Crystal Engineering as Molecular Recognition in the Solid State: Some Studies of Weak Intermolecular Interactions

A Thesis Submitted for the Degree of
DOCTOR OF PHILOSOPHY

By

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To

my mother

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Statement

I hereby declare that the matter embodied in this Thesis is the result of investigations carried out by me in the School of Chemistry, University of Hyderabad, India under the supervision of Professor Gautam R. Desiraju.

In keeping with the general practice of reporting scientific observations due acknowledgements have been made wherever the work described is based on the findings of other investigators.

Hyderabad
August, 1994

C.V. Krishnamohan Sharma

Certificate

Certified that the work "**Crystal Engineering as Molecular Recognition in the Solid State: Some Studies of Weak Intermolecular Interactions**" has been carried out by **C.V. Krishnamohan Sharma** under my supervision and that the same has not been submitted elsewhere for a degree.

Dean
School of Chemistry

Gautam R. Desiraju
Thesis Supervisor

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C.V. Krishnamohan Sharma

Chapter One

Introduction

1.1 Supramolecular Chemistry

Supramolecular chemistry has been defined by Lehn as 'chemistry beyond the molecule, and is the *designed* chemistry of the intermolecular bond, just as molecular chemistry is that of the covalent bond'.[1] This field is developing rapidly, as it has been realised that intermolecular interactions are the primary cause for many interesting properties of materials (conducting, magnetic and optical) and several biological functions (receptor binding to a protein and enzyme reactions).[1,2] Various aspects of supramolecular chemistry are schematically shown in Figure 1. Though the idea of constructing supermolecules was initiated to mimic biological functions, subsequent research on supermolecules led to the invention of many novel species and new processes. Now it has become a highly interdisciplinary field with a wide range of applications in the physical, chemical and biological sciences.

The organic crystal is a supermolecule 'par excellence'.[3] The study of organic crystal structures by X-Ray diffraction methods provides precise and unambiguous information on the intermolecular interactions which are essential for the development of systematic supramolecular chemistry. Information on these interactions is conveniently retrieved from the Cambridge Structural Database (CSD) and analysis of this information by statistical procedures results in extremely reliable descriptions of intermolecular interactions, especially in case of weak interactions.[2,4,5] Indeed the study of intermolecular interactions in crystal structures dates back to the 1980's when these interactions were used to control crystal packing to design solid state reactions. Such design strategies defined a new subject known as Crystal Engineering.[6]

Conventionally, molecular recognition studies are concerned with the binding of a substrate with the receptor through intermolecular interactions.[7–9] In principle both crystal engineering and molecular recognition depend on

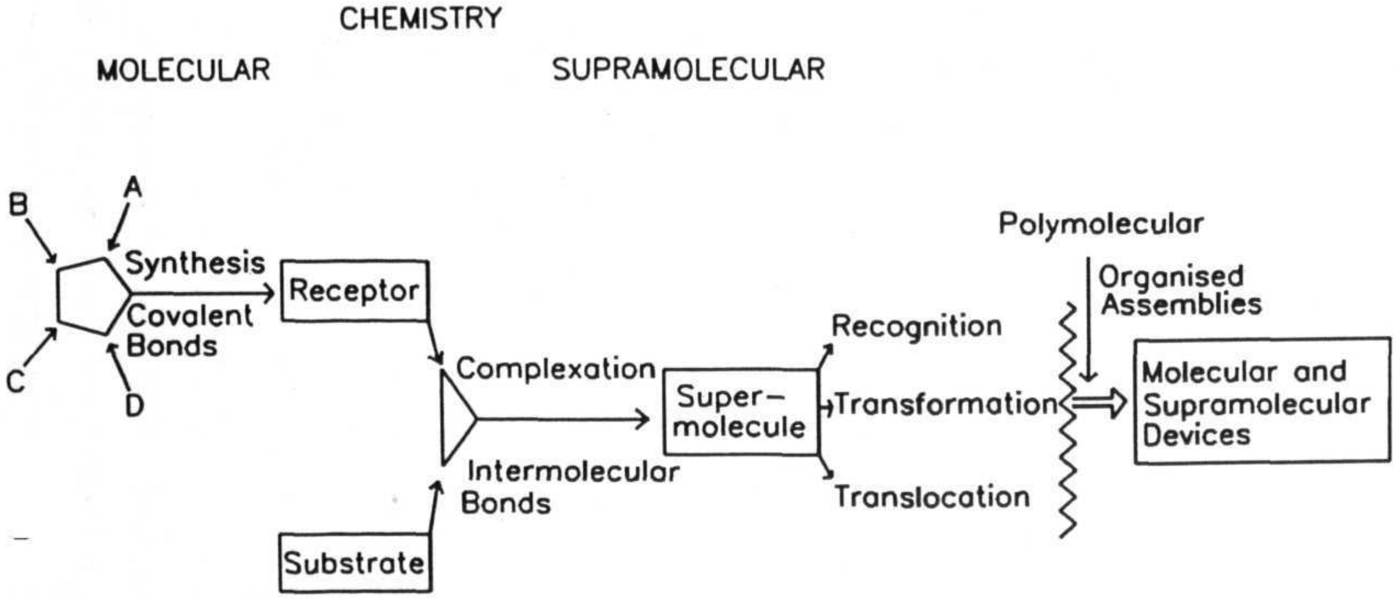

CHEMISTRY
MOLECULAR
SUPRAMOLECULAR
A
B
C
D
Synthesis
Covalent Bonds
Receptor
Substrate
Complexation
Intermolecular Bonds
Super-molecule
Recognition
Transformation
Translocation
Polymolecular
Organised Assemblies
Molecular and Supramolecular Devices

Figure 1

multiple matching of functionalities among molecular components so as to optimise a number of intermolecular interactions which are of different strengths. So it is possible to extend the principles of crystal engineering to molecular recognition studies. Such an extension will enable one to study the role of weak intermolecular interactions in molecular recognition events.

This chapter is intended to give a brief introduction to intermolecular interactions (based on X-ray crystal structural analysis), crystal engineering, molecular recognition and host-guest complexation. Finally it is attempted to reveal the complementarity of crystal engineering and molecular recognition in the development of supramolecular chemistry.

1.2 Intermolecular Interactions

The design of supermolecules requires a correct manipulation of the energetic and stereochemical features of the noncovalent, intermolecular forces within a defined molecular structure. Hence understanding the nature and strength of intermolecular interactions is of fundamental importance in supramolecular chemistry. Intermolecular interactions in organic compounds can be classified as isotropic, medium-range forces, which define molecular shape, size and close-packing and anisotropic, long-range forces, which are electrostatic and involve heteroatom interactions.[2] In general, isotropic forces include C...C, C...H, H...H interactions and anisotropic interactions include ionic forces, strongly directional hydrogen bonds (O-H...O, N-H...O) and weakly directional hydrogen bonds (C-H...O, C-H...N, C-H...halogen, O-H...π) and other weak forces such as aryl...aryl, halogen...halogen, N...halogen, S...halogen interactions and so on. In a crystal, various strong and weak intermolecular interactions co-exist and determine the three-dimensional scaffolding of molecules. It is customary to designate the strong, moderately weak and weak interactions as primary, secondary and tertiary interactions respectively. But this nomenclature is quite subjective because the definition of a strong or a weak interaction varies from structure to structure. For example, in benzoic acid, O-H...O hydrogen bonds and C-H...O hydrogen bonds may be named primary and secondary interactions, while herringbone interactions may be called tertiary interactions. On the other hand in p-benzoquinone, the C-H...O interactions may be termed primary while the stacking interactions are secondary. These terms are frequently used in the text and must be understood as appropriate.

Hydrogen bonds, aryl...aryl forces and van der Waals interactions are the important intermolecular forces in most biological and organic molecules. The structures of the organic solids studied in the present work are by and large controlled by these interactions only. So the discussion is confined mostly to these interactions.

1.2.1 Isotropic Interactions

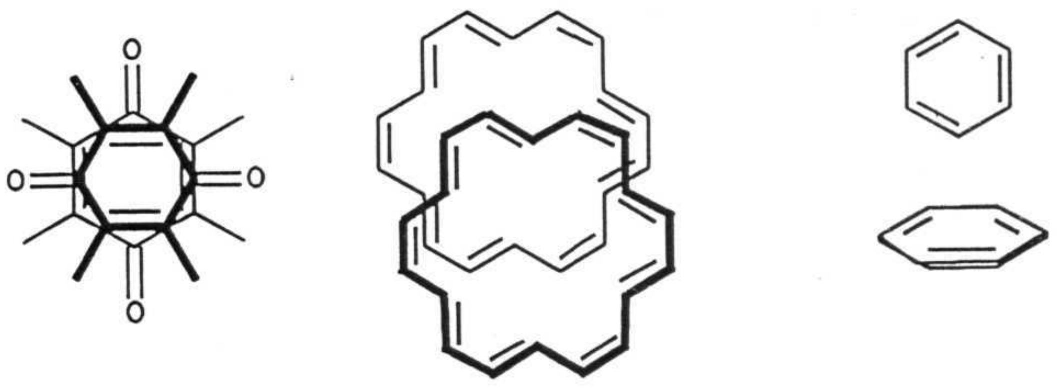
The isotropic or van der Waals interactions primarily constitute dispersion and repulsion forces. The dispersion forces are attractive in nature and are caused by the interaction between fluctuating multipoles in adjacent molecules. The strength of these forces is proportional to the inverse sixth power of the interatomic separation (r^{-6}) and are roughly proportional to the size of the molecule. The repulsive forces balance the dispersion forces and have an approximate twelfth power distance dependence. These two parameters form the basis for the popular Buckingham or $(6 - \exp)$ and Lennard-Jones or (6-12) atom-atom potential methods which are used to calculate the total crystal stabilisation energy.[10–12]

$U = 1/2 \sum_{ij} -Ar_{ij}^{-6} +$ Bexp$(-Cr_{ij})$ Buckingham

$U = 1/2 \sum_{ij} -Ar_{ij}^{-6} + Br_{ij}^{-12}$ Lennard-Jones

Here U is the total energy, r_{ij} is the distance between a pair of adjacent non-bonded atoms i and j and A, B and C are constants characteristic of the specific atoms involved in the interaction. The close-packing principle of Kitaigorodskii is a natural consequence of the atom-atom potential method, that is 'molecules in a crystal tend to assume equilibrium positions so that the potential energy of the system is minimised'.[13] In other words, the molecules pack in ways such that the projections of one molecule dovetail into the hollows of its neighbours for a maximum number of intermolecular contacts.

The close-packing principle generally holds well for hydrocarbons.[13] The binding features of a series of pure hydrocarbons have been successfully explained based on this principle.[14] However, it has been shown recently that the importance of van der Waals interactions in aromatic hydrocarbons depends on the nature of electrostatic interactions.[15] This can be explained as follows. Aromatic molecules are known to interact with each other in three possible geometrical arrangements: 1. stacking (face-face overlapping); 2. offset-stacking; 3. herringbone (T-shaped or edge-face interactions). From Figure 2 it is clear that of these three, the face-face overlapping causes the maximum number of intermolecular contacts (C...C interactions) and consequently more van der Waals interaction energy. So one would always expect a very good face-face overlapping between aromatic molecules if van der Waals forces were to determine the molecular geometry. However, in reality this is not the case. This fact indicates that the van der Waals interactions do not play a significant role in controlling crystal packing of aromatic compounds and that there is a large electrostatic barrier in face-face stacking due to $\pi...\pi$ repulsions which dominate the geometry of the interaction. The nature of these interactions is discussed in Section 1.2.3.



Stack Offset–stack Herringbone

Figure 2

Aliphatic hydrocarbons in general (usually alkyl chain length longer than five) show predominant H...H interactions. These so called hydrophobic forces lead to close packing and have been employed in many crystal engineering and molecular recognition studies.[16,17] These interactions are found to be important in establishing the tertiary and quaternary structures of biological macromolecules.

1.2.2 Hydrogen Bonds

$$X^{\delta-} - H^{\delta+} ..... A^{\delta-} - Y^{\delta+}$$

Surprisingly there is still an ambiguity in the definition of a hydrogen bond! But this may not be surprising, because the ideas of what constitutes a hydrogen bond have always been in a state of flux.[18] The first definition of the hydrogen bond was given by Pauling in 1940, who stated that 'a hydrogen bond is largely ionic in character and is formed only between the most electronegative atoms.'[19] The definition given by Atkins is that 'a hydrogen bond is a link formed by a H atom lying between two strongly electronegative atoms.'[20] If we accept these definitions strictly, only interactions such as O-H...O, N-H...O, N-H...N, F-H...F and so on can be considered as hydrogen bonds. A more general definition that does not consider the nature of donor and acceptor atoms of a hydrogen bond was given by Pimentel and McClellan, who stated that 'a hydrogen bond said to exist when (1) there is evidence of a bond, (2) there is evidence that this bond sterically involves a hydrogen atom already bonded to another atom.'[21] According to this definition, weak interactions like C-H...O, C-H...N, C-H...π , O-H...π and so on can also be referred to as hydrogen bonds along with the strong hydrogen bonds mentioned above.

Table 1

Some hydrogen bond donors and acceptors

Donors	Acceptors
F-H	F
O-H	O
Cl-H	Cl
N-H	N
Br-H	Br
I-H	I
S-H	S
P-H	P
C-H	C≡C, C=C, arenes

A much simpler and general definition for the hydrogen bond was given by Saenger recently who stated that 'any cohesive interaction X-H...Y, where H carries a positive and Y a negative (partial or full) charge and the charge on X is more negative than on H can be regarded as a hydrogen bond.'[22] So the hydrogen bond has to be viewed with respect to overall electronic effects of the molecule of which X-H forms a part. Typical hydrogen bond donors nd acceptors are listed in Table 1. The hydrogen bond may be classified nto two types, strong and weak and both may have very different properties nd are briefly discussed here.

.2.2.1 Strong Hydrogen Bonds

In strong hydrogen bonds, X is highly electronegative and has an effect f removing electron density from the hydrogen atoms leaving them with ignificant positive charge, while the noncovalently bound electronegative cceptor atom, A is involved in a Coulombic interaction with the positively harged H atom. The strong hydrogen bonds O-H...O or N-H...O are widely revalent in biological molecules. In crystals, these hydrogen bonds are haracterised by the lengths of X...A and H...A and angles X-H...A and I...A-Y which are referred to θ and ϕ respectively. The typical values for I...A are 1.60-2.00Å, θ angles lie in the range of 150-180^o and ϕ angles luster around 120^o (when A-Y is a carbonyl group).

A more interesting question concerns the distance cut-off criteria for ...A and H...A separations while assessing a possible X-H...A contact as a ydrogen bond. In fact, van der Waals radii are sometimes inconsistent with heory and sometimes give rise to incorrect conclusions (for example, the atom has been assigned different van der Waals radii, 1.53Å, 1.70Åand .75Åby Pauling, Bondi and Allinger respectively).[23] In strong hydrogen onds, the potential minima of electrostatic attractive and repulsive forces ccur at intermolecular distances greater than the sum of the respective van er Waals radii (see Section 1.2.2.2.1). For this reason it is necessary to onsider more relaxed values of interatomic distances H...A and X...A for ssessing hydrogen bond geometries. So the distances for H...A and X...A ay be taken from 1.40 to 2.20Åand from 2.50 to 3.00Åto effectively account r the electrostatic nature of hydrogen bonding interactions.

Although the hydrogen bond is a predominantly linear interaction, the configuration of hydrogen bonds usually observed in crystal structures is rarely linear ($\theta \cong 180^o$), because the number of possible spatial configurations with the X-H...A angle in the range of θ to $\theta + d\theta$ is proportional to sin θ (Figure 3).[24] The most probable value for θ is therefore around 165°. A further reason for this bent approach may be that the H atoms are often approached by a second acceptor in an attractive fashion. This type of interaction may be termed bifurcated-donor hydrogen bonding (or three centred interactions). Similarly, three acceptor atoms may also form interactions with a H atom (trifurcated-donor, Figure 4a). These bifurcated hydrogen bonds are most common in the crystal structures which are acceptor-rich. Another possibility for the occurence of three-centred interactions is when the acceptor is bifurcated by donor H atoms (Figure 4b). The hydrogen bonds in such cases may be termed bifurcated-acceptor hydrogen bonds. It should be stated here that it may not be possible to realise the importance of bifurcated interactions if we do not consider the long range electrostatic nature of hydrogen bonds.[23]

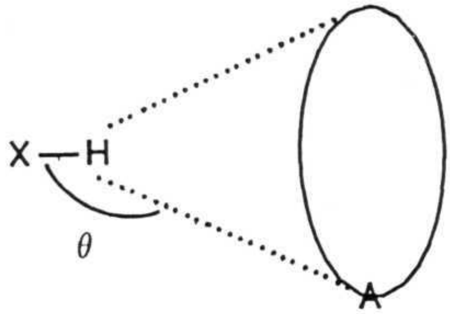


Figure 3

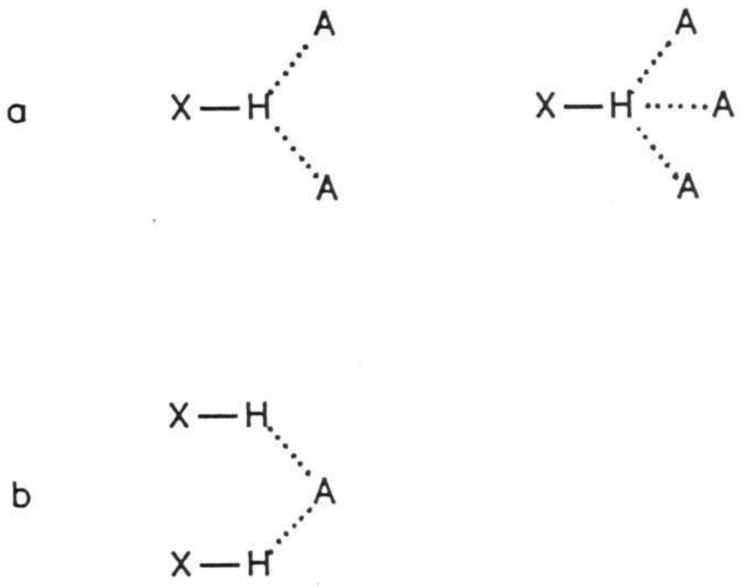


Figure 4a,b

1.2.2.1.1 Cooperativity

Hydrogen bonding is usually associated with the property of cooperativity and this property is more pronounced in organic crystal structures.[25] Polarisability and the charge transfer nature of hydrogen bonds in molecular aggregates makes the total binding energy of all hydrogen bonds in the aggregate greater than the sum of the individual bonds and this effect is known as cooperativity. So hydrogen bonds will be more stable when they form dimers, trimers, chains and continuous two or three dimensional structures (Figure 5).

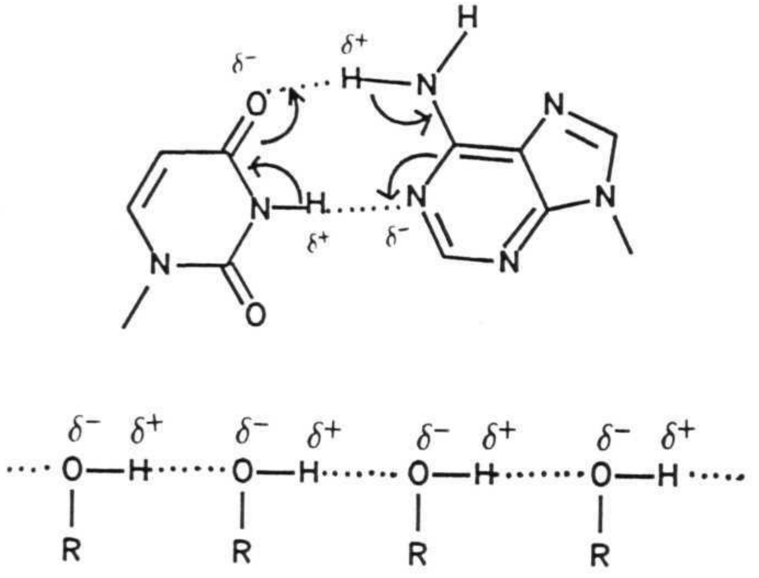


Figure 5

1.2.2.2 Weak Hydrogen Bonds

In contrast to strong hydrogen bonds, weak hydrogen bonds are compressed and expanded by crystal packing forces and the characteristic equilibrium bond length is governed by statistical factors.[26] The weaker the hydrogen bond, the less are the associated directional characteristics. As the present work is mostly concerned with weak C-H...O hydrogen bonds, these are discussed at length. The related (N,O)-H...π and C-H...π, are also mentioned briefly.

1.2.2.2.1 C-H...O Hydrogen Bonds

C-H...O Hydrogen bonds are commonly encountered interactions in organic crystal structures, due to the frequent occurrence of the oxygen atom in simple organics (72% of the entries in the 1993 version of the CSD contain an O atom). These interactions play a significant role in stabilising the molecular geometry in the crystal lattice. Unlike strong hydrogen bonds, these interactions cannot be determined routinely from spectroscopic studies and there are difficulties in evaluating the geometrical attributes of these weak interactions from crystal structures because they can be easily perturbed by crystal packing forces. The advent of the CSD has made it possible to approximate the interatomic potentials for these interactions by considering geometrical properties in various crystal structures. Such a statistical procedure improves the information-to-noise ratio for the interaction.

C-H...O Interactions are largely electrostatic in nature, with a long-range distance character. The length of the bond, C...O (D) is more sensitive to the nature of the H atom than to the nature of the basic acceptor.[27] The more acidic C-H groups form shorter C...O distances and these distances extend well beyond the conventional van der Waals limit.[28] The typical C...O and H...O distances of these interactions usually lie between 3.00-4.00Åand 2.20-3.00Å.[24] As mentioned earlier, the concept of van der Waals radii varies based on the chemical factors associated with a particular group. Hence, chemically meaningful results can only be obtained by observing systematic trends of intermolecular interactions in various groups of compounds statistically, instead of applying a common van der Waals cut-off.

The geometrical consequences of weak C-H...O hydrogen bonds in the crystal structures can be explained on the basis of their electrostatic nature. The strength of electrostatic interactions is inversely dependent on the separation between two interacting atoms (r^{-1}), so the magnitude of these interactions reduces gradually with the separation distance unlike van der Waals interactions where the strength diminishes sharply as the distance rises (r^{-6} dependence). Therefore electrostatic forces between approaching molecules prior to crystallisation are important and even long C...O separations may have to be considered as they may define the orienting effect on molecules before the influence of van der Waals forces is felt.[26] This fact is the key point for the employment of these bonds in crystal engineering and molecular recognition studies.

Typical C-H...O hydrogen bond angles θ, occur in the range 100-180°, but cluster around 150-160° for reasons stated earlier in Section 1.2.2.1. Interestingly, these angles are insensitive to C...O distances unlike the strong hydrogen bond analogues O...O or N...O where shorter distances are associated with linear angles ($\approx 180^o$). Perhaps in strong hydrogen bonds shorter O...O and N...O distances cause repulsions between negatively charged atoms and O-H...O or N-H...O angles tend to straighten out. But in C-H...O interactions, the C...O distances are probably too long for such repulsions to exert a significant effect on angle geometry.

