger, Encyclopedia of Computational Chemistry, 1-5 (1997) 1580.

16. P. Politzer and J. Murray, Theoretical and Computational Chemistry: Energetic Materials, Part 1. Decomposition, Crystal and Molecular Properties, 2003, Elsevier Pubs.

Abbreviations

NMR – Nuclear Magnetic Resonance

GAMESS- The General Atomic and Molecular Electronic Structure System

MOPAC- Molecular Orbital PACkage

SYNGEN- SYNthesis GENerator

SOS-Simulated Organic Synthesis

SAS-Simulated Analytical Synthesis