1.2.2.2.2 (N,O)-H...Π Hydrogen Bonds

O-H...π Interactions are rare unlike C-H...O hydrogen bonds. Recently these interactions have been described in calixarene host-guest complexes wherein the water guest molecule is involved in O-H...π hydrogen bonds.[29] A systematic study of these interactions in alkyne, alkene and aromatic compounds using the CSD revealed that these interactions occur between more acidic hydrogens and more basic π-systems (electron rich C atoms).[30] Further it was shown that these interactions involving weaker acids (N-H) and weaker π-bases (alkene, phenyl) prefer to form inramolecular interactions and/or accompany by bifurcation to strong hydrogen bond acceptors (O,N).

1.2.2.2.3 C-H...Π Hydrogen Bonds

These interactions are weaker than O-H...π and C-H...O interactions as the C atoms are less electronegative than O atoms. Indeed there is still no well-accepted convention of considering C-H...π interactions as hydrogen bonds. No distinction has been made in earlier studies between C atoms of the π-system (alkyne, alkene, arene) and aliphatic compounds. C-H...C interactions found in both cases are collectively referred as van der Waals type interactions. But now there is an increasing body of evidence that C-H...C interactions of π-systems are Coulombic in nature ($C\delta$-...$H\delta$+) and probably for this reason, C-H...π interactions are frequently observed in aromatic compounds.[31] In general, more acidic H atoms and electron rich π-clouds are involved in these hydrogen bonds.[32] The crystal structure of butynoic acid is an early example where this interaction was recognised.[33]

1.2.3 Π...Π Interactions

Stacking or π...π interactions are well known and widely used intermolecular interactions in supramolecular assembly.[34,35] These interactions are common in aromatic organic molecules and play a decisive role in determining geometry of the molecules. Earlier studies on predicting the nature of these interactions in organic solids have been carried out by Desiraju and Gavezzotti.[14,31] These authors suggested that aromatic hydrocarbons tend to stack when the C:H ratio is high because stacking results in large number of C...C interactions and causes efficient close-packing. It was also shown that a plot of ratio of the glide and stack areas versus the total molecular area gives a useful information in predicting crystal type structure from molecular structure. Recently Hunter and Sanders proposed a simple model for stacking interactions which indicates that that the geometries of π...π interactions are controlled by electrostatic interactions but that the major energetic contribution comes from other factors (see also Section 1.2.1).[15] According to this model, the π system consists of a positively charged σ-framework sandwiched between two negatively charged π electron clouds (Figure 6). The C atom of a π -system is assigned a charge of +1 at its nucleus, -1/2 at a constant distance (0.47Å) above and below the plane of the π-system. This model states that the net favourable π...π interactions are actually the result of $\pi - \sigma$ attractions that overcome $\pi ... \pi$ repulsions.

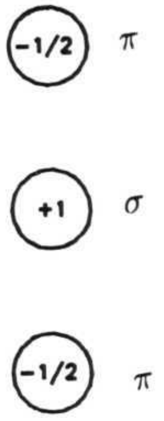


Figure 6

1.3 Crystal Engineering

The term 'Crystal Engineering' was coined by Schmidt to describe solid state reactions of organic solids, especially cinnamic acids.[6] The (initial) objective behind crystal engineering was to design novel organic materials such that they obey topochemical principles (that is, intermolecular geometry in crystals can be correlated with solid state chemical reactivity) and lead to solid state reactions. Many solid state reactions have been designed since the statement of the topochemical principles, but often these principles failed to explain the chemical reactivity of organic compounds solely on the basis of consideration of intermolecular geometry. The reason for this disagreement is that, chemical reaction involves movement of electrons (electronic phenomenon) which need not always correlate with the disposition of atoms in the solid state.[36,37] In the present work, a solid state reaction has been described that carefully considers both crystal engineering principles and electronic effects together to synthesise novel organic host materials.

Though solid state synthesis is not a serious alternative to conventional organic synthesis, it has emerged as an interesting area of research for developing new materials because the molecular arrangement of solids can be intimately linked to physical properties. In addition, organic solids are superior to inorganic compounds in several of their optical, electronic and magnetic properties and can be designed to conform to a required molecular geometry in the crystal. More importantly, crystal engineering principles provide an insight into the nature of intermolecular interactions and it is possible to understand the structures of many complex biomolecules based on these principles. In light of the broadened scope of the crystal engineering a more general and elegant definition for crystal engineering has been given by Desiraju as 'the understanding of intermolecular interactions in the context of crystal packing and in the utilisation of such understanding in the design of new solids with desired physical and chemical properties.'[2]

1.3.1 Crystal Engineering Strategies

There are three possible ways to attain the goal of prediction of crystal structures. These are: (i) empirical methods (close-packing model or atom-atom potential method) (ii) quantum mechanical methods (*ab initio* or semi-empirical methods). (iii) pattern recognition (identifying patterns of intermolecular interactions). The atom-atom method involves calculating the stable geometry of crystal structures; the parametrisation in this method is carried out by fitting the potential to observed properties of the crystal such as the heat of sublimation. This method explains the gross crystal packing features for many organic compounds but very often cannot predict the precise molecular arrangement correctly. *Ab initio* quantum-mechanical methods are very difficult to use in crystal engineering strategies because they require huge computational times to calculate the energies of molecular aggregates and this factor alone has obstructed the utilisation of such methods in predicting crystal structures. Semi-empirical methods have recently been used to explain crystal structures of small-sized molecules.[38,39] However, significant progress has not been made. Pattern recognition is an important strategy for crystal engineering. Here, information concerning intermolecular interactions is extracted and deconvoluted to design solid state supermolecules with specific properties. The present work is chiefly focused around this last and most practical strategy.

1.3.1.1 Atom-Atom Potential Method

Close-packing is a fundamental principle in crystal engineering strategies.[13] It explains the crystal packing features of the vast majority of organic solids on a simple rationale. According to this principle, molecular solids crystallise with a packing coefficient ranging between 0.65 and 0.77 and with a maximum coordination number of six in any dissection of the crystal structure.[2] This principle has important applications in the area of host-guest complexes and is discussed in Section 1.5.2. This principle also predicts that a vast majority of organic compounds utilise only about 20 space groups out of a theoretically possible 230 with around half of them crystallising in a single monoclinic space group $P2_1/c$.

Atom-atom potential calculations successfully predict crystal geometry of simple hydrocarbons, but fail to do so when heteroatoms are present. For example, this method predicts a similar packing arrangement for benzene and pyridine. However, this prediction is not realised in practice, because the method of calculation does not take into account the directionality and variable distance dependence of heteroatom interactions. Many empirical methods suggested are not successful in effectively parametrising electrostatic interations of heteroatoms because they are subject to variation based on the chemical environment.

1.3.1.2 Pattern Recognition

The forces in an organic crystal are a complex blend of isotropic and anisotropic, short range and long-range, polar and non-polar interactions. However it has been observed that certain molecular building blocks (functional groups, ions, geometrically characteristic interactions) display a clear pattern preference and tend to crystallise in specific energetically favourable arrangements that co-exist with efficient close packing. By identifying, classifying and rationalising such networks, it may be possible to utilise them as active design tools in the crystal engineering of novel materials with specific structural features. The CSD gives an excellent opportunity in this context to work backwards (retrosynthesis) from observed crystal structures to formulate empirical rules about recognition patterns of various geometrical and functional groups in crystals.

Strategies for crystal engineering are concerned with single and multi component systems (molecular complexes or mixed crystals of different species). Thus, recognition patterns can be effectively used to architect supermolecules of many types. The prerequisite for the formation of a molecular complex is that the heteromolecular species should contain stronger intermolecular interactions than either of the homomolecular starting materials. This condition will be satisfied in the following instances: 1. When there are differences in the strength of the hydrogen bond donating and accepting capability between different molecular types and functional groups. 2. When there are donor-acceptor interactions between different species. 3. When one or both of the individual molecules lack close-packing features in their individual crystal structures. 4. When the two different species are isostructural or geometrically and sterically similar (these mixed solids are generally known as solid solutions).[40] Complexation studies are useful especially for monitoring competing interactions that determine the selective binding process and for enhancing the scope of designing novel materials. The crystal engineering strategies addressed in the forthcoming chapters are mainly concerned with multi-molecular complexes with special reference to weak intermolecular interactions. Here we mention a few examples of hydrogen bond directed pattern recognition in single and multi component systems, while the examples concerned with close packing factors are discussed in Section 1.5.2.

1.3.1.2.1 Single Component Systems

Carboxylic groups: Carboxylic acids are the most widely used functional groups in crystal engineering strategies. In general, carboxylic acids form two types of patterns, dimers and catemers based on the size of the substituent group R (Figure 7). The acids containing small substitutent groups (e.g, formic acid, acetic acid) form the catemer motif and others form dimers (e.g, benzoic acid).[33] The dimer motif of the carboxyl group may be used to assemble a variety of supermolecules. For example, terephthalic acid, **1** gives a one dimensional ribbon structure,[41] trimesic acid, **2** containing threefold symmetry results in two dimensional hydrogen bonded sheet[42] and adamantane-1,3,5,7-tetracarboxylic acid, **3** with its tetrahedrally disposed carboxyl groups forms a three dimensional diamondoid network.[43]

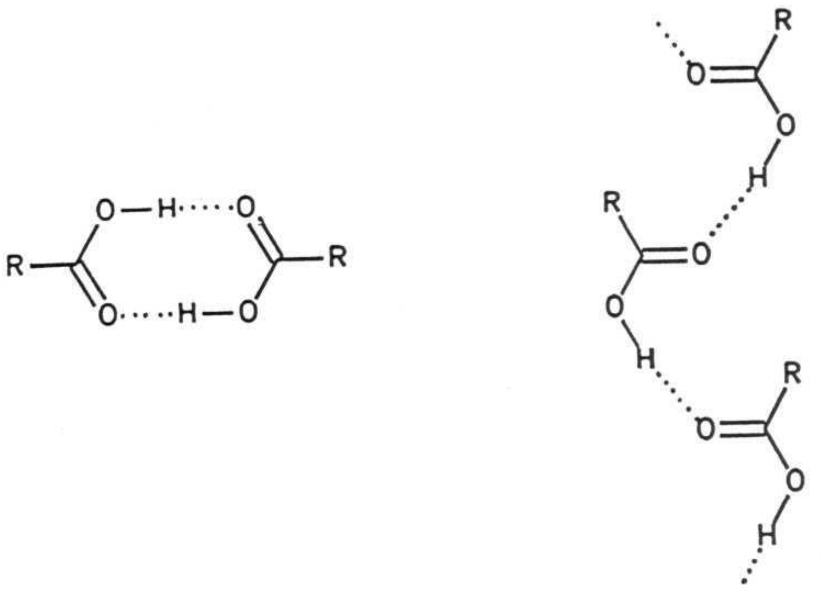
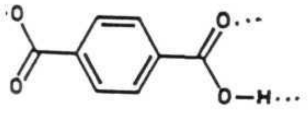


Figure 7



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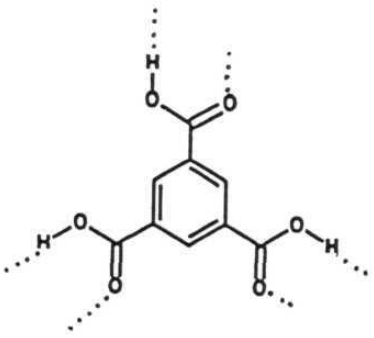

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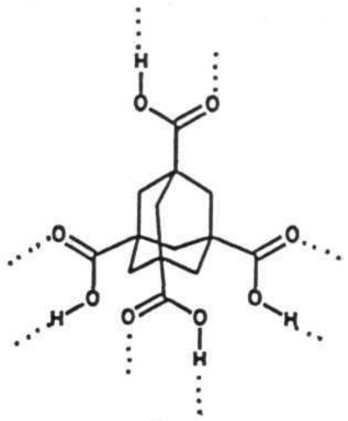


3

nides: A vast majority of primary amides form one dimensional hydrogen ıded networks, where the hydrogen bonded cyclic dimers are linked by litional N-H...O=C bonds generating a ribbon (Figure 8).[44]

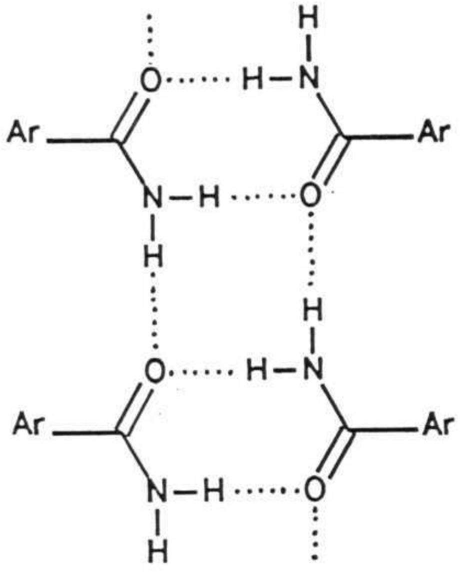


Figure 8

Pyridones: In general, 2-pyridones form cyclic dimers using N-H...O interactions. The two pyridone units linked by rigid spacers create self complementary supermolecules (Figure 9).[45]

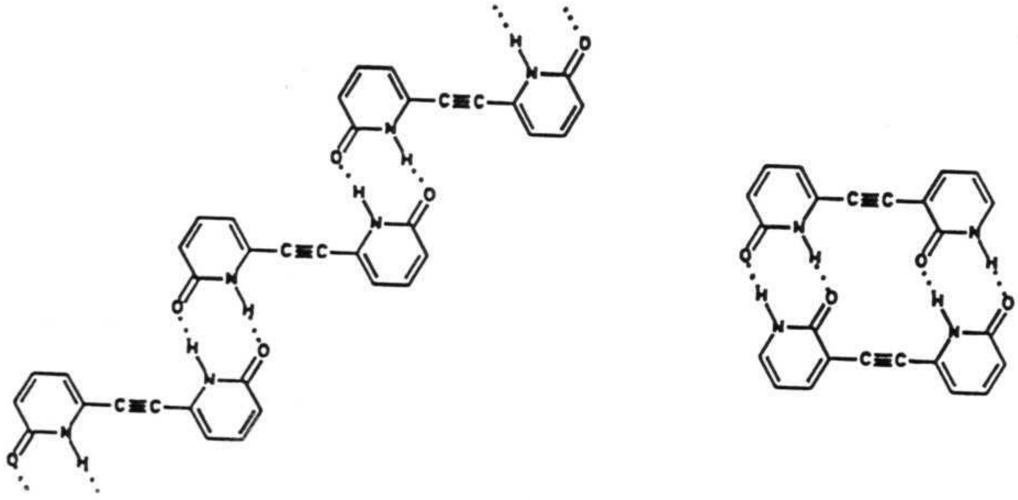


Figure 9

Aminopyrimidines: 2-aminopyrimidines form hydrogen bonded dimers in its crystal structure as shown in Figure 10.[46]

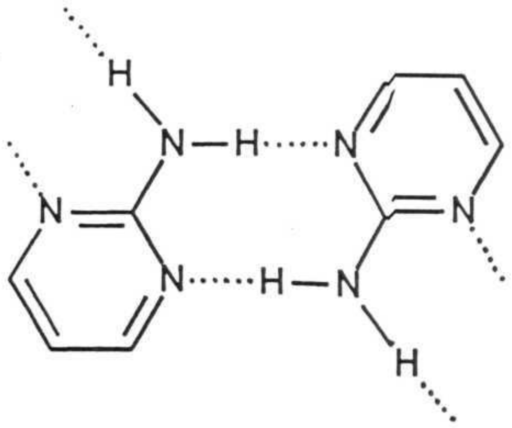


Figure 10

Nitroanilines: Nitroanilines prefer a motif involving one amino proton associating both oxygens of a nitro group (three-centre or donor-bifurcated hydrogen bonding, Figure 11).[47]

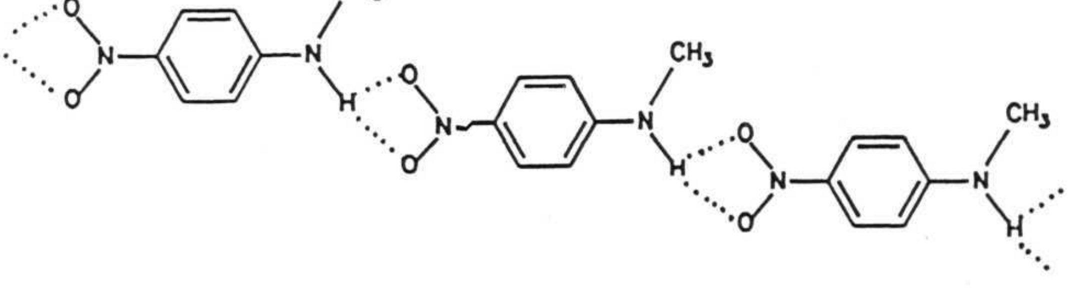


Figure 11

1.3.1.2.2 Pattern Recognition Involving Weak Intermolecular Interactions

Most of the recognition patterns known in the literature are concerned with strong hydrogen bonds. The directional patterns of weak intermolecular interactions have not been extensively studied. Indeed these interactions are crucial in crystal engineering strategies as they determine secondary and tertiary features of crystal structures which are seemingly built up with much stronger forces. The objective of predicting crystal structures often becomes elusive unless we take these interactions into account. As far as the C-H...O hydrogen bonds are concerned there are quite a few studies on their binding patterns and mostly confined to single component systems (e.g., cinnamic acids and quinones, Figure 12).[26] The present work mainly addresses the recognition patterns of C-H...O hydrogen bonds in single and multicomponent systems as well as a few other weak intermolecular interactions in the context of molecular recognition.

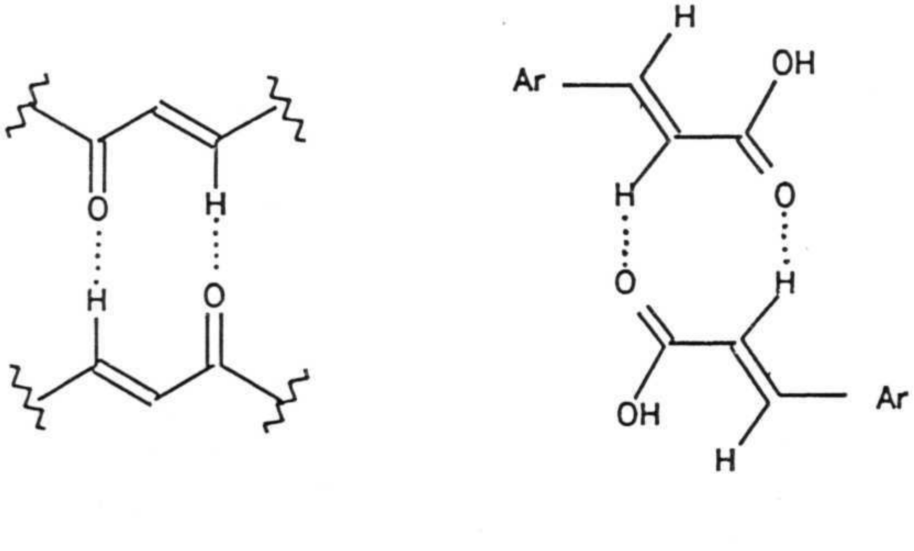


Figure 12

1.3.1.2.3 Multicomponent Systems

The complementarity of hydrogen bonding between melamine, **4** and barbituric acid, **5**, has been used by Whitesides to design various self-assembling structures, a linear tape, crinkled tape and a cyclic structure ('rosette').[48] Minor modifications in the molecular structures of the starting materials leads to major changes in crystal architecture of these 1:1 complexes, (Figure 13).

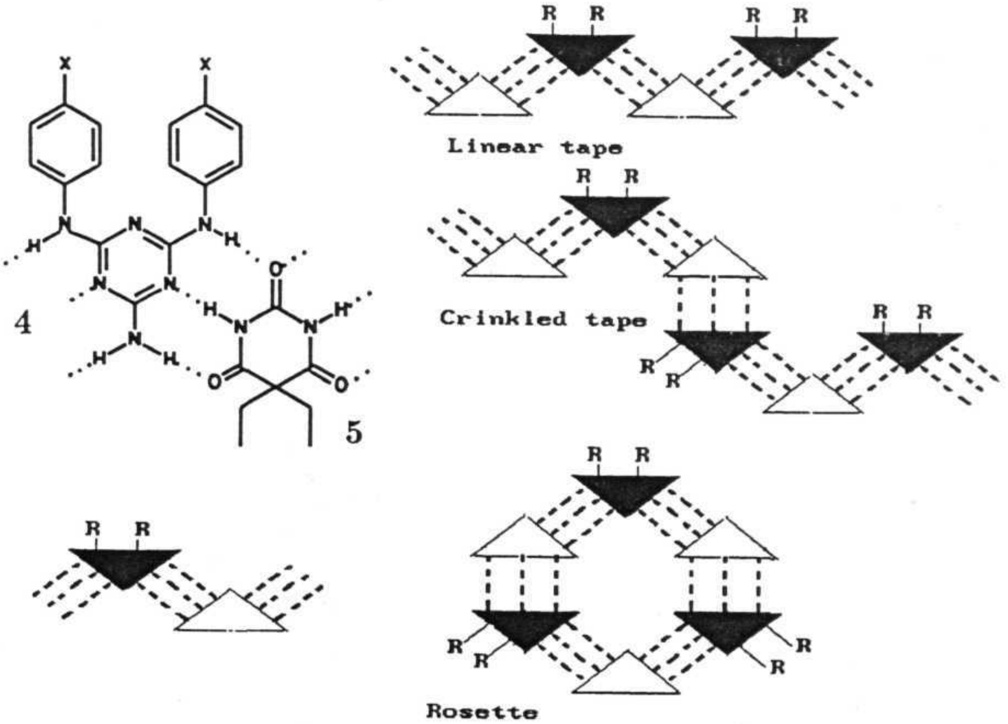
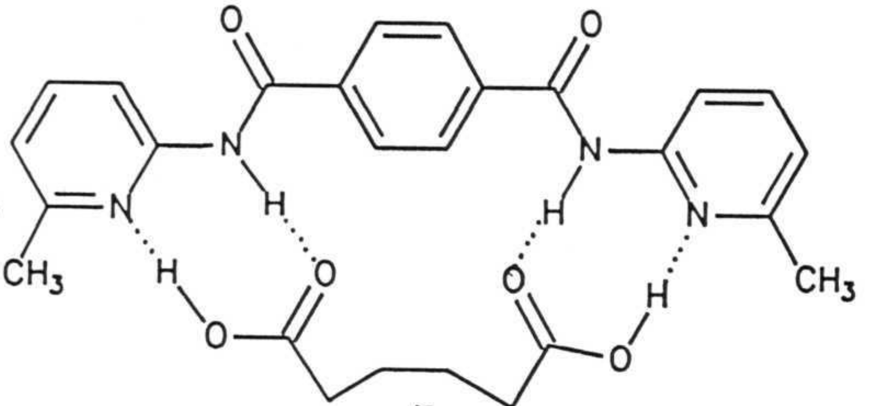


Figure 13

2-Aminopyridines and pyrimidines preferentially form hydrogen bonds with the acid groups. Hamilton has showed that the unit containing two aminopyridine groups separated by a rigid spacer, **6** provides a receptor unit for dicarboxylic acid, **7**, with a correspondence between the length of the spacer and that of the carboxylic acid (Figures 14).[49]



6

7

Figure 14

1.3.2 Polymorphism

Polymorphism is an inherent drawback in crystal engineering strategies. Observed structures often represent only one of several minima in the free energy surface and need not always correspond to the global minimum. Polymorphism occurs due to variations in enthalphy (intermolecular interactions) and entropy (extent of disorder) since either type of change could result in many local minima and the free energy differences between these minima may be very small. For these reasons, the systematic design of organic solids may not lead to the expected structure. But, fortunately it has been found that in many cases, the occurrences of particular polymorphs can be traced to certain conditions of temperature, pressure, solvent or to certain molecular features. By identifying these factors, the problem of polymorphism in crystal engineering strategies can be largely surmounted.[2]

1.4 Molecular Recognition

The phenomenon of molecular recognition has evolved around the principles of biological functions, such as substrate binding to a receptor protein, enzyme reactions, assembling of protein-protein complexes, immunological antigen-antibody association, intermolecular reading of the genetic code, signal induction by neurotransmitters and cellular recognition. Many of these functions can be manipulated by designing artificial (abiotic) receptors that can efficiently and selectively function like their biological counterparts. The design of artificial receptors requires a perfect match of energetic and stereochemical features of the non-covalent intermolecular forces between substrate and receptor. Thus molecular recognition has been defined as 'a process involving both binding and selection of a substrate by a given receptor molecule as well as possibly a specific function' or more simply as 'a strategy by which a molecule bears supramolecular functions.'[7,50]

Receptors which can effect molecular recognition may be classified into two types based on their directional properties. 1. exo-receptor (directed outward, divergent receptor) 2. endo-receptor (directed inward, convergent receptor, Figure 15).[51] Molecular size and shape are not so important for exo-binding compared to endo binding because it is difficult to use the full functional group capacity of substrate and receptor in exo-binding. Recognition through exo-binding leads to the self-assembly of a molecular species. In contrast to the exo receptors, the binding sites in endo-receptors are oriented into a molecular concavity and most of the investigations in molecular recognition are focused on these receptors especially host-guest complexes which will be discussed in Section 1.5. The functional groups in this case are convergent/divergent and hence can recognise each other with a complete set of functional groups. To summarise, endo-binding is superior to exo-binding in molecular recognition studies (Figure 15). Most of the binding studies of molecular recognition are concerned with the solution state and the strength of intermolecular forces is studied using spectroscopic techniques. Recently, however, molecular recognition studies are making inroads into the solid state and the aim of the present work is along these lines. A few selected features of molecular recognition have been discussed here in order to impress upon the reader the progress of this research area and to compare crystal engineering strategies with molecular recognition.

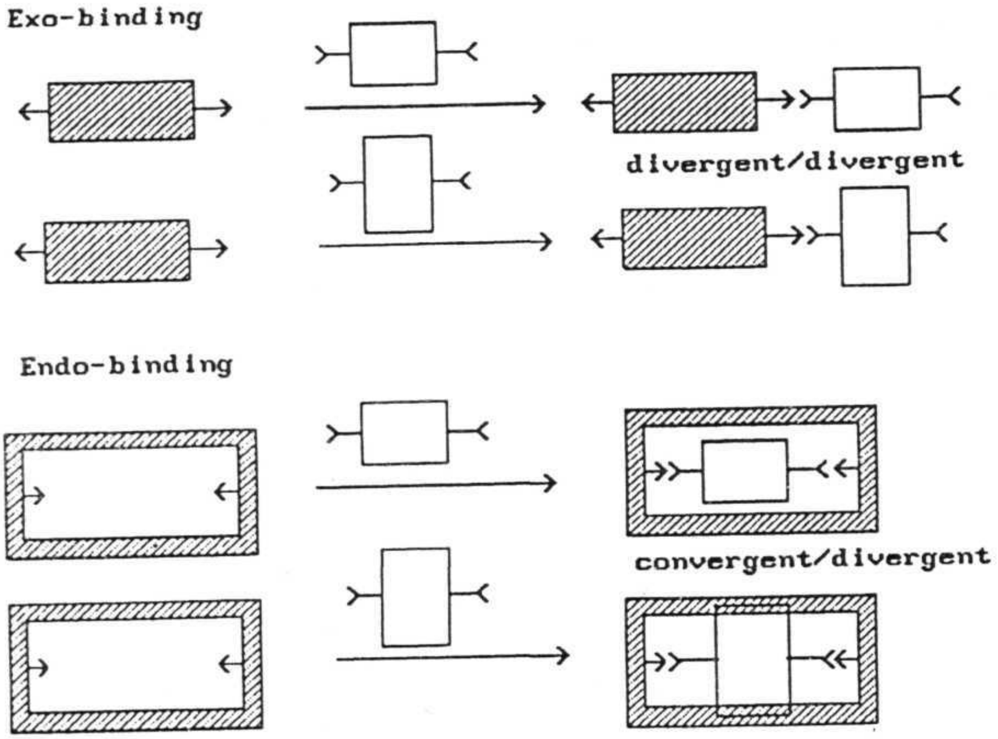


Figure 15

1.4.1 Matching of Multiple Binding Sites

The early work on molecular recognition is concerned mainly with a single site strategy that is, it either considers molecular shape and surface characteristics (cyclodextrins, zeolites, crown ethers) or the binding nature of hydrogen bonded functional groups (carboxylic acids, amide groups). But in fact, selective binding in biological recognition requires a perfect match of size, shape and functional groups between substrate and the receptor. So for an efficient design of artificial receptors, the matching of multiple interactions is essential. A few such examples are discussed here.

The substrate, **8** not only provides correct spacing and rigidity but also six directed hydrogen bonds for receptors based on barbiturate, **9** which is pharmaceutically important and widely used as a sedative and an anticonvulsant (Figure 16).[52]

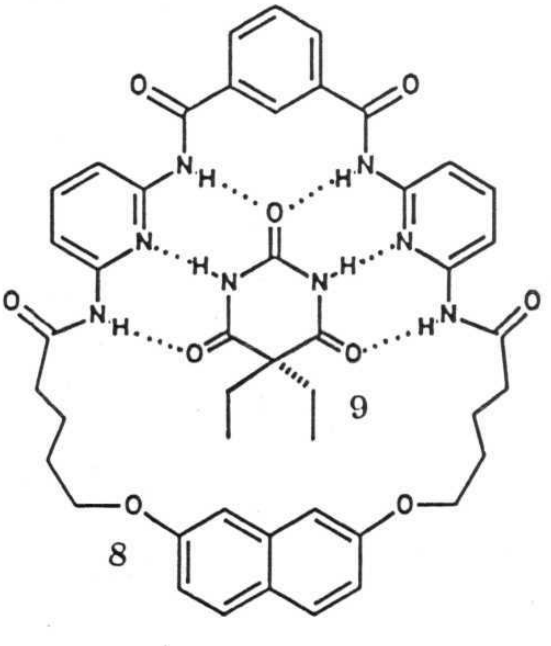


Figure 16

The combination of hydrogen bonding sites and π-stacking sites in molecular recognition offers a powerful approach for the recognition of planar heterocyclic substrates such as nucleic acids (e.g., guanine binding with protein ribonuclease T1). Molecular recognition using this two-site strategy was employed successfully with substrate **10**. The receptor 1-butylthymine **11** stacks with the aromatic ring and hydrogen bonds with the diaminopyridine moiety of **10** (Figure 17). Interestingly, by varying the hydrogen bonding region and the electronic properties of the aromatic ring of **10**, one can find the differences in binding specificity for other nucleotide bases.[52]

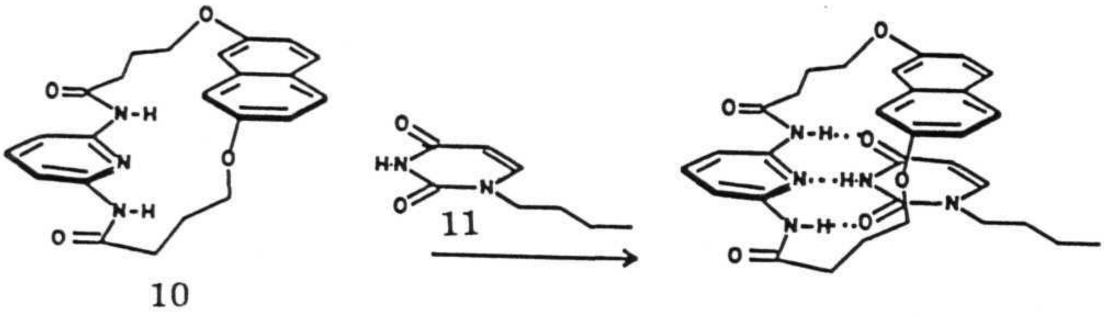


Figure 17

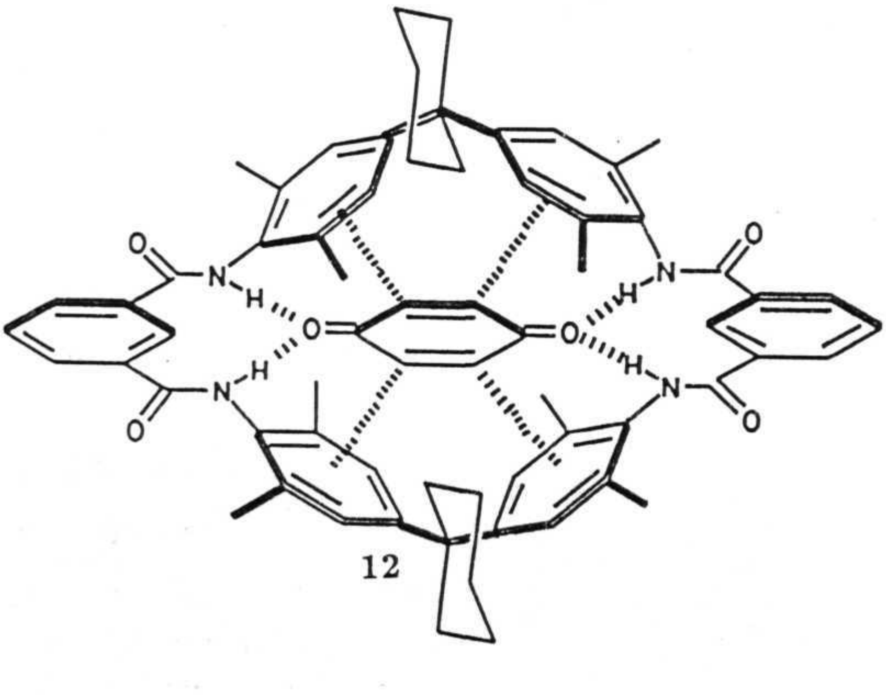


Figure 18

Another interesting example of multiple matching of binding sites is the selective binding of 1,4-benzoquinone with the tetramide host, **12** where four hydrogen bonds and four herringbone interactions are involved (Figure 18).[53]

1.4.2 Self Assembly

The spontaneous assembly of many molecules into a single, highly structured supramolecular aggregate may be termed self-assembly.[54] The nature

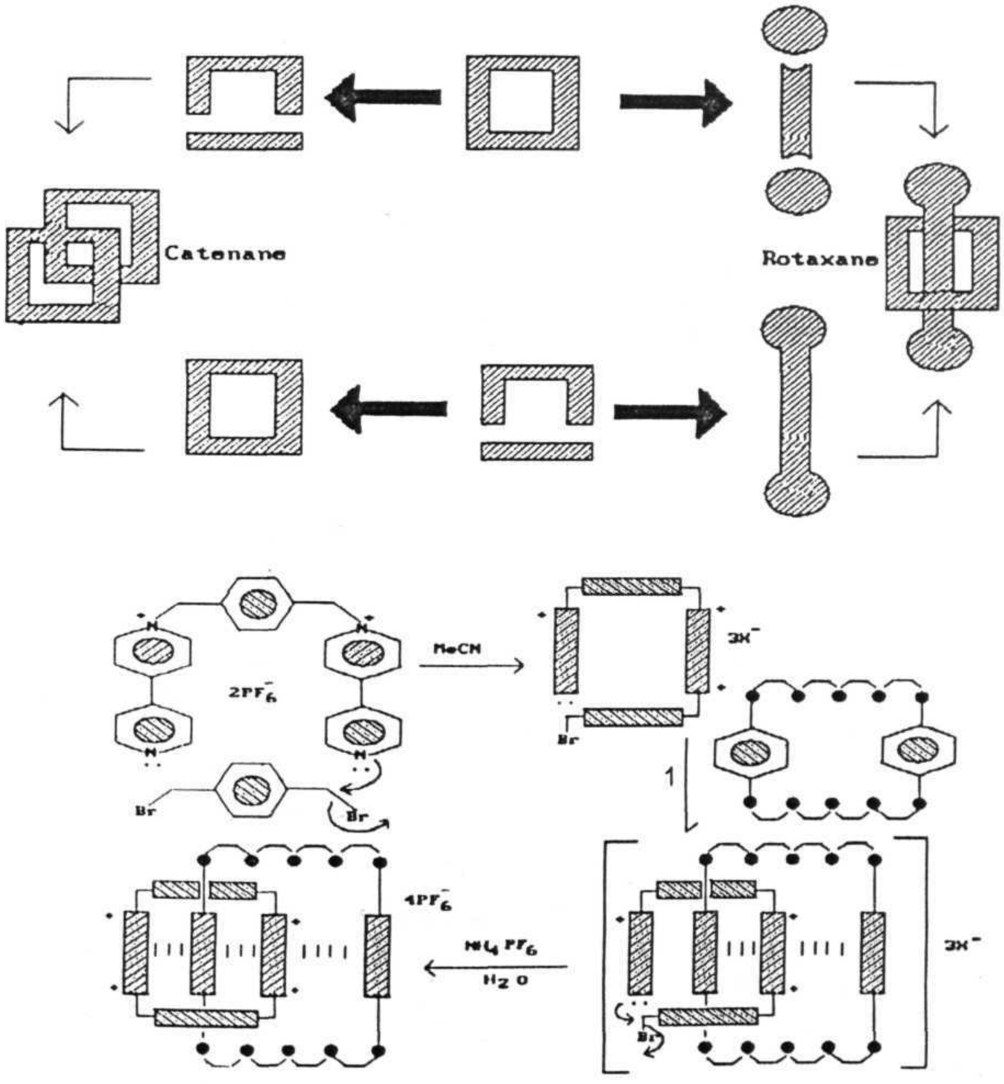
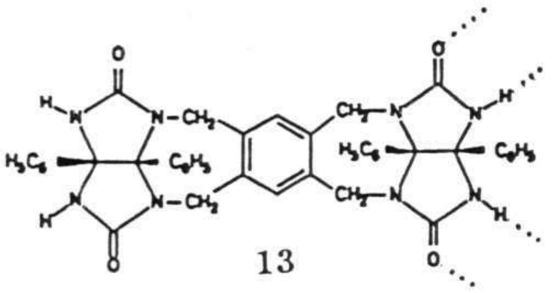


Figure 19

of the supramolecular species obtained will depend on the information stored in the components. A novel self-assembly process has been developed by Stoddart for interlocking molecular components irreversibly using $\pi ... \pi$ interactions.[55] The strategies for preparing catenanes and rotaxanes are schematically shown along with an example in Figure 19. Recently it was shown by Rebek that a tennis ball shaped molecular aggregate can be constructed by the self-assembly of compound **13** that has a curved shape and complementary hydrogen bonding sites.[56] This is schematically shown in Figure 20.



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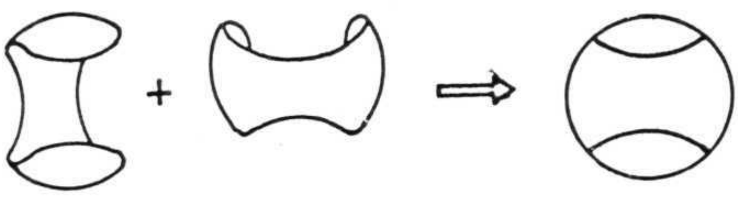
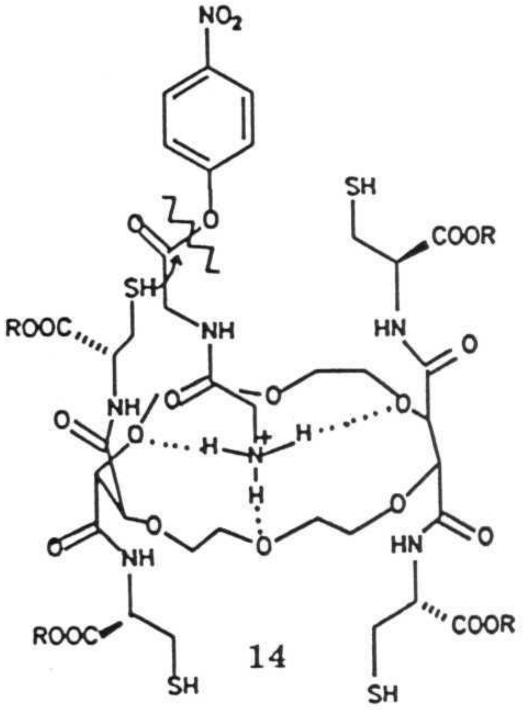


Figure 20

1.4.3 Catalysis

Molecular receptors bearing appropriate reactive groups in addition to binding sites may complex a substrate, react with it and finally release the product, thus regenerating the reagent for a new cycle.[7,57] For example, the macrocycle **14** binds with *p*-nitrophenyl esters of amino acids and peptides and reacts with bound species and cleaves the ester releasing *p*-nitrophenol as shown in Figure 21.



14

R = CH_3

Figure 21

1.4.4 Molecular and Supramolecular Devices

An important application derived from the concepts of molecular recognition is the design of molecular devices that would be capable of processing information and signals at molecular and supramolecular levels.[1] These devices have been defined by Lehn as 'structurally organised and functionally integrated chemical systems built into supramolecular architectures.' A variety of functions can be performed by supramolecular devices, with the integration of various components that are specific to some elementary functions (e.g., photoactive, electroactive or ionoactive). For example, the wavelength of incident light can be changed by a light conversion molecular device consisting of two components, a light collector and an emitter. An europium (III) cryptate of a macrocycle ligand functions as a light converter (Figure 22).

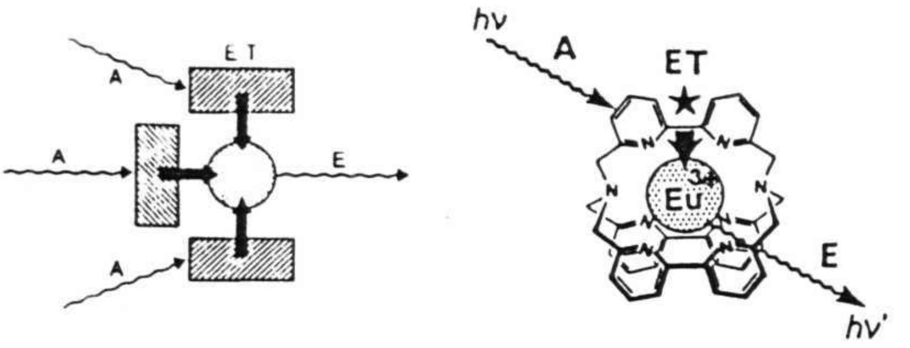


Figure 22

1.5 Host-Guest Complexes

Host-guest complexes result when the sizes, shapes and functional sites of guest molecules are complementary to the cavity of the hosts. The host may be of two types (1) molecular host or cavitate (contains macrocyclic cavity) (2) supramolecular host or clathrate (contains multimolecular cavity). These are shown schematically in Figure 23. The host and guest can be defined as 'a chemical combination in which one component (the guest) fits in to a cavity of the other (the host)[58] or where 'the convergent binding partners of the molecular aggregate are specified as host while the divergent species is called the guest' (Figure 23).[59] There are some advantages and disadvantages with these two types of hosts in preparing host-guest complexes. It is tedious to synthesise chemical substances which act as macrocylic hosts. However, the cavities of the hosts are well defined and suitable guests can be identified based on the nature of the hosts. The guest has a limited role to play in these complexes. Compared with macrocyclic hosts, supramolecular hosts can be formed by simpler host molecules, since the cavity is generated by aggregation of several small host molecules in the crystal lattice. But the cavity of these hosts is subject to variation and guest properties are important in this class of complexes.

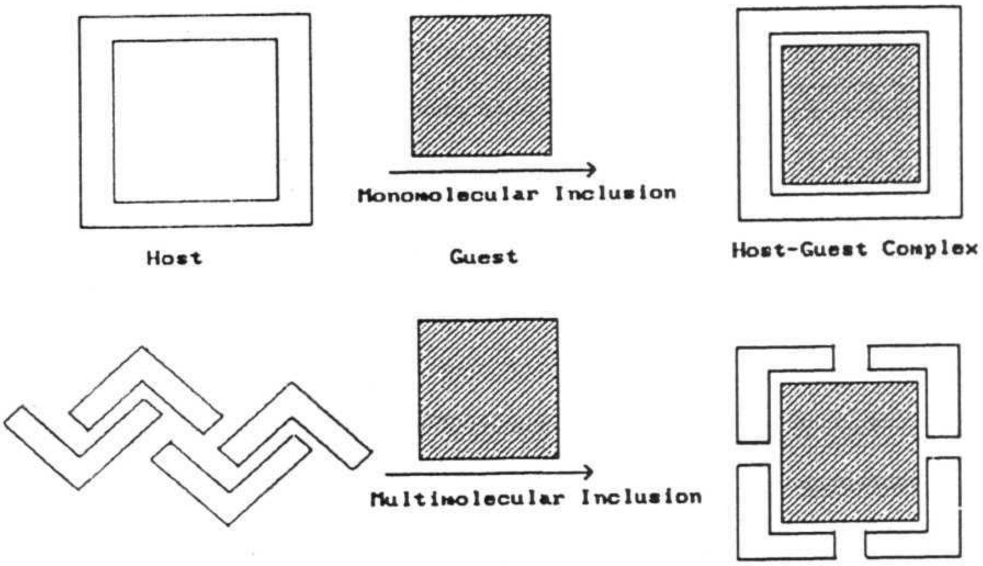
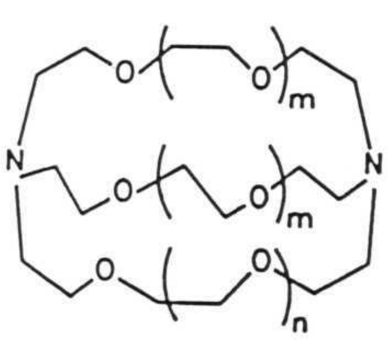


Figure 23

1.5.1 Molecular Hosts

The formation of monomolecular host-guest complexes depend on intermolecular interactions between two molecular species only, the guest and the host which surrounds it completely. A vast amount of literature is available on these hosts and initial ideas of molecular recognition originated from this class of compounds.[60] There are many molecular hosts with varying cavity sizes, shapes and functional sites and these can selectively bind different guest molecules according to their nature. Some of the more popular hosts are: cyclodextrins, zeolites, calixarenes, cryptands, carcerands, cavitands, crowns, podands, spherands and so on. It is beyond the scope of this section to discuss these complexes at length but the following are illustrative examples of selective binding of a cation and a neutral molecule with molecular hosts.

The cryptate **15** recognises cations and shows selectivity as a function of the size complementarity between the cation and the intramoleular cavity. As the bridges of the macrobicycle are lengthened i.e, m=0 and n=1, m=1 and m=0, and m=n=1, the most strongly bound ions become respectively Li^+, Na^+ and then K^+ (Figure 24).



15

Figure 24

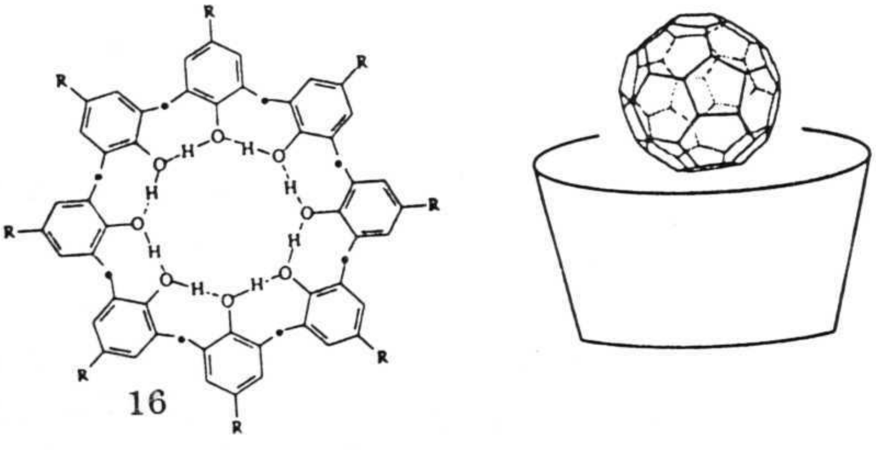


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Figure 25

Recently calixarenes were shown to form host-guest complexes with fullerenes C_{60} and C_{70}. The calixarene **16** has a higher affinity to form complexes with C_{60} than C_{70} as the cavity size matches the volume of the C_{60} molecule (Figure 25).[61] Interestingly this host-guest complexation seems to be a simple and economical way of purifying C_{60} from fullerene soot.

1.5.2 Supramolecular Hosts

Very diverse classes of organic compounds can be used as supramolecular hosts. As these hosts are mostly viable only in the solid state, the principles of crystal engineering have a significant role in preparing such host-guest complexes. These hosts have not been studied systematically and the subject is still in a stage of development. The following features of these hosts are pertinent.

Multimolecular cavities may result primarily for two different reasons. 1. Molecules having a bulky constitution and a rigid molecular conformation cannot close-pack in the crystal and as a consequence, a cavity may be formed. 2. The directional properties of robust intermolecular interactions of the host molecules in the crystal lattice may often leave a cavity between them (Figure 26).[62] However, there may be yet another possibility for the formation of multicomponent host-guest complexes where the guest plays a crucial role. For example, the hosts partially satisfying any of the above two conditions often manage to avoid cavity formation if there is an energetically undemanding alternative molecular arrangement for close-packing. Such hosts may clathrate if they are crystallised in the presence of specific guest molecules because clathration may achieve the global minimum of intermolecular interaction energy. This class of host-guest complexes may be termed guest-induced host-guest complexes and are discussed in Chapter 4.

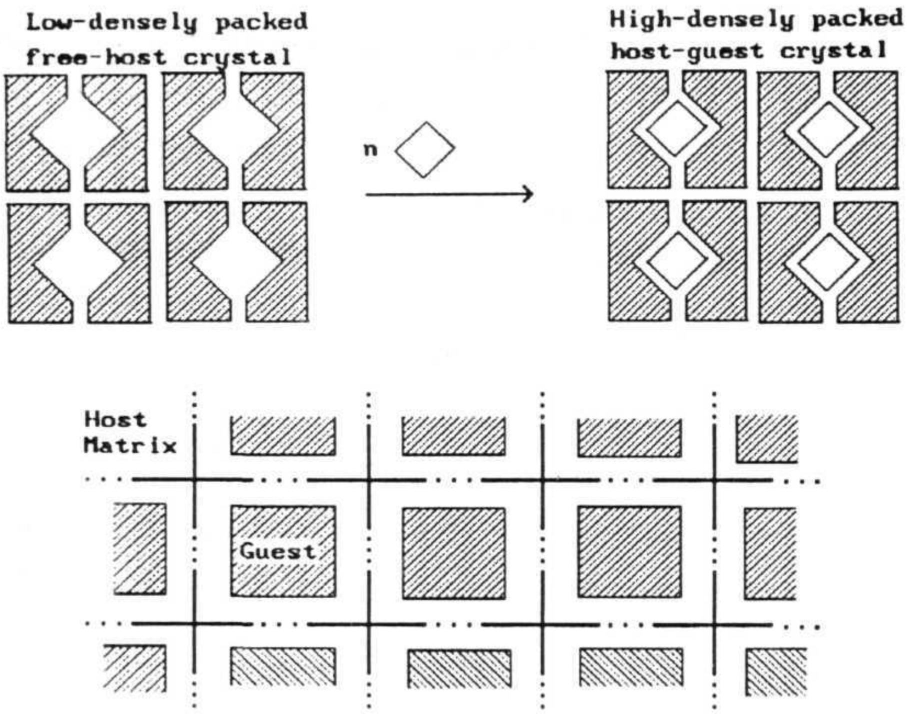

Figure 26

1.5.2.1 Supramolecular Hosts Based on Rigid Molecular Framework

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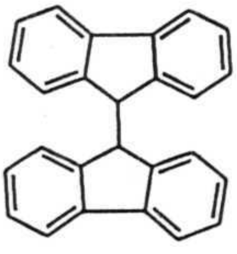

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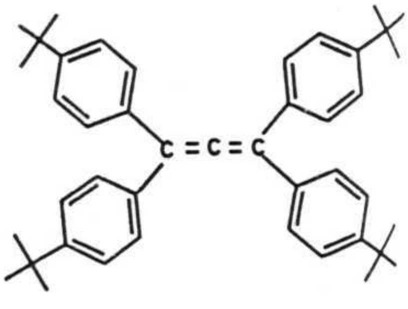
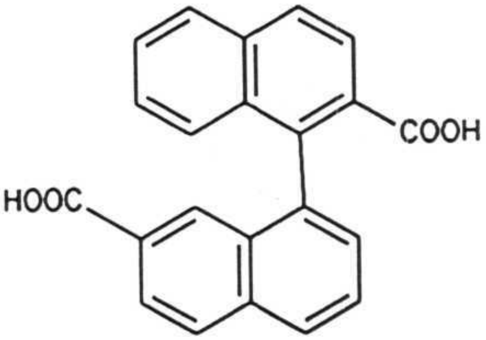


19

If an organic molecule has an awkward shape and size, it cannot pack efficiently, that is the packing coefficient falls around 0.6 and crystallisation cannot take place.[2] But crystallisation can be achieved by an inclusion of a guest molecule that fulfills close packing requirements. Arene units and other bulky groups (**17, 18, 19**) create porous host lattices with channels or cages that make hydrocarbon guest enclosure possible.[62] Inclusion of guest species is driven by close-packing which is obtained when the guest molecules fill the hollow spaces of the host.



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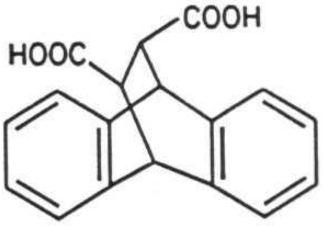

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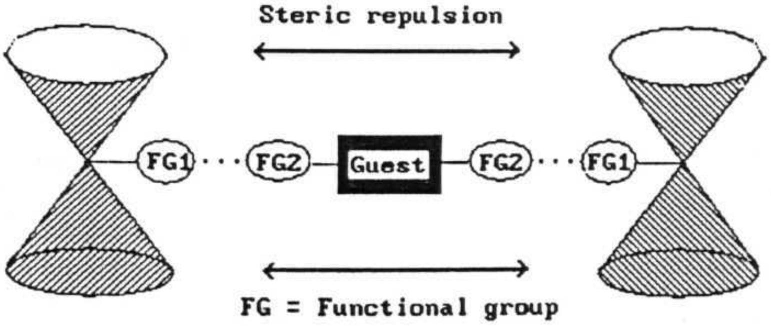


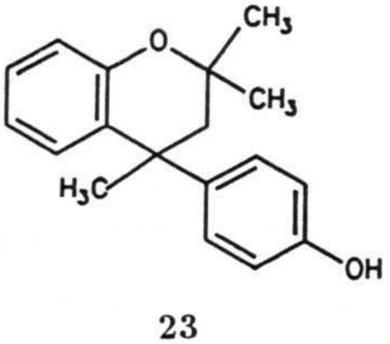
Figure 27

Host-guest complexes of this type can also be formed by coordinating guest molecule to hydrogen bonded functional groups attached to the rigid molecular frameworks, **20** and **21**. But this is possible only if the functional groups of the host framework do not hydrogen bond with themselves. In other words there should be a preference for the host molecules to form hydrogen bonds with the guest molecules. Hydrogen bonding possibilities within the host with itself can be suppresed by creating a situation where the hydrogen bonding functional groups of a host molecule are prevented sterically from coming into mutual contact (Figure 27).

1.5.2.2 Supramolecular Hosts Based on Intermolecular Interactions

Host-guest complexes classified under this category are the first compounds to be known as inclusion compounds. Hydroquinone, **22**,[63] Dianin's compound, **23**,[64] the alicyclic diol, **24**[65] and so on are the few examples of this type. Hydroquinone molecules form hydrogen bonded hexameric units and these units form a ceiling and floor of a cage structure shown in Figure 28.

22



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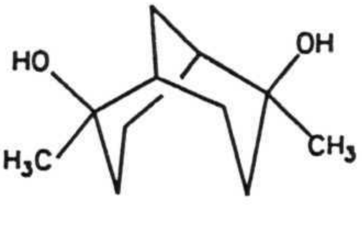


24

Intermolecular interactions, between two different molecular species may also lead to the formation of a supramolecular cavity which may be occupied by guest molecules. The charge transfer complex of benzidine, **25** and

TCNQ, **26** reported by Yakushi and co-workers reveals N-H...N hydrogen bonds and the directional preferences of these interactions lead to a hexagonal cavity that is quite suitable for clathrating benzene molecules (Figure 29).[66]

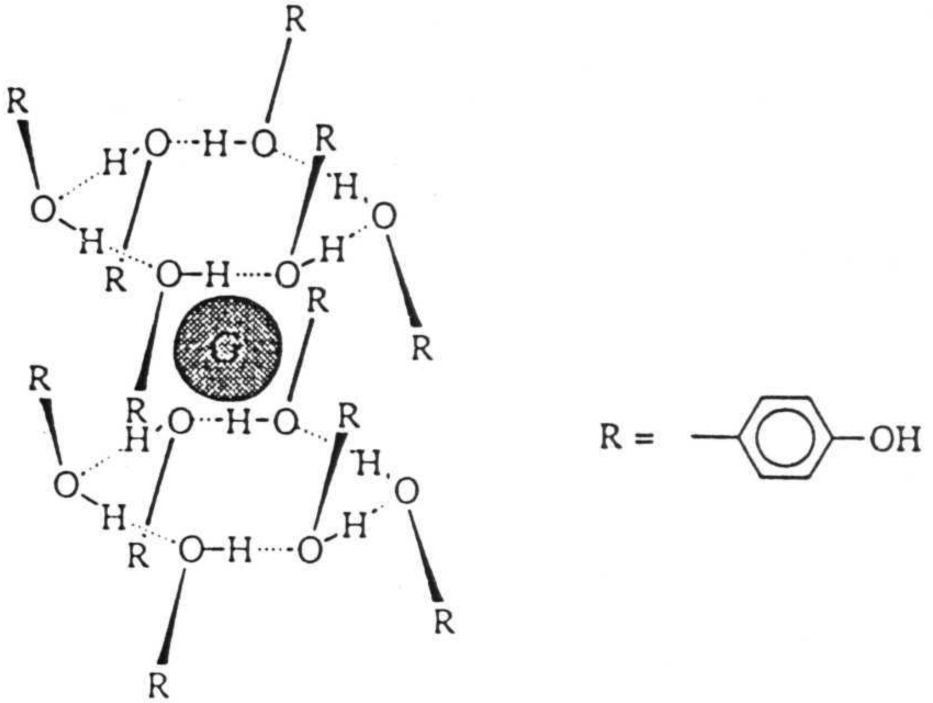
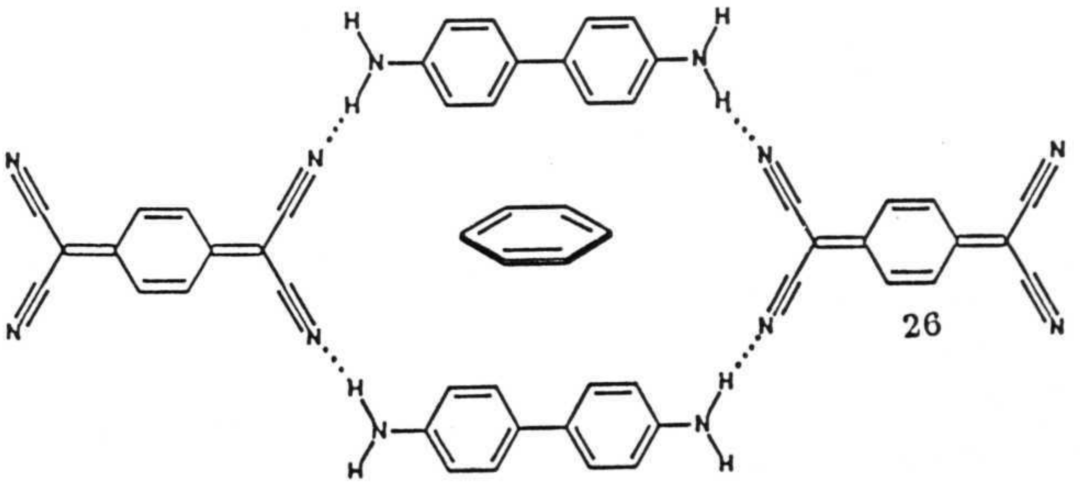


Figure 28



26

25

Figure 29

1.6 Crystal Engineering as Molecular Recognition in the Solid State

The basic concepts of crystal engineering and molecular recognition are similar and both fields are concerned with architecturing supermolecules through intermolecular interactions to attain required chemical, physical and structural properties. It may appear artificial to view them as different fields in spite of their unified approach to supramolecular chemistry. The possible reason for this rather superficial separation may be that crystal engineering and molecular recognition have been developed independently by researchers with varying backgrounds and research interests. Crystal engineering has been developed by structural chemists with a knowledge of crystallography, with a view to designing solid state reactions and novel materials, while molecular recognition has been developed by physical organic chemists having some biological background and with an interest in developing synthetic processes which occur in biology. The conventional differences in methodologies and goals of these two fields have been summarised in Table 2.

Crystal structures are usually a result of a perfect balance between various intermolecular interactions and hence any design strategy to control crystal packing should consider all types of intermolecular interactions (primary, secondary and tertiary interactions) to account for a particular molecular assembly. It is clear from the earlier discussion and from Table 2 that crystal engineering strategies are superior to molecular recognition strategies in dealing with intermolecular interactions because X-Ray crystallography is the only technique that gives precise information concerning intermolecular interactions. Additionally, statistical analysis through the CSD is a powerful way to understand the nature of weak intermolecular interactions and for determining molecular building blocks.

Table 2

Crystal Engineering	Molecular Recognition
Concerned with the solid state only.	Concerned chiefly with the solution state.
Strength of the intermolecular interactions is measured precisely in terms of bond lengths and angles that are obtained from X-Ray Crystallography.	Strength of the intermolecular interactions is measured in terms of association constants, that are obtained from spectroscopic studies (NMR, UV).
Design strategies involve controlling the three-dimensional arrangement of molecules and such design results in desired chemical and physical properties.	Design strategies are confined to the recognition of two molecular species, the substrate and receptor and such recognition should result in biological functions, and well-defined recognition patterns.
Both strong and weak intermolecular interactions are considered either independently or collectively for designing supermolecules.	Strong intermolecular interactions that is, strong hydrogen bonding and to some extent $\pi ... \pi$ interactions and herringbone interactions are considered for the engineering of supramolecular structure.
The design may involve either single or multimolecular species. A one-component crystal is the best example of self-recognition.	The design generally involves two different species, the substrate and the receptor or the host and guest. Ideas concerning self-recognition are poorly developed
The cavity of the host can be be formed by multimolecular species.	The cavity of the host is usually formed only by a single macrocyclic molecule.
There is a systematic way to work backwards to identify (new) recognition patterns of both strong and weak intermolecular interactions from known crystal structures.	There is as yet no systematic way to search for new recognition patterns.

Crystal engineering strategies firstly identify characteristic binding features of various intermolecular interactions. Secondly, based on this information, they further consider all possible directional and non-directional intermolecular interactions and their interplay to obtain a complete three dimensional structure with required physical and chemical properties. However, these efforts may not always be fruitful. Often well-defined structural patterns may only be obtained in one or two dimensions instead of in three dimensions. As a consequence, the expected physical and chemical properties (especially NLO properties) may not be observed for the designed compound. But the construction of supermolecules in one or two dimensions may be termed solid state molecular recognition. These recognition patterns may well be extended to solution state molecular recognition studies as *the nature of the intermolecular interactions in solid state are exactly the same as in solution.* Thus, crystal engineering strategies may form the basis for both solid state and solution state molecular recognition methodologies. The importance of crystal engineering strategies in molecular recognition is far more apparent in the case of weak intermolecular interactions. The title of this thesis reflects this fact.

It is to be mentioned here that merely analysing a three-dimensional crystal structure cannot be termed crystal engineering, unless the architecture of the crystal is based on systematic (step-wise) engineering strategies and the designed compound should have required physical or chemical properties (see Section 1.3) or a well-defined three-dimensional supramolecular molecular arrangement (for instance, adamantane-1, 3, 5, 7-tetracarboxylic acid). So in fact, there are two different aspects to crystal engineering studies. One is to design compounds with desired properties and the other one is to build well-defined three dimensional structures.[67,68] These supermolecules may well be compared to the synthesis of organic molecules where molecules are synthesised either for their interesting chemical or physical or biological properties or for their aesthetically appealing structural features.

1.7 Aim of the Present Work

The present work tries to address several facets of crystal engineering in the context of developing new ideas for supramolecular assembly. These facets are: (i) The use of weak C-H...O hydrogen bonds in molecular recognition. (ii) Interplay of strong and weak intermolecular interactions. (iii) Engineering solid state topochemical reactions for organic synthesis. (iv) The role of guest molecules in host-guest complexes.

References

1. J.-M. Lehn, *Angew.Chem.Int.Ed.Engl.*, 1990, **29**, 1304.
2. G.R. Desiraju, *Crystal Engineering: The Design of Organic Solids*, Elsevier, Amsterdam, 1989.
3. J.D. Dunitz, *Pure Appl.Chem.*, 1991, **63**, 177.
4. F.H. Allen, O. Kennard and R. Taylor, *Acc.Chem.Res.*, 1983, **16**, 146.
5. F.H. Allen, J.E. Davies, J.J. Galloy, O. Johnson, O. Kennard, C. F. Macrae and D.G. Watson, *J.Chem.Inf.Comp.Sci.*, 1991, **31**, 204.
6. G.M.J. Schmidt, *Pure Appl.Chem.*, 1971, **27**, 647.
7. J.-M. Lehn, *Angew.Chem.Int.Ed.Engl.*, 1988, **27**, 89.
8. D.J. Cram, *Angew.Chem.Int.Ed.Engl.*, 1986, **25**, 1039.
9. C.J. Pedersen, *J.Am.Chem.Soc.*, 1967, **89**, 2495.
10. A.I. Kitaigorodskii, *Izvest.Akad.Nauk* S.S.S.R., 1951, **15**, 157
11. F.H. Westheimer, *J.Chem.Phys.*, 1946, **14**, 73.
12. T.L. Hill, *J.Chem.Phys.*, 1948, **16**, 938.
13. A.I. Kitaigorodskii, '*Molecular Crystals and Molecules*', Academic, New York, 1973.
14. G.R. Desiraju and A. Gavezzotti, *J.Chem.Soc., Chem.Commun.*, 1989, 621.
15. C.A. Hunter and J.K.M. Sanders, *J.Am.Chem.Soc.*, 1990, **112**, 5525.
16. F.H. Quina and D.G. Whitten, *J.Am.Chem.Soc.*, 1975, **97**, 1602.
17. C. Tanford '*The Hydrophobic Effect. Formation of Micelles and Biological Membranes*', Wiley, New York, 1980.
18. C.B. Aakeroy and K.R. Seddon, *Chem.Soc.Rev.*, 1993, 397.
19. L. Pauling, '*The Nature of Chemical Bond and the Structure of Molecules and Crystals- An Introduction to Modern Structural Chemistry*', Oxford University Press, London, 1940.
20. P.W. Atkins, '*General Chemistry*', Scientific American Books, New York, 1989.

21. G.C. Pimentel and A.L. McClellan. '*The Hydrogen Bond*'. Freeman, San Fransico. 1960.
22. T. Steiner and W. Saenger, *J.Am.Chem.Soc.*, 1993, **115**, 4540.
23. G.A. Jeffrey and W. Saenger, '*Hydrogen Bonding in Biological Structures*', Springer-Verlag, Berlin, 1991.
24. R. Taylor and O. Kennard, *Acc.Chem.Res.*, 1984, **117**, 320.
25. G. Gilli, F. Bellucci, V. Feretti and V. Bertolasi., *J.Am.Chem. Soc.,* 1989, **111**, 1023.
26. G.R. Desiraju, *Acc.Chem.Res.*, 1991, **24**, 290.
27. R. Taylor and O. Kennard, *Acc.Chem.Res.*, 1982, **104**, 5063.
28. V.R. Pedireddi and G.R. Desiraju, *J.Chem.Soc., Chem.Commun.,* 1992, 988.
29. J.L. Atwood, F. Hamada, K.D. Robinson, G.W. Orr and L.R. Vincent, *Nature*, 1991, **349**, 683.
30. M.A. Viswamitra, R. Radhakrishnan, J. Bandekar and G.R. Desiraju, *J.Am.Chem.Soc.,* 1993, **115**, 4868.
31. G.R. Desiraju and A. Gavezzotti, *Acta Crystallogr.,* 1989, **B45**, 473.
32. R. Hunter, R.H. Haueisen and A. Irving, *Angew.Chem.Int.Ed.Engl.*, 1994, **33**, 566.
33. L. Leiserowitz, *Acta Crystallogr*, 1976, **B32**, 775.
34. R. Foster, '*Organic Charge Transfer Complexes*', Academic Press, London, 1969.
35. P.L. Anelli, P.R. Ashton, R. Ballardini, V. Balzani, M. Delgado, M.T. Gandolfi, T.T. Goodnow, A.E. Kaifer, D. Philp, M. Pietraszkiewicz, L. Prodi, M.V. Reddington, A.M.Z. Slawin, N. Spencer, J.F. Stoddart, C. Vicent and D.J. Williams, *J.Am.Chem.Soc.*, 1992, **114**, 193.
36. M.J. Begley, M.A. Mazid and D.A. Whitting, *Acta Crystallogr.,* 1978, **A34**, 896.
37. S.K. Kearsley and G.R. Desiraju, *Proc.R.Soc.London*, 1985,

A397, 1985.

38. L. Turi and J.J. Dannenberg, *J.Phys.Chem.* **1992**, 96, 5819.
39. L.K. Vinson and J.J. Dannenberg, *J.Am.Chem.Soc.,* 1989, **111**, 2777.
40. A.I. Kitaigorodskii, '*Mixed Crystals*', Springer, Berlin, 1984, pp 214-216.
41. M. Bailey and C.J. Brown, *Acta Crystallogr.,* 1967, **22**, 387.
42. F.H. Herbstein in '*Topics in Current Chemistry*', ed. E. Weber, Springer, Berlin, 1987, pp 107-140.
43. O. Ermer, *J.Am.Chem.Soc.,* 1988, **110**, 3747.
44. L. Leiserowitz and G.M.J. Schmidt, *J.Chem.Soc.,* 1969, 2372.
45. Y. Ducharme and J.D. Wuest, *J.Org.Chem.,* 1988, **53**, 5789.
46. M.C. Etter and D.A. Adsmond, *J.Chem.Soc., Chem.Commun.*, 1990, 589.
47. T.W. Panunto, Z.Urbanczyk- Lipkowska, R.B. Johnson and M.C. Etter, *J.Am.Chem. Soc.,* **1987**, 109, 7786.
48. J.A. Zerkowski, C.T. Seto and G.M. Whitesides, *J.Am.Chem.Soc.,* 1992, **114**, 5473.
49. F.G. Tellado, S.J. Geib, S. Goswami and A.D. Hamilton, *J.Am.Chem. Soc.*, 1991, **113**, 9265.
50. Y. Aoyama in '*Supramolecular Chemistry*', eds. V. Balzani and L.de.Cola, Kluwer, Dordrecht, 1992, pg. 27.
51. E. Weber, *J.Mol.Graphics*, 1989, **7**, 12.
52. A.D. Hamilton, *J.Chem.Edu.,* 1990, **67**(10), 821.
53. C.A. Hunter, *J.Chem.Soc., Chem. Commun.,* 1991, 749
54. G.M. Whitesides, J.P. Mathias, C.T. Seto, *Science*, 1991, **254**, 1312.
55. D. Philip and J.F. Stoddart, *Syn Lett.*, 1991, 445.
56. R. Wyler, J.de Mendoza and J. Rebek, *Angew.Chem.Int.Ed.Engl.,* 1993, **32**, 1699.
57. R. Hoss and F. Vogtle, *Angew.Chem.Int.Ed.Engl.*, 1994, **33**, 375.
58. J.F. Brown, *Sci.Am.,* 1962, **207**(7), 82.

59. G.R. Desiraju in '*Comprehensive Supramolecular Chemistry*' Vol. 6. eds. D.D. MacNicol, F. Toda and R. Bishop, Pergamon, 1995, in press.
60. F. Vogtle and E.Weber (eds.), '*Host-Guest Complex Chemstry. Macrocycles*', Springer, Berlin, 1985.
61. J.L. Atwood, G.A. Koutsantonis and C.L. Ratson, *Nature*, 1994, **368**, 229.
62. I. Csoregh, M. Czugler, E. Weber and J. Ahrendt *J.Incl.Phenom.*, 1990, **8**, 309.
63. D.D. MacNicol, in '*Inclusion Compounds*', eds. J.L. Atwood, J.E.D. Davies and D.D. MacNicol, Academic Press, London, 1984, Vol. 2.
64. W. Baker, A.J. Floyd, J.F.W. McOmie, G. Pope, A.S. Weaving and J.H. Wild, *J.Chem.Soc.*, 1956, 2010.
65. R. Bishop and I.G. Dance, *J.Chem.Soc., Chem. Commun.* 1979, 992.
66. K. Yakushi, I. Ikemoto and H. Kuroda, *Acta Crystallogr*, 1974, **B30**, 1738.
67. D.S. Reddy, D.C. Craig, A.D. Rae and G.R. Desiraju, *J.Chem.Soc., Chem.Commun.*, 1993, 1737.
68. D.S. Reddy, D.C. Craig and G.R. Desiraju, *J.Chem.Soc., Chem.Commun.*, 1994, 1457.

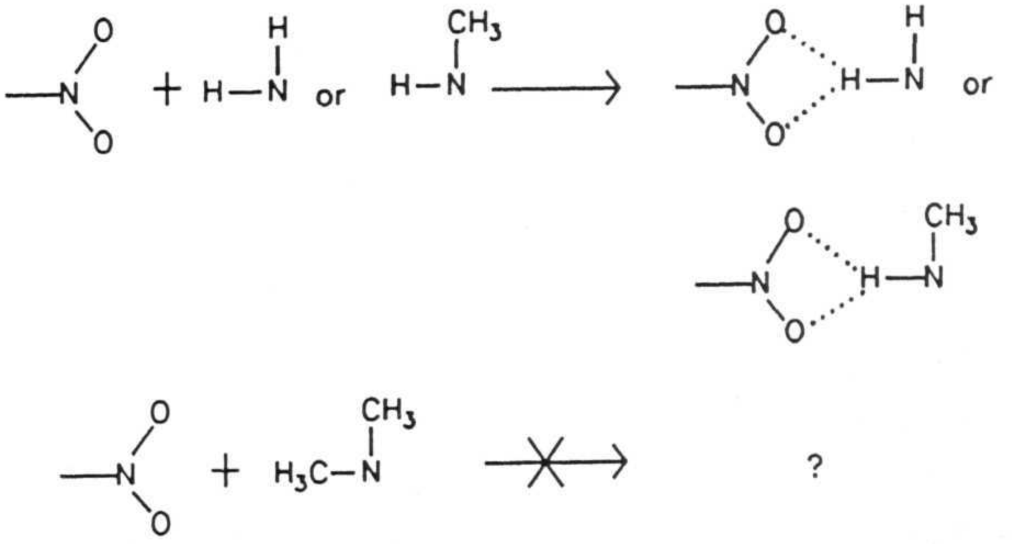
Chapter Two

Molecular Recognition in Crystalline Nitro Compounds Using C-H...O Hydrogen Bonds

2.1 Introduction

The emergence of supramolecular chemistry as a major area of research has been accompanied by the corresponding study of the intermolecular forces which must be implicated in the self-assembly of molecular components into supramolecular species with pre-desired architectural and functional features.[1] Most of these efforts have concentrated on strong or conventionally hydrogen bonded O-H...O or N-H...O building blocks (carboxylic acid, pyrimidine, aminopyridine, acylaminopyridine) and are necessarily limited to a small number of substances.[2] Yet, the scope of supramolecular assembly can be enhanced considerably if one considers, in addition, weak intermolecular interactions.[3] The C-H...O hydrogen bond is one such weak interaction with potential for solid state supramolecular assembly.[4,5] C-H...O based supramolecular design is interesting because most organic compounds do not contain functional groups capable of strong hydrogen bonding and in such instances one ought to be able to consider C-H...O interactions for the design of new supramolecular structures. Additionally, consideration of these interactions is useful even in strongly hydrogen bonded materials because it can reveal secondary and tertiary structural features which are often crucial to the optimisation of specific properties of these materials. The co-existence of these weak and strong hydrogen bonds may at times offer suitable explanations for anomalies in the patterns of strong hydrogen bonds[6,7] (see Chapter 3) and rationalise the structural features of biological molecules.[8]

Though the energy of C-H...O hydrogen bonds is only in the range of 1-5 Kcal/mol, the interaction is directional.[4b] In addition, for successful molecular recognition the selective and directional binding of the substrate by a molecular receptor is important and not the strength by which the receptor interacts with the substrate. Of course, the strength of the interactions becomes important when there is competition. So, the weak C-H...O hydrogen bonds can effectively be used in molecular recognition and the present work is aimed to demonstrate this fact.



Scheme I

The idea of employing C-H...O hydrogen bonds in molecular recognition traces back to the statement of Dannenberg that, the '...H bonding between the nitro and amino groups is precluded by the methylation of the amino groups.' (Scheme I).[9,10] So this project was initiated basically to look at the C-H...O hydrogen bonds of NMe_2 with NO_2, **1-3**, because it is well known that the CH_3 group is a good C-H...O bond donor.[11] Further, a few other molecular complexes of nitrobenzoic and nitrocinnamic acids, **4-11** prepared for various other reasons also revealed a systematic trend in C-H...O hydrogen bonding. These results warranted a detailed study of C-H...O recognition patterns in nitro compounds. The C-H...O patterns are discussed based on exhaustive searches of the Cambridge Structural Database (CSD)[12] and an attempt is made to formulate some guidelines for the effective practice of nitro group crystal engineering with C-H...O interactions.

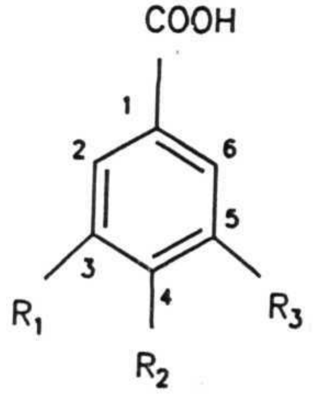
Cooperativity is a distinctive property associated with supramolecular assembly and this phenomenon has been well-studied for strong hydrogen bonds both experimentally[13] and computationally.[14] There is no corresponding study for C-H...O hydrogen bonds, though it is assumed that this property is operational in these bonds.[4b] Cooperativity permits additional stabilisation to supermolecules to overcome entropic barriers.[14] A dimer must be stabler than a monomer, a tetramer stabler than a pair of dimers and so on; otherwise the molecular (or oligomeric) species would be preferred to the supramolecular species. The energy of cooperativity is a crucial resource for self-assembly *via* weak intermolecular interactions. For the first time the cooperativity in C-H...O hydrogen bonds is visualised in this study.

1a. $R_1 = R_3 = H$; $R_2 = NO_2$

1b. $R_1 = R_3 = NO_2$; $R_2 = H$

1c. $R_1 = R_3 = H$; $R_2 = N(CH_3)_2$

1d. $R_1 = R_3 = H$; $R_2 = NH_2$



2a. $R_1 = R_3 = R_4 = H$; $R_2 = NO_2$

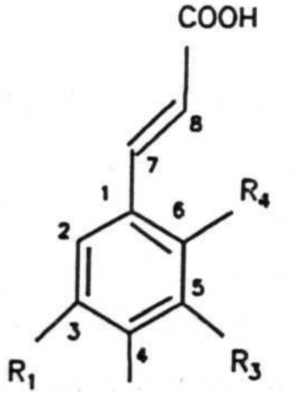
2b. $R_1 = R_3 = NO_2$; $R_2 = R_4 = H$

2c. $R_1 = R_3 = H$; $R_2 = R_4 = NO_2$

2d. $R_1 = R_3 = R_4 = H$; $R_2 = N(CH_3)_2$

2e. $R_1 = R_4 = OCH_3$; $R_2 = R_3 = H$

2f. $R_1 = R_2 = OCH_3$; $R_3 = R_4 = H$

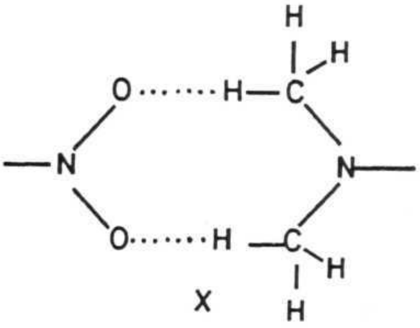


1. 1a.1c **2. 1a.2d** **3. 2a.2d** **4. 2b.1c** **5. 2b.2d**
6. 2b.2e **7. 2c.2f** **8. 2c.2e** **9. 1b.1c** **10. 1b.2d**

The numbering scheme used for the compounds **1a-1d**, **2a-2f** and complexes, **1-10** will be maintained in the subsequent chapters also.

2.2 Results and Discussion

2.2.1 C-H...O Hydrogen Bond Patterns in Complexes 1 and 2 and Cooperativity



X

In complex **1** (Figure 1), a linear ribbon that comprises O-H...O and C-H...O dimers (X) is the main structural element. The two acid molecules are linked by O-H...O hydrogen bonds of 2.606(3) and 2.632(3)Åto form dimers and both the carboxy groups are completely disordered (C-O, **1a**, 1.26 and 1.26Åand **1c**, 1.28 and 1.27Å). More interestingly, these dimers are themselves organised using two C-H...O bonds involving NO_2 and $N(CH_3)_2$ groups to form dimer X(C...O 3.658(4), 3.725(4)Å; H...O 2.71(3), 2.71(3)Å; C-H...O 164(2), 172(2)°). It is worth noting that the H atoms of the CH_3 groups were located from difference-Fourier syntheses and are ordered. The low R-factor and positional e.s.d.s allow one to make confident statements regarding the position of the H atoms. The conformations of the two CH_3 groups are such that the two C-H...O angles within the C-H...O dimer are very close to 180°. The relevant H atoms lie only 0.11(3) and 0.16(3)Å

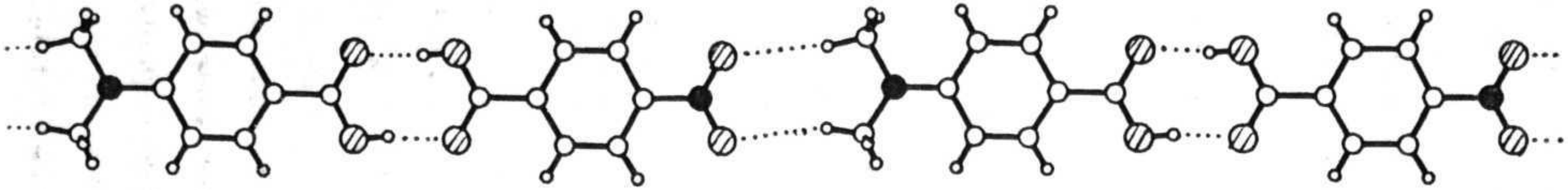


Figure 1. O-H...O and C-H...O Hydrogen bonds in the crystal structure of complex **1**. Notice the dimer rings formed in each case. N = ● O = ⊜

from the mean C-H...O dimer ring plane (atoms NO_2, NC_2) and the angle between the NO_2 and NC_2 planes is only 8.4°, It is to be mentioned here that the ordering of the CH_3 group and its directional specificity has been unequivocally demonstrated by Dunitz and coworkers in a tri-hydrated tricyclic orthoamide, where an energy of 1.8 Kcal/mole was estimated for each of the three C-H...O hydrogen bonds formed by the CH_3 groups with water O atoms.[11]

Complex **2** also forms a similar linear acentric molecular ribbon which is characterised by a carboxyl O-H...O heterodimer (O...O, 2.570(3), 2.657(3)Å) and the C-H...O dimer X (Figure 2). The carboxyl group of acid **1a** is fully disordered (C-O, 1.26, 1.27 Å) while that of acid **2d** is partially disordered (C-O 1.25, 1.28Å). Figure **2** shows that dimer X obtained in complex **2** has bifurcated (3-centred) C-H...O interactions[15] instead of two linear C-H...O hydrogen bonds as obtained in complex **1**. A H atom of the $N(CH_3)_2$ group is bifurcated by the two NO_2 O atoms while one of the NO_2 O atoms forms C-H...O bonds with two H atoms. Hence dimer X in complex **2** is more properly represented by three C-H...O interactions, C...O, 3.618(5), 3.700(5), 3.803(5)Å, H...O 2.82(4), 2.80(4), 2.88(4)Åand with the C-H...O angles being 147(3)°, 168(3)°, 164(3)°. The H atoms of the CH_3 groups were located from difference Fourier maps and are ordered, with the six C-H bond lengths being in the range 0.91-1.06(4)Å. Notably the two H atoms of dimer X lie within the plane of the C-H...O dimer (0.08(5) and 0.10(5)Å). Also the NO_2 and NC_2 planes of this complex make an interplanar angle of 8.76°, so the whole arrangement is quite planar.

It was also attempted to prepare single crystals of complex **3** (**2a** : **2d**) to observe the binding characteristics between these two electronically differently substituted cinnamic acids but the poor quality of the crystals did not permit any X-Ray studies. Yet another attempt was to build a linear chain exclusively with dimer X (for example, see Figure 3) and for this pur-

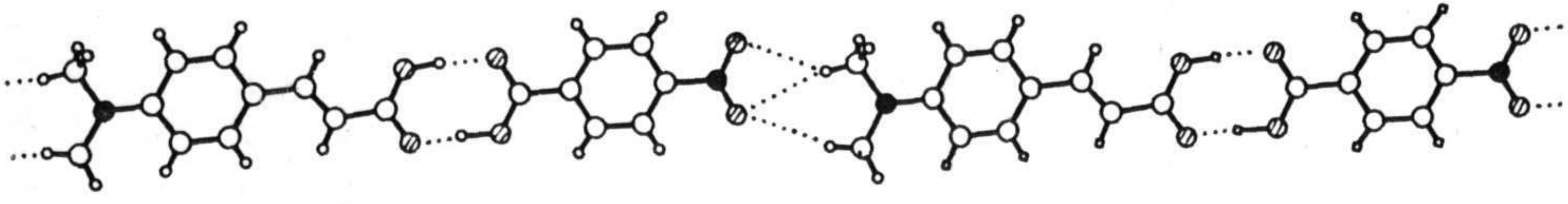


Figure 2. O-H...O and C-H...O Hydrogen bonds in the crystal stucture of complex **2**. The **1a** and **2d** molecules form a linear chain. Notice that dimer X is comprised of bifurcated C-H...O bonds unlike in complex **3**. N = ● O = ▨

pose, a complex **11** of 1,4-dinitrobenzene and N,N,N',N'-tetramethyl- *p*-phenylenediamine was prepared but the diffraction data on this twinned crystal were so poor that though an approximate structure was obtained, it failed refine. This rough structure with an R-value of 0.15 hints at the possibility of a NO_2-$N(CH_3)_2$ recognition pattern, but it appears that the C-H...O hydrogen bonded chain is criss-crossed instead of being linear and probably involves bifurcated C-H...O interactions.[1]

The change of the donor species from **1c** to **2d** in complexes **1** and **2** does not alter the gross recognition features of the NO_2 and $N(CH_3)_2$ groups but the relative approach of groups is altered slightly. This example indicates that the exact nature of dimer X is dependent on the molecular geometry and other (isotropic) crystal packing forces present in the solid. Such substitutional changes (like **1c** → **2d**) are of interest and significance because the conjugation (hyperpolarisability) in the chain increases and this property is of relevance in the design of NLO materials.[16]

It has been found in the literature that a prototype molecule, N,N-dimethylnitramine, **12** self assembles through NO_2·$N(CH_3)_2$ recognition (Figure 3).[17] Interestingly the structure of this compound has also been determined by neutron and gaseous state electron diffraction techniques, besides the X-Ray diffraction method.[17,18] This abundance of structural data provided a unique opportunity to ascertain the significance of cooperative effects experimentally, that is by comparing molecular geometries of solid and gaseous state structures. In addition, the simple molecular geometry of **12** makes it easy to approximate the energetics and cooperativity of C-H...O interactions theoretically using AM1 calculations.[19,20]

For a supermolecule to be formed, the molecules must initially form a dimer, then a trimer and continue to aggregate till a supramolecular struc-

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[1] **Complex 11:** Monoclinic, a=11.36(2), b=10.93(2), c=11.14(1)Å; β=92.32(5)°.

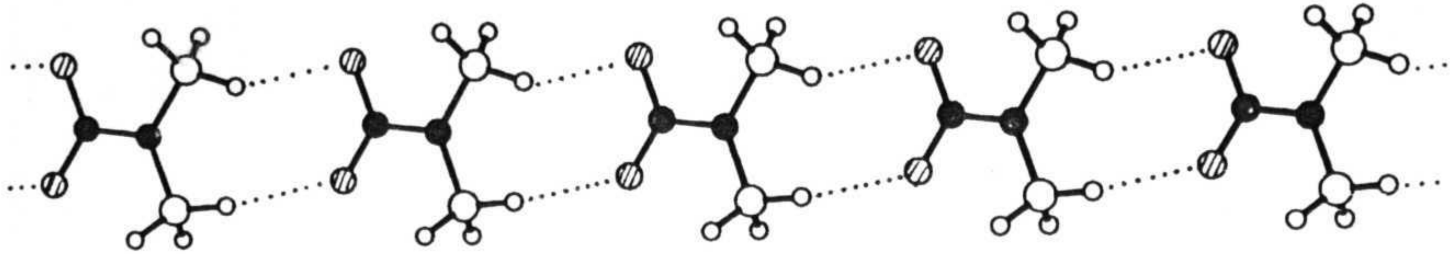
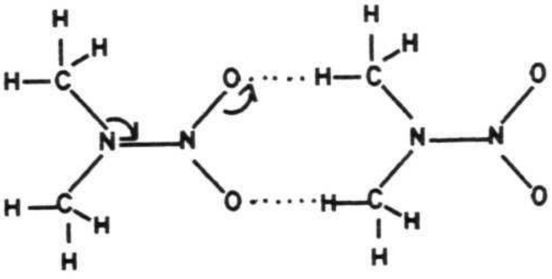


Figure 3. C-H...O Hydrogen bonds (dimer X) formed in the crystal structure of N,N-dimethylnitramine **12**.N = ● O= ▨

e is attained. In order for this process to occur, cooperativity should y an important role in the addition of individual units to the growing gregate. The cooperative effects in C-H...O hydrogen bond formation are w discussed by considering molecular and supramolecular structures of **12** a model (Figure 3). The H atoms of **12** point exactly towards the O atoms the NO_2 group. As these H atoms are obtained from a neutron study ≈ 0.036) there is little ambiguity regarding their position. The NO_2 and $_2$ groups of **7** are accurately coplanar. At this stage, it may be interesting recall the rhetorical argument of Cotton and Luck on the determination H atom position by X-Ray and neutron diffraction methods that 'the utron experiments sees with considerable accuracy (*ca.* ±0.001Å), the ation of the hydrogen atoms's *nucleus*, *the proton*. In a very favorable se [...], the X-ray experiment sees with less accuracy (*ca.* ±0.02Å), the drogen atom's *electron cloud*. Which of these is '*the* hydrogen atom'? th the nucleus and the electron density of an atom are the essential parts d it is therefore impossible to assert rationally that the position of either e one or the other is 'the' position of the atom.'[21]



Scheme II

Charge transfer through C-H...O hydrogen bonds in the linear chain of lecules **12** in the solid state (Figure 3), causes systematic changes in ramolecular geometry of **12** compared to that of the isolated gaseous te structure (Scheme II). The intramolecular bond lengths and angles observed for **12** in the solid state are in consonance with charge transfer (Table 1). The solid state structure of **12** reveals a slight decrease in N-N and N-C bonds lengths and an increase in N-O bond length compared to the gaseous state structure. In addition, the O-N-O and C-N-C bond angles of **12** in the solid state are decreased with respect to the value in the isolated molecular structure and such a decrease in bond angles may facilitate the direction of the H atoms towards the lone pairs of the O atoms, accentuating cooperativity. However, there is no elongaton in the C-H bond length as might have been expected. Indeed, it is difficult to detect the cooperative effects of C-H...O bonds in the solid state unless we have an isolated molecular structure for comparison as the changes involved in bond lengths and angles are marginal. The energy gained through cooperativity in C-H...O hydrogen bonds is still quite low compared to that in strong hydrogen bonds.

Table 1

Selected intramolecular bond lengths and angles of **12** obtained from neutron, X-Ray and gaseous state electron diffraction methods

	Neutron	X-ray	Electron(gas)
N-N	1.326(3)	1.324(4)	1.382(3)
N-C	1.452(4)	1.457(4)	1.460(3)
	1.449(3)	1.445(4)	,,
O-N	1.233(5)	1.244(4)	1.223(2)
	1.240(4)	1.241(4)	,,
O-N-O	123.7(3)	123.4(3)	130.4(6)
C-N-C	124.5(2)	124.5(3)	127.6(6)
C-H	1.081(7)	0.99(2)	1.121(5)

The energies of O-H..O and C-H...O hydrogen bonds in complex **1** were evaluated computationally with the semi-empirical AM1 approximation.

This method has previously been used to compute energy in O-H...O hydrogen bonds of carboxylic and 1,3-diketone aggregates.[10,14] It has also been shown to reproduce C-H...O interaction energies and geometries well.[20] The hydrogen bond energy for the O-H...O dimer of complex **1** was found to be -6.7 Kcal/mole and that of the C-H...O dimer -2.45 Kcal/mole. It should be noted that while the O-H...O geometry and energy are poorly calculated in SCF methods because of overestimation of the H...H repulsions in the carboxy dimer ring and the neglect of electron correlation effects,[13b,22] there are no similar sources of error in the calculation of C-H...O bond energies. The hydrogen bonds in the optimised structure of **1** are as follows: O-H...O dimer O...O 3.04, 3.10Å, H...O 2.07, 2.12ÅO-H...O 174.6°, 175.0°; C-H...O dimer C...O 3.49, 3.45 Å, H...O 2.42, 2.33Å, C-H...O 157.0, 174.7°. It is difficult to compute the cooperative effects of C-H...O bonds in complexes **1** and **2**, because the size of the linear molecular aggregates impede calculations before the cooperativity limit can be reached.

The optimised C-H...O hydrogen bond energies and averaged partial charges of the O and H atoms of dimer X in the linear molecular aggregates of **12** are given in Table 2. The stabilisation *per* dimer unit *via* C-H...O hydrogen bonding increases with an increase in the number of molecules in the linear chain. A linear molecular assembly is preferred because of the additional cooperativity energy and this extra energy may discriminate against other possible molecular arrangements which do not have this cooperative advantage. The enhancement of charges on the H and O atoms from monomer to n-mers indicates mutual induction and charge transfer through C-H...O hydrogen bonds. Table 2 shows that the cooperativity effect begins to level off at the pentamer stage.

Table 2

C-H...O Incremental interaction energies (Kcal/mol) in linear molecular aggregates of **12** and the averaged partial charges of the H and O atoms

	Total Energy	Total C-H...O Bonds Energy	Average C-H...O Bonds Energy (*per* dimer unit)	Atom charges	
				H	O
monomer	21.7	–	–	0.0764	-0.3588
dimer	40.2	3.2	3.2	0.1320	-0.3709
trimer	58.0	7.1	3.6	0.1365	-0.3770
tetramer	75.4	11.4	3.8	0.1384	-0.3799
pentamer	93.1	15.4	3.9	0.1395	-0.3817

2.2.2 C-H...O Hydrogen Bond Patterns in Complexes 4-9

The NO_2 group in complexes **4-9** is particularly suited for the formation of C-H...O hydrgen bonds and in general, three distinct patterns of C-H...O bonds have been observed. The choice between these three C-H...O patterns seems to depend on the stoichiometry and arrangement of the functional groups (mostly $-NO_2$) in the respective complexes **4-9**. Complex **10** formed twinned crystals and only an approximate structural analysis was possible and for this reason its C-H...O interaction patterns are not discussed here.[2] The first pattern (Figure 4a) is found in complexes of 3,5-dinitro-substituted benzoic or cinnamic acids with 4-$N(CH_3)_2$-substituted benzoic or cinnamic acids (**4, 5, 9**) and is characteristic of the NO_2 to $N(CH_3)_2$ approach. The C-H...O bonds in this first pattern involve mainly sp^3 H atoms of the $-N(CH_3)_2$ groups and $-NO_2$ O atoms (Complex **5**; C...O; 3.68, 3.50, 3.79, 3.60, 3.37Å: C-H...O; 157, 161, 132, 166, 132°).

The second pattern is a self-motif found in all complexes containing 3,5-dinitrocinnamic acid **2b** (**4, 5** and **6**, Figure 4b). This pattern is charact-

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[2] **Complex 10: Monoclinic, $P2_1/c$, a= 7.89(1), b= 16.55(2), c= 14.41(1)Å;β= 97.31(1)°.**

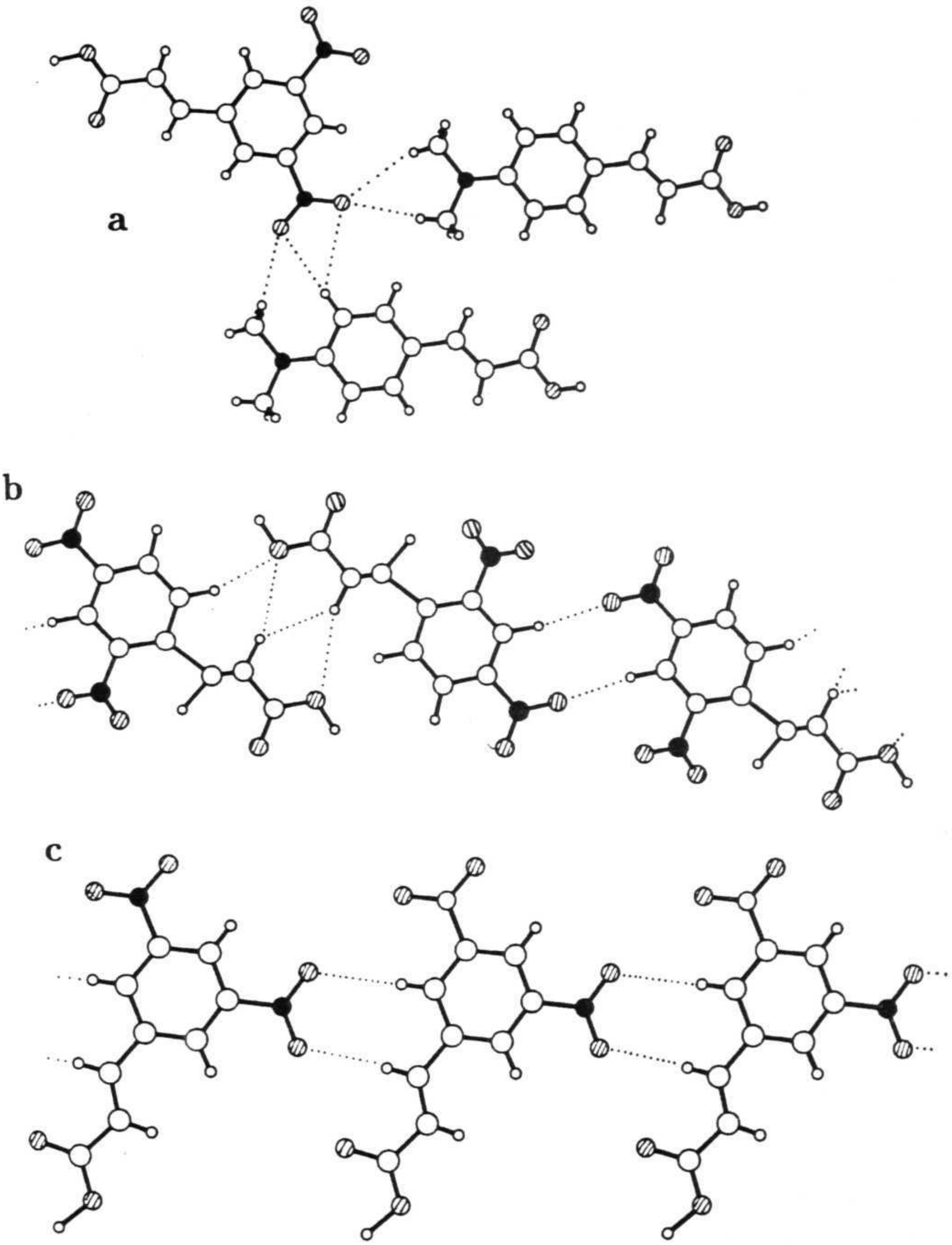


Figure 4 Three types of C-H...O bonding patterns observed in complexes 3- **9**. (a) Recognition pattern of 3,5-dinitro to 4-NMe_2 in complexes **4**, **5** and **9**. (b) Self assembly of **2b** molecules in **4**, **5**, **6** and in acid **2b**. (c) Self assembly of **2b** molecules with two types of motifs in **7** and **8**. N = ● O = ◍

erised by translation of 8.3 to 8.4Åand involves linear C-H...O bonds between both O atoms of a particular NO_2 group with the styryl and aromatic H atoms of the translated neighbour (Complex **4**; C...O; 3.50, 3.50Å: C-H...O; 173, 167°). This pattern is also found in the crystal structure of the free acid **2b**[7] and can be considered to be a molecular ribbon obtained by self-assembly.

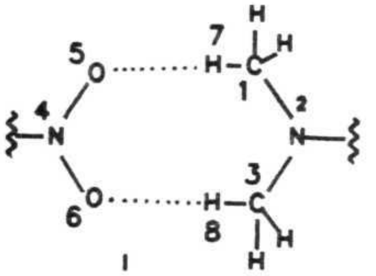
That the arrangement of NO_2 groups in a molecule is also critical in determining the C-H...O pattern, is clear on inspection of Figure 4c which illustrates the third C-H...O pattern in these complexes, a pattern characteristic of the isomeric 2,4-dinitrocinnamic acid **2c** (**7** and **8**, Complex **7**; C...O; 3.52Å: C-H...O; 162°). The 2,4-arrangement of NO_2 groups results in a different C-H...O pattern than is obtained for the 3,5-arrangement shown in Figure 4b. In fact, there are two motifs, but both involve inversion-related molecules. One of the motifs involves an O atom of the 4-NO_2 group and the H3 atom while the other involves the carboxyl O and H6 and H8.

These three patterns along with NO_2-$N(CH_3)_2$ pattern are exclusive to each of the four substitutional categories described above and it is noteworthy that the particular pattern obtained depends not only on the stoichiometry (one or two NO_2 groups) but also on the arrangement of groups (2,4-dinitro or 3,5-dinitro). C-H...O networks in complexes **4**-**9** are therefore predictable and consequently C-H...O bonds can be well-utilised for molecular recognition and self-assembly in related organic solids. The non-centrosymmetric nature of some of these C-H...O patterns (Figures 1, 4a and 4b) may also be exploited for the deliberate design of non-centrosymmetric crystals leading to NLO materials.[16] These recognition patterns also highlight an interesting common feature and that is, the more acidic protons on the nitro-substituted acids, (especially acids **2b** and **2c**) are actively involved in the molecular recognition process and support arguments that hydrogen atom acidity is more important than O-atom basicity in the formation of

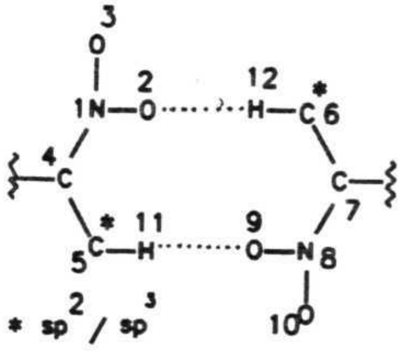
C-H...O bonds.[4b,23]

2.2.3 A General Study of C-H...O Recognition Patterns

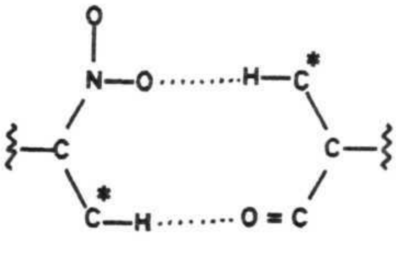
It has been observed that the C-H...O hydrogen bonds in NO_2 groups frequently show patterns I-V.[6,24][3] Thus, an exhaustive search was carried out with the CSD on recognition patterns that are characteristic of functional groups (pattern I) and geometry (patterns II-V). The recognition features of these patterns are now described.



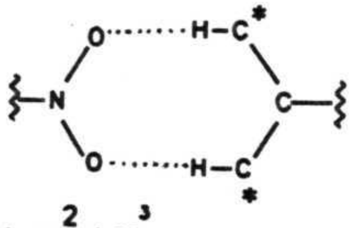
I



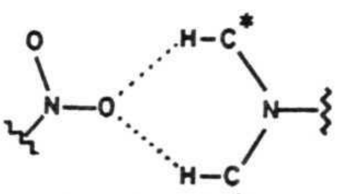
II $*$ sp^2 / sp^3



III $*$ sp^2 / sp^3



IV $*$ sp^2 / sp^3



V $*$ sp^2 / sp^3

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[3] Starred atoms can be either (a) sp^2 or (b) sp^3 hybridised.

2.2.3.1 Binding Features of Pattern I

The CSD was searched to find out the occurrence and the geometrical specificity of pattern I in NO_2 and $N(CH_3)_2$ compounds. Of the 69 unique structures considered (see Section 2.4.5), motif I is found in 29 compounds whose bibiliographic information is given in Table 3. The NO_2- $N(CH_3)_2$ approach can be described in terms of three parameters:(1) The interplanar angle between the NO_2 and NC_2 planes with H atoms ignored. Figure 5a represents a histogram of the interplanar angles; (2) The vertical offset or the translation perpendicular to the NO_2/NC_2 plane. To represent this offset we have calculated the average interplanar distances of the NO_2 and NC_2 planes. These distances are shown in histogram 5b; (3) The lateral offset of NO_2 and NC_2 groups that is, the translation in the mean NO_2/NC_2 plane. This parameter may be described in terms of the difference between the distances of diagonally disposed C and O atoms of pattern I, C1...O6 and C3...O5. This is shown in Figure 5c. Small differences in these diagonal distances indicate more symmetrical C-H...O dimers with little lateral offset between NO_2 and NC_2 groups while large differences in diagonal distances indicate more unsymmetrical C-H...O dimers.

It is clear from Figure 5a that the NO_2 and NC_2 groups prefer to be in plane (most of the points lie below 15°). Figure 5b indicates that there is hardly any vertical offset between NO_2 and NC_2 groups as most of the points cluster within 0.20Åof a coplanar arrangement. In contrast, lateral offsets are common and Figure 5c shows that many points are scattered with lateral offsets between 0.10 and 1.80 Å. The lateral offset arrangement in pattern I is possibly stabilised by additional bifurcated C-H...O interactions as in complex **2**. A superposition stereoplot of pattern I viewed along the plane of the NO_2 group for all the 29 compounds with the NO_2 group being fixed, is shown in Figure 6. This plot facilitates a visualisation of the relative orientation of the NO_2 and NC_2 groups

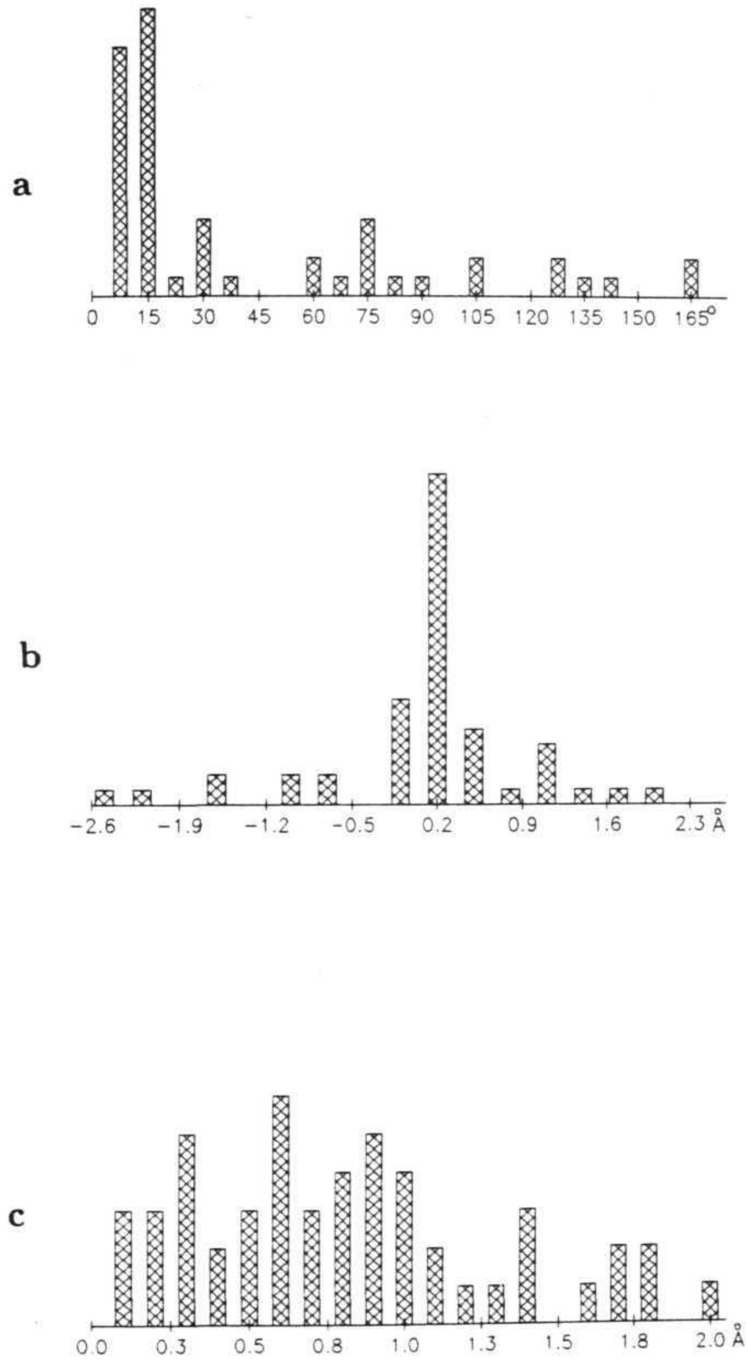


Figure 5 Histograms of three parameters which represent the NO_2-NC_2 approach in pattern **I**. (a) Interplanar angle (^{o}) between NO_2 and NC_2 planes. (b) Vertical offset translation (Å) perpendicular to NO_2/NC_2 planes. (c) Lateral offset translation (Å) in the NO_2/NC_2 planes.

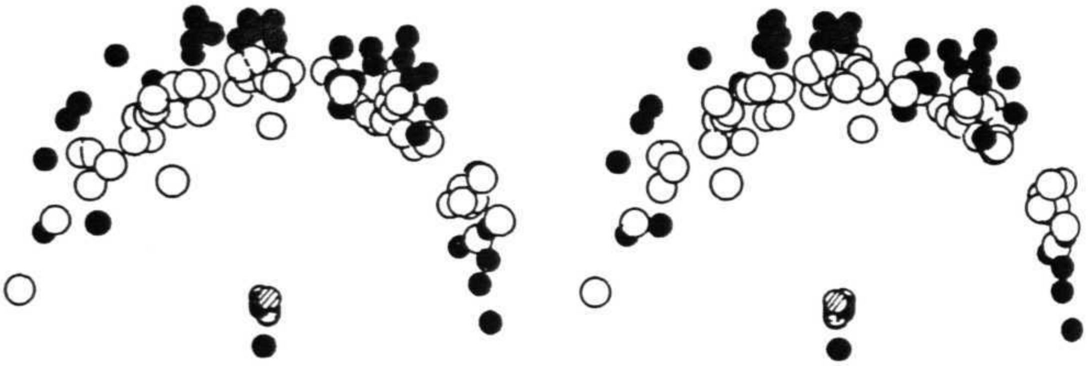


Figure 6. Stereodiagram of a superposition plot of NO_2 and NC_2 fragments of pattern I in 29 compounds. The plane of the NO_2 group is perpendicular to the plane of the paper and this NO_2 plane is kept fixed from structure to structure. N = ● O = ▨

Table 3

Bibiligraphic Information on Nitro compounds containing Pattern I

BUFXOP: N-Isopentyl-N'-(p-nitrophenylcarbonyl)-urea N-(benzylacetyl)- N'-(p -dim ethylaminophenyl) -urea; C13 H17 N3 O4, C18 H21 N3 O2; T. Endo, H.Tasai, K.Miyazawa, M.Endo, K.Kato, A.Uchida, Y.Ohashi, Y.Sasada; J.Chem.Soc., Chem.Comm., 636, 1983.

CADFOC: 1, 1, 5, 5-Tetramethyl-1, 2, 5-triazapentadienium picrate; C6 H14 N3 1+, C6 H2 N3 O7 1-; R.O.Gould, H.McNab, M.D.Walkinshaw; Acta Cryst., C (Cr.Str.Comm.), 39, 1097, 1983.

CIFHOO: 1, 5-bis(Dimethylamino)-2, 4-dinitro-pentamethinium perchlorate; at -150deg.C ; C9 H15 N4 O4 1+, Cl1 O4 1-; J.Dale, S.Kruger, C.Romming; Acta Chem.Scand.Ser.B, 38, 117, 1984.

CMANEY10: trans-1-(2-Chloro-4-dimethylaminophenyl) -2 -nitroethylene; C10 H11 Cl1 N2 O2; T.S.Cameron, D.J.Cowley, J.E.Thompson; J.Chem.Soc., Perkin Trans.2, 774, 1974.

DADZIR: E, E-1-(p-Dimethylaminophenyl)-5-(o-hydroxyphenyl)-penta-1, 4-dien-3-one m-dinitrobenzene clathrate; C19 H19 N1 O2, C6 H4 N2 O4; F.H.Herbstein, M.Kapon, G.M.Reisner, M.B.Rubin; J.Inclusion Phenomena, 1, 233, 1984.

DIXJEZ: N$6!, N$6!-Dimethyl-adeninium picrate; C7 H10 N5 1+, C6 H2 N3 O7 1-; T.Dahl; Acta Chem.Scand.Ser.B, 40, 226, 1986.

DUPHIF: 1, 1-bis(Dimethylamino)-2-nitroethylene; C6 H13 N3 O2; F. Ganazzoli, S. V.Meille, P.Gronchi ; Acta Cryst., C (Cr.Str.Comm.), 42, 1385, 1986.

FAJYIY: N, N-Dimethyl-4-(1-(p-nitrophenyl)ethylene)aniline; C16 H16 N2 O2; Yun Yi Wei, B.Tinant, J.P.Declercq, M.Van Meerssche; Acta Cryst., C (Cr.Str.Comm.), 43, 86, 1987.

FAWWIJ: N, N-Dimethyl-2, 4-dinitro -3-toluidine; C9 H11 N3 O4; J.K. Maurin, T.M. Krygowski; Acta Cryst., C (Cr.Str.Comm.), 43, 64, 1987.

FNDMAN: 2-Fluoro-4-nitro-N, N-dimethylaniline; C8 H9 F1 N2 O2; P.J.Cox, A.D.U.Hardy, R.K.Mackenzie, D.D.MacNicol ; J.Chem.Res., 292, 3341, 1977.

GADHEY: 1, 8-bis(Dimethylamino)naphthalene 2, 4-dinitroimidazolate C3 H1 N4 O4 1-, C14 H19 N2 1+ T.Glowiak, Z.Malarski, L.Sobczyk, E.Grech; J.Mol.Struct., 157, 329, 1987.

GIMRUP10: 1, 3-bis(m- Nitrophenyl)urea N, N-dimethyl- p-nitroaniline clathrate; C8 H10 N2 O2, C13 H10 N4 O5 ; M.C.Etter, Z.Urbanczyk-Lipkowska, M.Zia-Ebrahimi, T.W.Panunto; J.Am.Chem.Soc., 112, 8415, 1990.

JISZAM: rac-1H-1 -Hydroxy-2, 3-dihydro-2, 2, 3-trimethyl-7- methoxyisoindolium 3, 5- dinitrobenzoate; C12 H18 N1 O2 1+, C7 H3 N2 O6 1- ; J.D. Carroll II, P.R.Jones, R.G.Ball; J.Org.Chem., 56, 4208, 1991.

JOLNED: 3, 3-Dimethyl-1-(4-nitrophenyl)triazene; C8 H10 N4 O2; S.Neidle, D.E.V.Wilman ; Acta Cryst., B (Str.Sci), 48, 213, 1992.

KOVGIL: 1, 1-bis(Dimethylamino)-2, 2-dinitroethylene; C6 H12 N4 O4; K.Baum, S.S.Bigelow, N.V.Nguyen, T.G.Archibald, R.Gilardi, J.L.Flippen-Anderson, C.George; J.Org.Chem., 57, 235, 1992.

MABZNA02: N-(p-Dimethylaminobenzylidene)-p-nitroaniline ; form iii ; C15 H15N3 O2; H.Nakai, K.Ezumi, M.Shiro ; Acta Crystallogr., Sect.B, 37, 193, 1981.

MACINA10: 4- Dimethylamino- 3-nitrocinnamic acid; C11 H12 N2 O4; C.P.Huber; Acta Cryst., C (Cr.Str.Comm.), 41, 1076, 1985.

MANCPP: Methyl-(2E, 4Z)- 5-dimethylamino- 2-nitro- 4-(4-chloro- 2-nitrophenyl)-2, 4- pentadienoate; C14 H14 Cl1 N3 O6; U. Hengartner, A.D.

Batcho, J.F. Blount, W. Leimgruber, M.E. Larscheid, J.W. Scott; J. Org. Chem., 44, 3748, 1979.

METNAM07: N, N-Dimethyl-nitramine ; neutron study, at 125 deg.K; C2 H6 N2 O2; A.Filhol, G.Bravic, M.Rey-Lafon, M.Thomas ; Acta Crystallogr., Sect.B, 36, 575, 1980.

MNETAM: trans-N, N-Dimethyl-2-nitro-ethenamine ; trans-N, N-Dimethyl-2-nitrovinylamine ; C4 H8 N2 O2 ; A.Hazell, A.Mukhopadhyay; Acta Crystallogr., Sect.B, 36, 747, 1980.

NBZMAA: p-Nitrobenzylidene-p-dimethylaminoaniline; C15 H15 N3 O2; H.Nakai, M.Shiro, K.Ezumi, S.Sakata, T.Kubota ; Acta Crystallogr., Sect.B, 32, 1827, 1976.

NMADPS: 4-Nitro- 4'- dimethylamino - diphenylsulfide; C14 H14 N2 O2 S1; A.Krajewski, L.Riva di Sanseverino, A.Dondoni, A.Mangini ; J.Cryst. Mol.Struct., 5, 345, 1975.

PACSOB: 4-Nitrobenzoic acid 4-(N, N-dimethylamino) benzoic acid; C9 H11 N1 O2, C7 H5 N1 O4; C.V.K.Sharma, K.Panneerselvam, T.Pilati, G.R. Desiraju ; J.Chem.Soc., Chem.Comm., 832, 1992.

TACWOJ: 2'-(Dimethylamino)-3', 4'-dihydro-5', 7'-dinitrospiro (cyclopentane- 1, 3' -quinazoline) ; C14 H17 N5 O4 ; J.M. Villalgordo, B. R. Vincent, H. Heimgartner; Helv.Chim.Acta, 73, 959, 1990.

TAJKIY: 3, 4-Diethyl-3-(4'-nitrophenyl)-4-(4"-dimethylaminophenyl)hexane; C24 H34 N2 O2; P.Maslak, J.N.Narvaez, M.Parvez; J.Org.Chem., 56, 602, 1991.

VIZHER: 2, 4, 7 -Trinitro -10, 10 -dihydroxyphenanthren-9-one dimethylformamide solvate; C14 H7 N3 O9, 2(C3 H7 N1 O1); G.V. Gridunova, V.E. Shklover, Yu.T. Struchkov, R.V.Linko, A.N. Poplavskii, A.M. Andrievskii ; Izv.Akad.Nauk SSSR, Ser.Khim., , 575, 1990.

VUYKUV: N, N-Dimethyl-N'-p-nitrophenyl-formamidine; C9 H11 N3 02; E. Ciszak, M. Gdaniec, M. Jaskolski, Z. Kosturkiewicz, J. Owsianski, E. Tykarska ; Acta Cryst., C (Cr.Str.Comm.), 45, 433, 1989.

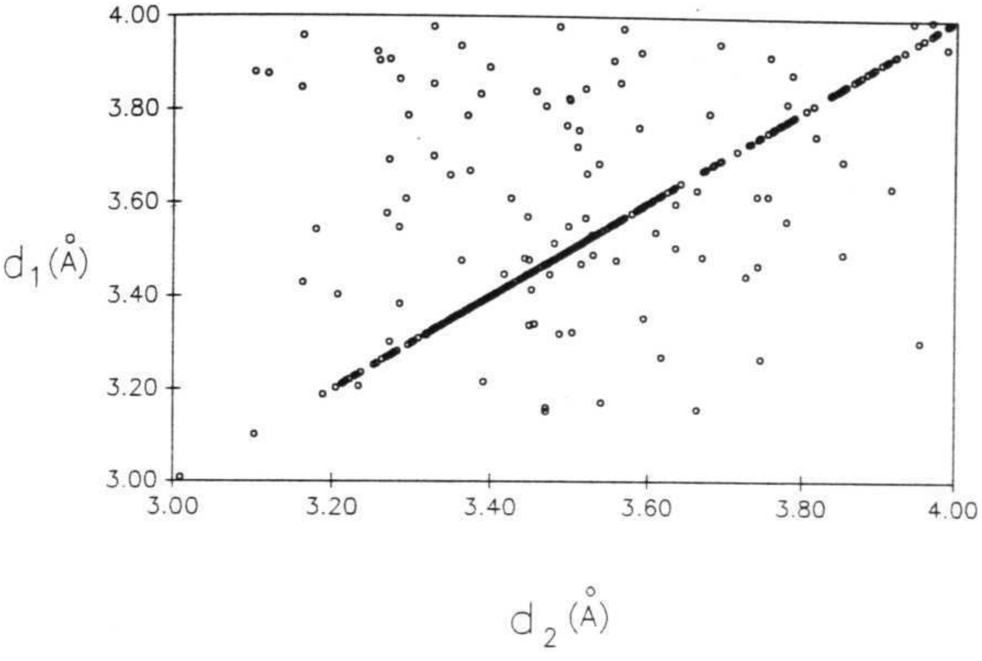
VUYLAC: N, N-Dimethyl-N'-p-nitrophenyl-acetamidine; C10 H13 N3 02; E. Ciszak, M. Gdaniec, M. Jaskolski, Z. Kosturkiewicz, J. Owsianski, E. Tydarska Acta Cryst., C (Cr.Str.Comm.), 45, 433, 1989.

ZZZFKK01: trans-4'-Dimethylamino-4-nitro-alpha-cyanostilbene; C17 H15 N3 02; B.Tinant, R.Touillaux, J.P.Declercq, M.van Meerssche, G.Leroy, J.Weiler; Bull.Soc.Chim.Belg., 92, 403, 1983.

2.2.3.2 Binding Features of Patterns II-V

The present analysis is statistical in nature and enables us to formulate the most frequent recognition patterns of NO_2 groups, which may be useful in crystal engineering. Patterns II-V are divided according to C-H group hybridisation, i.e sp^2 and sp^3 to visualise the impact of H atom acidity in C-H...O bond formation.[23] Table 4 presents some pertinent details.

Figure 7 shows that the patterns IIa and IIb are largely characterised by symmetrical C-H...O interactions, that is those with $d_1 = d_2$ and $\theta_1 = \theta_2$ (see Experimental Section for a definition of these terms). This plot indicates that pattern II is preferably centrosymmetric. The number of hits obtained



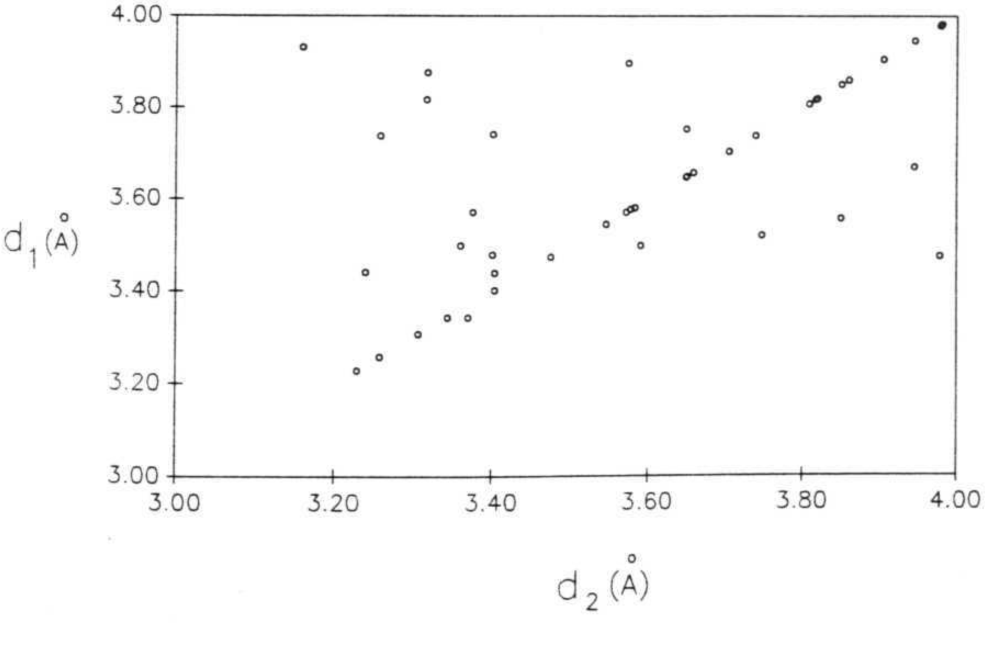


Figure 7. Scatterplots of C...O distances of pattern II; d_1 = C6...O2(Å), d_2= C5...O9(Å). **(a)** Motif IIa with sp^2 C-H. (b) Motif IIb with sp^3 C-H. The linear relationship of d_1 and d_2 indicates the significance of centrosymmetric contacts for this motif. Notice that there are far fewer points in IIb than in IIa.

Table 4

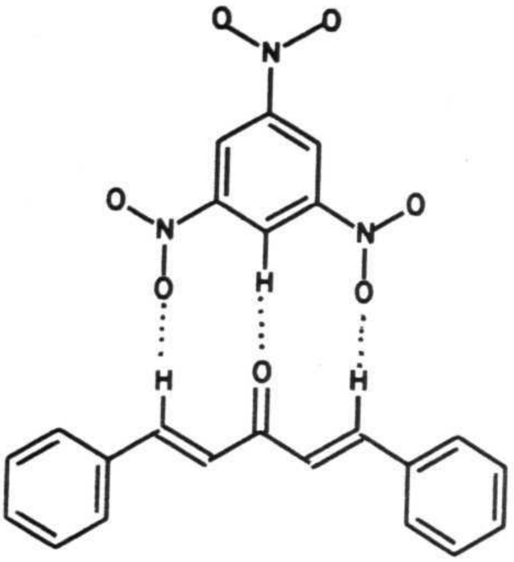
Statistical Data on Patterns I-V in Nitro Compounds

	Number of compounds with a potential to form pattern	Number of compounds which actually display pattern	Average hydrogen bonded parameters@	
			C...O (Å)	C-H...O (°)
I	69	29	3.65	138.0
IIa	817	280	3.52	127.5
IIb	88	25	3.61	125.8
IIIa	177	50	3.45	128.0
IIIb	33	0	–	–
IVa	136	19	3.59	137.6
IVb	103	10	3.66	135.9
Va	136	68	3.50	135.1
Vb	103	0	–	–

@ contact is considered a C-H...O hydrogen bond if $3.0 \leq$ C...O ≤ 4.0Åand $100 \leq$ C-H...O $\leq 180°$.

for IIb are reduced significantly compared to IIa because in that case the C-H group is specified to be sp^3 hybridised. Interestingly most of the hits observed for IIb correspond to cyclopropane derivatives (where strictly speaking the C-H group closely resembles alkenes rather than alkanes) and rigid alicyclic compounds like cubanes and prismanes.

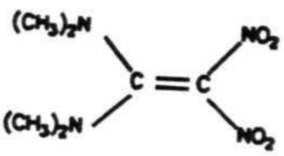
Pattern III is similar to II except that one of the NO_2 groups is replaced by a C=O group to give a non-centrosymmetric motif. The number of hits obtained for IIIa suggest that this is also a potential building block for molecular recognition and most of the hits observed in this case correspond to esters of nitroaromatic compounds. It may be mentioned here that we have succesfully employed such C-H...O hydrogen bonds in the solid state supramolecular assembly of molecular complexes of 1,3,5-trinitrobenzene and dibenzylideneacetone (Scheme III).[5b]



Scheme III

There is a very close relationship between patterns IV and V as both motifs involve similar molecular fragments. Two O atoms of the NO_2 group interact with two H atoms in IV, while only one O atom of the NO_2 group interact with two H atoms in V (this may be termed an acceptor-bifurcated interaction according to the nomenclature of Saenger and Jeffrey).[8] The number of hits obtained for these motifs suggest that pattern V is preferred to IV. It should be recalled that pattern I which is geometrically similar to motif IV also prefers to form bifurcated interactions (Figures 2 and 5). It seems then that the disposition of H atoms in patterns I and IV or V is conducive to acceptor bifurcation and this is in contrast with the general observation that the H atom (either C-H or O-H) prefers to interact with two O atoms (proton bifurcation).[15] This possibility for bifurcation does not exist for dimer motifs II and III.

2.2.4 Nitro Group Crystal Engineering



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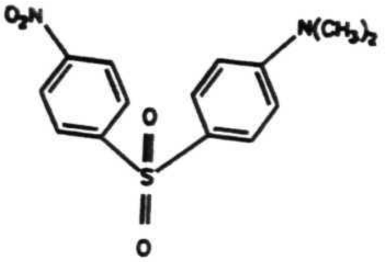

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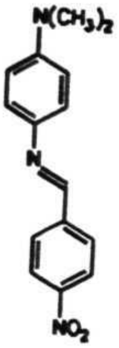

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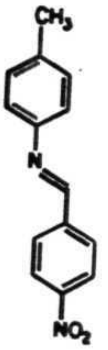


16

We now discuss a few occurrences of pattern I to highlight different aspects of this motif. The NO_2 and $N(CH_3)_2$ groups in **13** are sterically crowded, the molecular structure is non-planar and hence the I modules in the crystal are three dimensionally disposed (C...O, C-H...O; 3.73, 3.66Å, 123.9, 173.6° and 3.68, 3.81Å, 143.6, 142.3°). This is shown in Figure 8. The aromatic rings of **14** are mutually perpendicular and the molecule has a bent conformation. The crystal structure of **14** (Figure 9) has a sinusoidal chain with NO_2 and NC_2 planes being out of plane with an angle of 70.5° between them (C...O, C-H...O: 3.60Å, 3.72 Åand 147°, 141°). The planar molecule **15** forms an acentric linear chain with NO_2 and NC_2 groups being in-plane. Interestingly, when the $N(CH_3)_2$ group of **15** is replaced by a CH_3 group, (i.e, molecule **16**) motif V is adopted. These examples hint that pattern I can be used to steer the crystal packing reliably if the organic molecules bear only NO_2 and $N(CH_3)_2$ functional groups.

We will now try to address the role of C-H...O hydrogen bonding patterns in nitro group crystal engineering. For this purpose, the crystal structures of compounds **17-20** were chosen. These examples delineate various aspects of patterns II-V and are potential feedbacks in the deliberate design of nitro

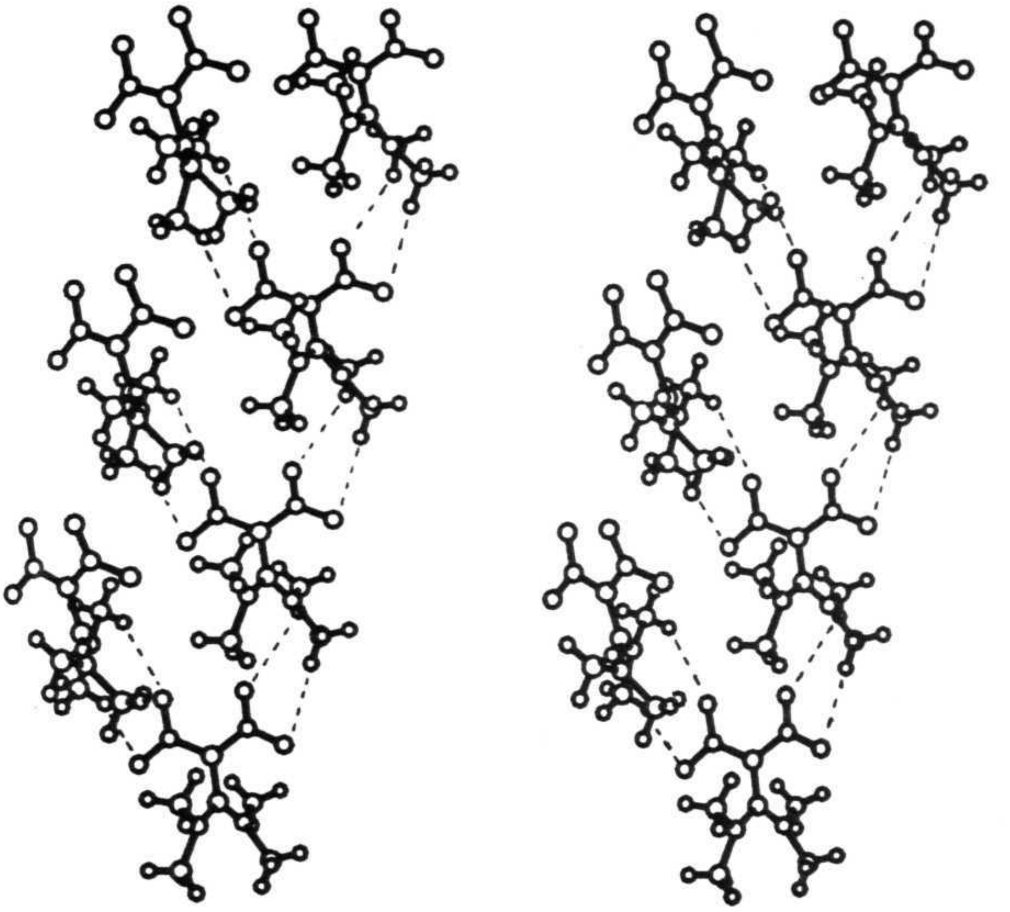


Figure 8. Stereoview of the crystal structure of alkene **13** to show pattern I. Notice the two dimensional molecular arrangement.

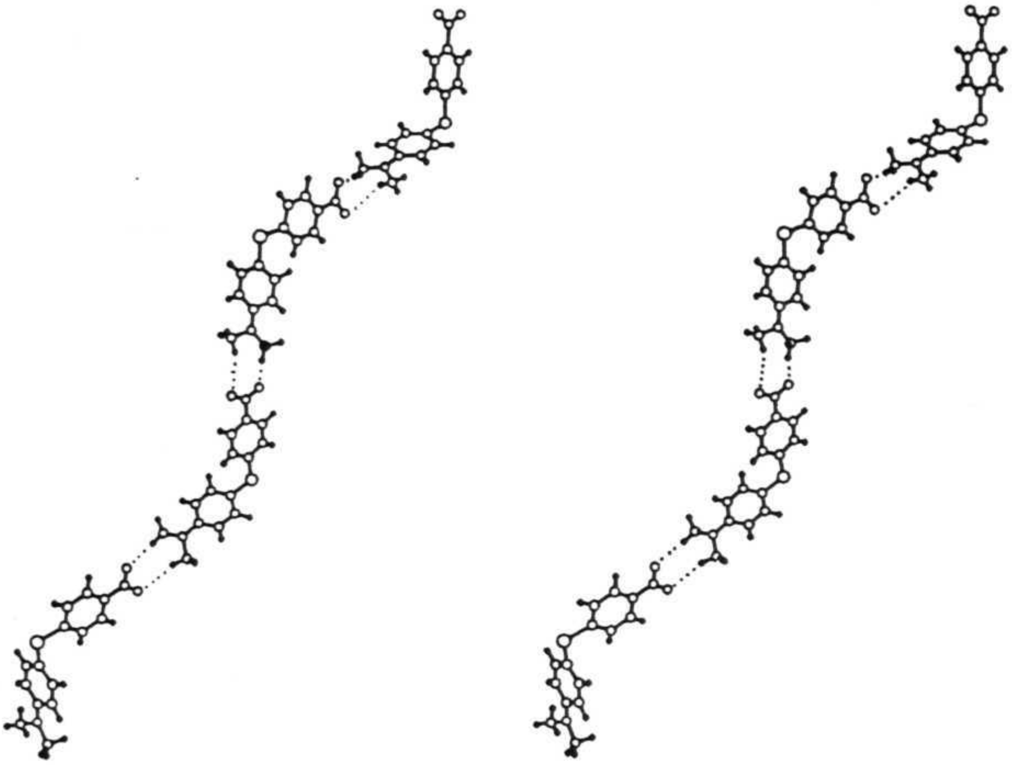
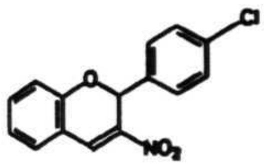


Figure 9. Stereoview of the crystal structure of thioether **14** to show the sinusoidal chain of molecules linked by pattern I. Note that the NO_2 and NC_2 planes are perpendicular to each other.



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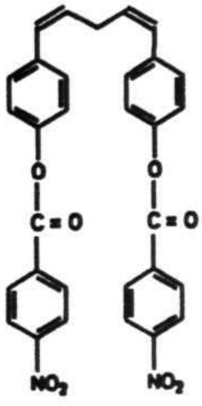

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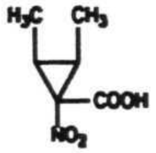

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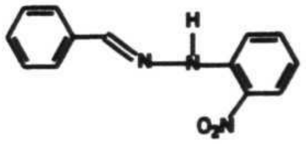


20

containing C-H...O mediated supermolecules. Molecule **17** manifests all three patterns IIa, IIb and Va in its crystal structure (Figure 10).[25] The molecular and supramolecular structures of **18** are very interesting in that two types of intramolecular phenyl-phenyl interactions are present.[26] The two unsubstituted phenyl rings are involved in herringbone interactions and the nitrophenyl rings are involved in stacking interactions. Curiously, these two stacked nitrophenyl moieties self assemble using motif IIIa as shown in Figure 11 (one of the O atoms is ethereal). Additionally, the crystal structure also displays pattern IIa (not shown in Figure 11 for the sake of clarity). The crystal structure of **19** shows a linear chain that has mutually perpendicular O-H...O and C-H...O dimers (IIb) in the chain (Figure 12).[27] The reason for this is that both the NO_2 and CO_2H groups are substituted on a single C atom of the cyclopropane ring and have a strong preference for linear and planar O-H...O and C-H...O dimer formation. The dimer of molecule **20** is shown in Figure 13 and exhibits patterns IV and/or V with good C-H...O interactions in addition to intramolecular N-H...O interactions.[28] This example indicates that if the strong proton donors are constrained by intramolecular factors, it is possible that C-H...O recognition patterns of the NO_2 group will determine the molecular assembly and in the present case

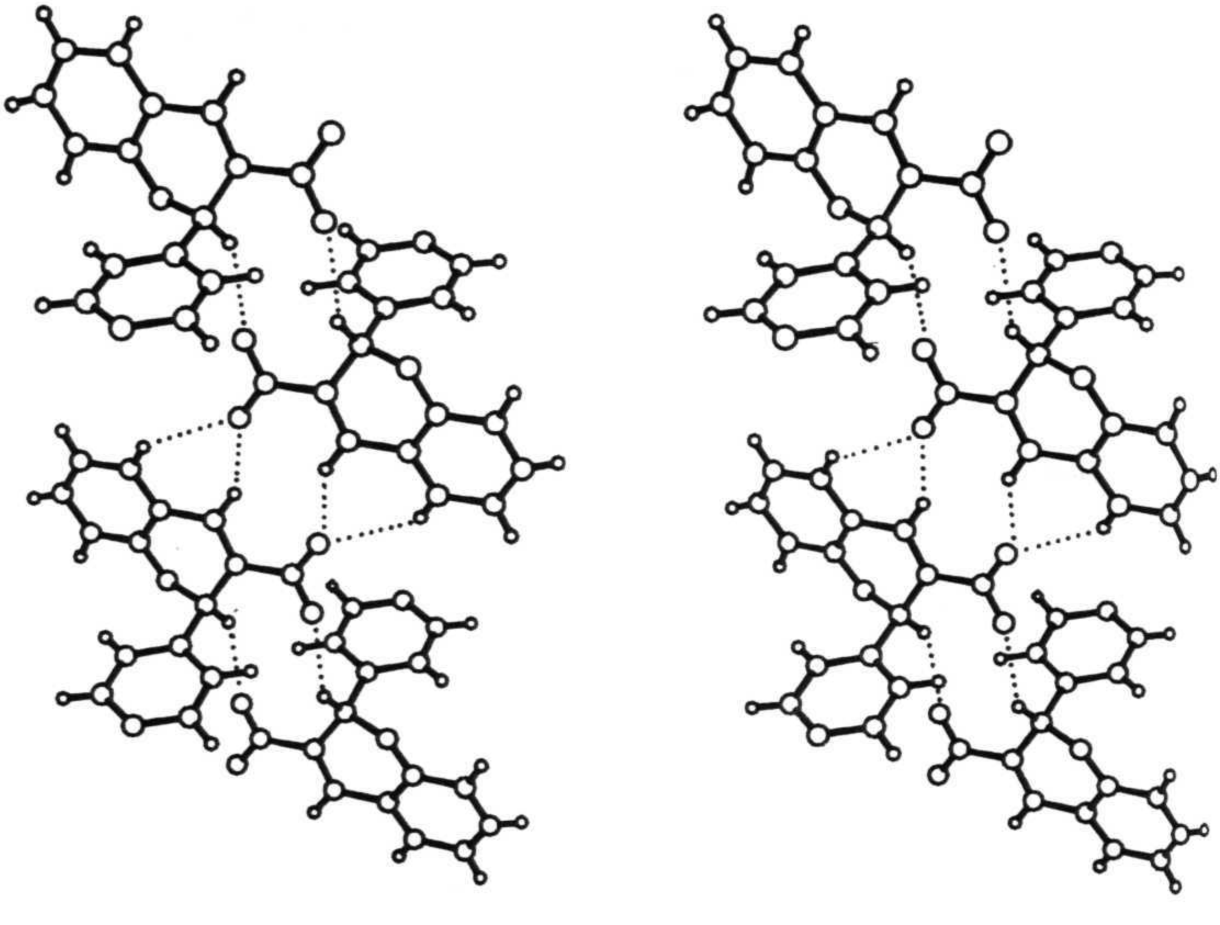


Figure 10. Stereoview of the crystal structures of **17**. Note that the molecules are stabilised by all three patterns IIa, IIb and V.

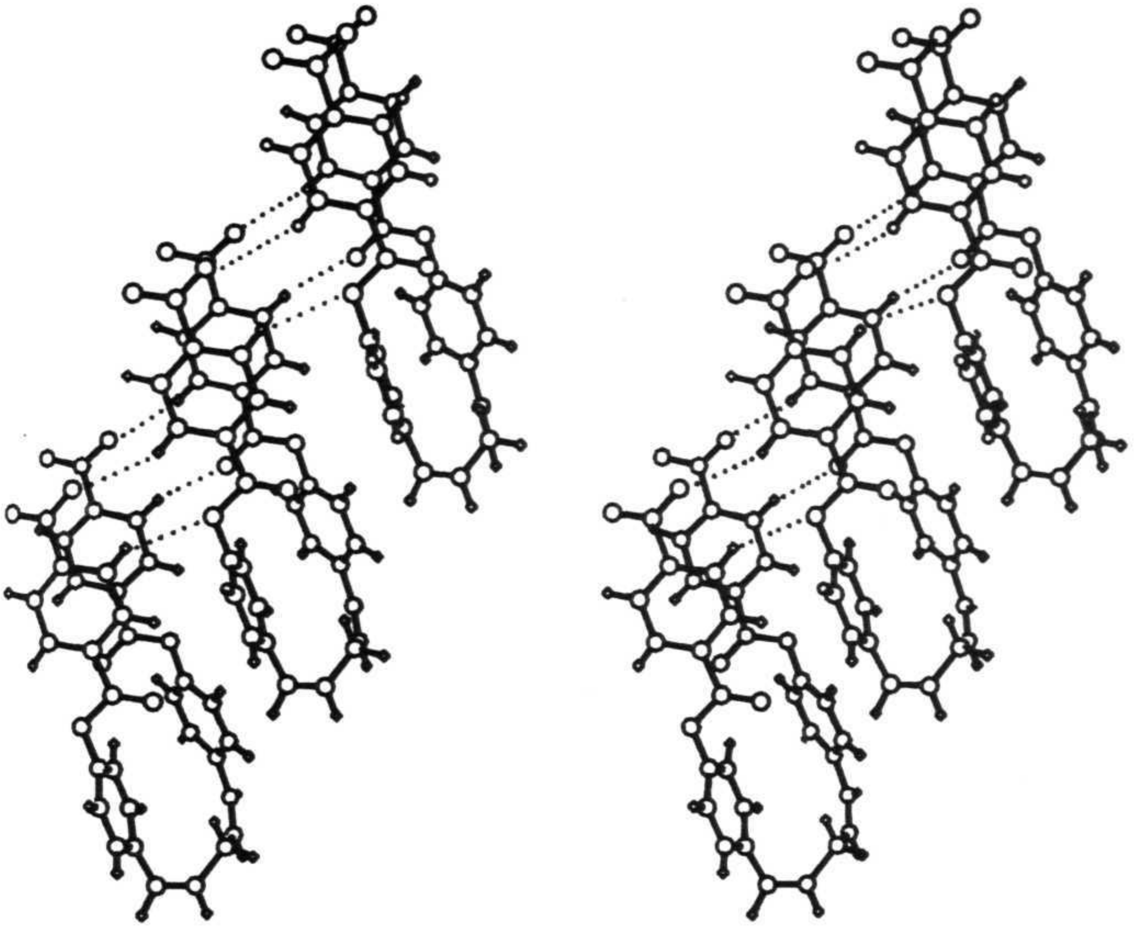


Figure 11. Stereoview of the crystal structure of diester **18**. Notice the appearance of pattern IIIa.

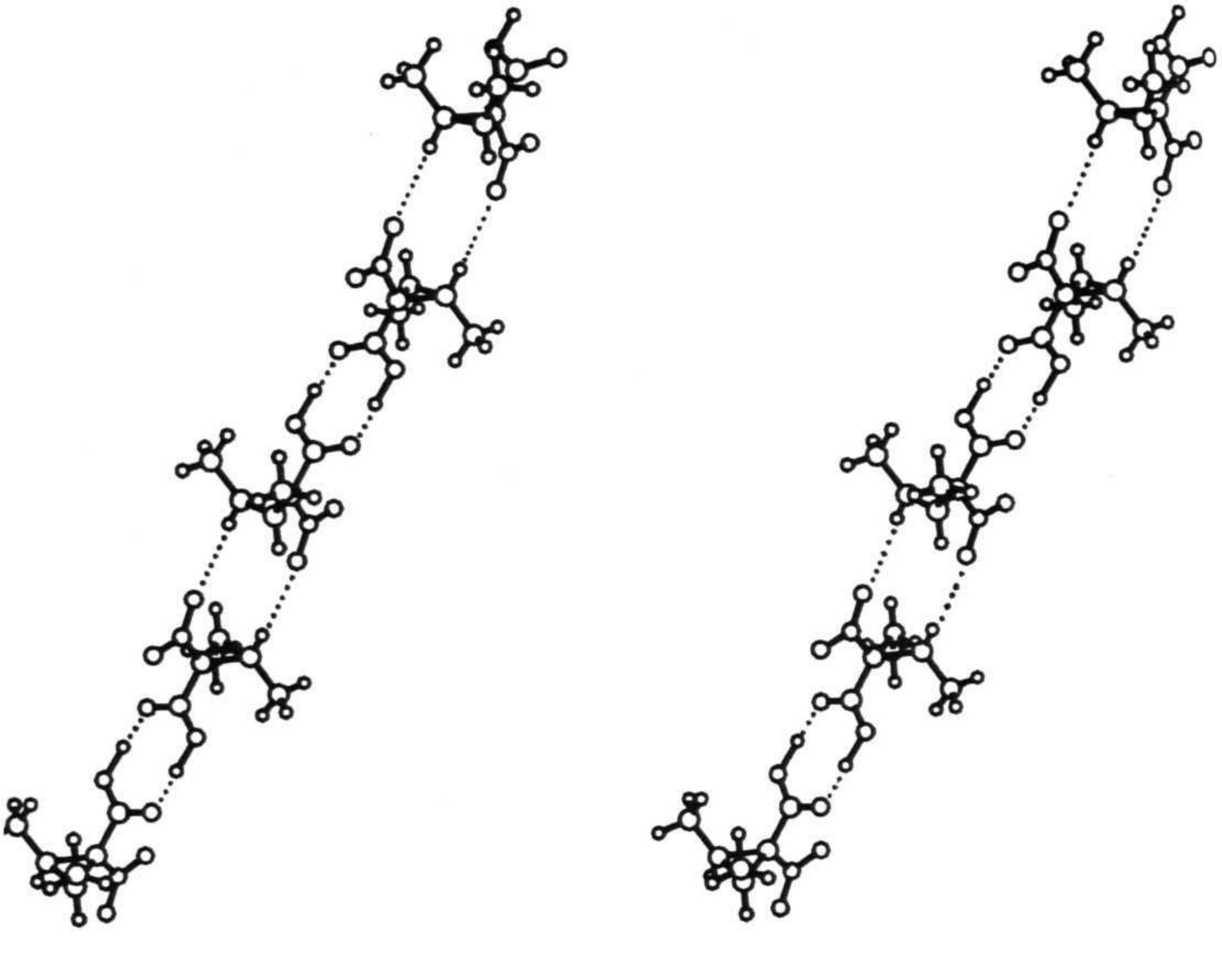


Figure 12. Stereoview in the crystal structure of cyclopropane **19** to show the linear chain arrangement. The chain is linked by carboxyl dimers and IIb dimers. These two dimers are mutually perpendicular.

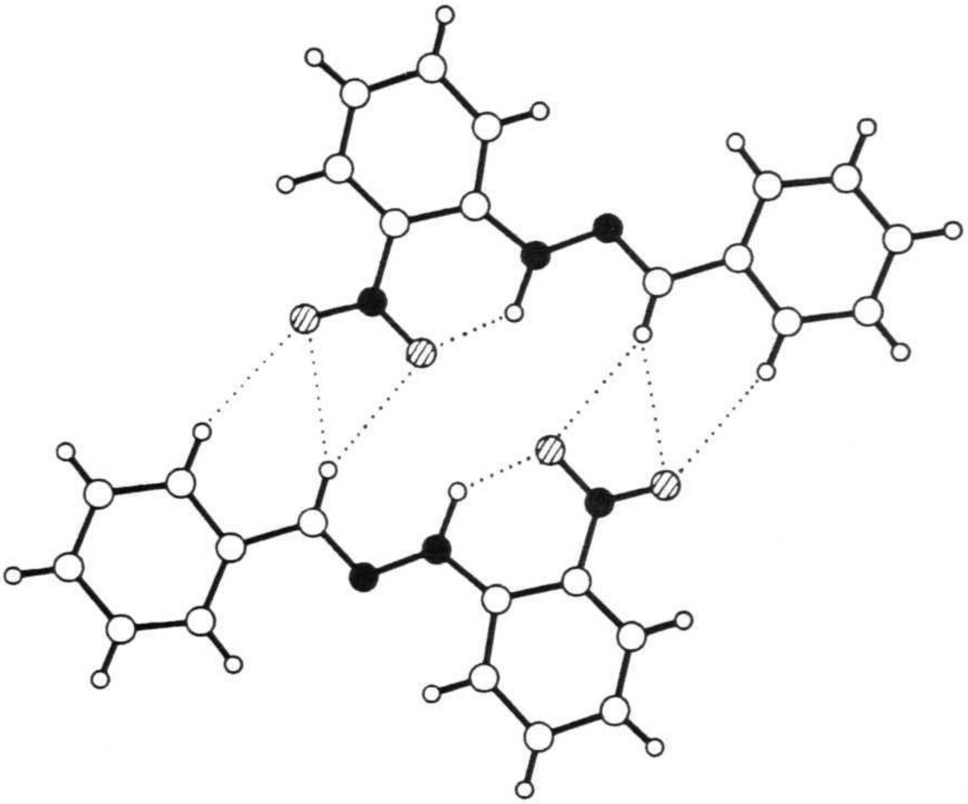


Figure 13. A dimer of **20** formed by C-H...O interactions in the crystal. This dimer reveals motifs IV and/or V which possibly stabilise the planar arrangement. The N-H...O bonds are intramolecular. N = ● O = ◍

it may be reasonable to assume that the planar dimer of **15** is a result of good lateral C-H...O interactions of the NO_2 group with intermolecular N-H...O interactions playing a passive role.

The statistical analysis given in Table 4 on the C-H...O hydrogen bonded motifs I-V clearly indicates that the H atom acidity and a rigid molecular geometry are crucial for the establishment of C-H...O recognition patterns. As Table 4 suggests, there are a small number of hits or no hits at all for fragments with sp^3 hybridised C-H groups. However, the electron-withdrawing nature of the NO_2 group enhances the H atom acidity and may promote the possibility of selective binding in this class of compounds. The larger number of hits obtained for I and IIb, despite their low acidity C-H groups indicates the importance of a rigid molecular framework. Many of the hits obtained in this study correspond to simple nitro-substituted compounds, with only sp^2 C atoms and it is suggested that such molecules which have the possiblity of forming only C-H...O interactions (and no other directional interaction) can be used to design supermolecules with high precision (Scheme III). However C-H...O recognition patterns can also be designed with success in the presence of strong interactions if these strong interactions do not interfere with either H or O atoms of patterns I-V. For example, complexes **1**, **2** and **19** (Figures 1, 2 and 12) form carboxyl dimers but the C-H..O recognition patterns are intact. Similarly in ester **18**, the major non-bonded interactions (van der Waals and $\pi ... \pi$) are optimised in the molecular conformation itself and their role in crystal packing is reduced with the result that the weakly directional C-H...O interactions can form pattern IIIa (Figure 11). While the crystal structure of **20** has intramolecular N-H...O hydrogen bonds, their role in crystal packing is undermined; consequently, C-H...O interactions play a key role in dimer formation (Figure 13). These examples suggest that one has to keep track of all the possible interactions of a molecule for efficient solid state supramolecular design. It is also to be mentioned here that if the recognition patterns I-V are assisted by additional C-H...O hydrogen bonds, that is by a matching of multiple C-H...O interactions in a single recognition pattern, supramolecular design would be very efficient as shown in scheme III.

2.3 Conclusions

The present study unequivocally demonstrates that weak C-H...O bonds are potential interactions for molecular recognition studies. C-H acidity is important in C-H...O recognition patterns which are additionally sensitive to the C:H:O stoicheometry and substitution pattern of functional groups in the molecular skeleton. These interactions can be efficiently used in the absence of strong intermolecular interactions or if strong interactions do not interfere with the C-H...O recognition patterns. Though the patterns suggested in this study involve only NO_2 O atoms, the idea can be extended to explore many new C-H...O building blocks with other types of O atoms. The general observations made on C-H...O recognition patterns in this analysis may facilitate the design of new materials based on these interactions and help in understanding and predicting secondary and tertiary structural features of many organic and bio-organic supermolecules with more reliability.

It is concluded then that weak C-H...O bonds too exhibit cooperativity and charge-transfer like strong hydrogen bonds and that better computational estimates of these interactions can be obtained only by considering multi-molecular aggregates.

2.4 Experimental Section

2.4.1 Synthesis of Acid Monomers

These were either purchased (**1a** - **1c**) or prepared (**2a** - **2f**) from the corresponding aldehydes by Knoevenagel condensation.[29]

Preparation of 3,5-dinitrobenzaldehyde :

A solution of 3,5-dinitrobenzoic acid (30 mmol, 6.36g) dissolved in dry THF (100 mL) was taken in a two-necked round-bottomed flask equipped with a condenser, diborane gas inlet and a side arm for passing N_2. Diborane gas was generated by dropwise addition of I_2 (30 mmol, 7.62g) in diglyme (100 mL) to $NaBH_4$ (60 mmol, 2.28g) in diglyme (30 mL). This diborane gas was bubbled into the acid solution for 3-5 h at 0°C. The reaction mixture was stirred for 5 h even after the bubbling of diborane gas ceased. The reaction mixture was carefully quenched with water (2 mL) and 3N HCl (5 mL) and the organic layer was extracted with ether. The combined organic extract was dried over anhydrous $MgSO_4$ and evaporation of ether solvent resulted in the pale-yellow coloured 3,5-dinitrobenzyl alcohol which was recrystalled from a 1:1 mixture of hexane-ether (m.p. 81°C). NMR ($CDCl_3$): δ 4.97 (s, 2H), 8.3 (m, 2H), 9.0 (m, 1H).

In a 100 mL round-bottomed flask fitted with a reflux condenser was suspended 6.46g (30 mmol) of PCC in 40 mL of anhydrous CH_2Cl_2. 3,5-dinitrobenzyl alcohol (20 mmol, 3.96g) was added in one portion to the stirred solution. After one hour, 40 mL of dry ether were added and the supernatant liquid decanted from the residual blackgum. The insoluble residue was washed thoroughly three times with 10 mL portions of anhydrous ether. The combined organic solution was passed through fluorosil and the solvent removed by distillation. The 3,5-dinitrobenzaldehyde obtained was recrystallised from 1:2 toluene-hexane (m.p. 81°C). NMR ($CDCl_3$): δ 9.05 (m, 1H), 9.29 (m, 2H), 10.21 (s, 1H).

Pyridinium Chlorochromate (PCC): To 184 mL of 6N HCl (1.1 mol) was added 100 g (1 mol) of CrO_3 rapidly with stirring. After 5 minutes the homogeneous solution was cooled to 0^oC and 79.1 g (1 mol) of pyridine was carefully added over 10 minutes. Re-cooling to 0°C gave a yellow-orange solid which was collected on a sintered glass funnel and dried for one hour in vacuum.

2.4.2 Preparation of 1:1 Acid Complexes

Complex **1**: Orange-yellow crystals of complex **1** (m.p. 235°C) were obtained readily from an equimolar solution of acids **1a** and **1c** in MeOH.

Complex **2**: Violet crystals of complex **2** (m.p. 181-183°C) were obtained from an equimolar solution of acids **1a**, and **2d** in toluene-MeOH.

Complex **3**: Violet crystals of complex **3** (m.p. 245°C) were obtained from an equimolar solution of acids **2a**, and **2d** in MeOH, but these were too thin for X-Ray work.

Complex **4**: Violet crystals of complex **4** (m.p. 200-202°C) were obtained from an equimolar solution of acids **2b** and **1c** in MeOH.

Complex **5**: Violet crystals of complex **5** (m.p. 175-177°C) were obtained from an equimolar solution of acids **2b** and **2d** in EtOH.

Complex **6**: Deep-yellow crystals of complex **6** (m.p. 159°C) were obtained from an equimolar solution of acids **2b** and **2e** in 2:3 toluene-benzene.

Complex **8**: Deep-yellow mixed crystals of complex **8** (m.p. 143°C) were obtained from an equimolar solution of acids **2c** and **2e** in EtOH.

Complex **9**: Violet mixed crystals of complex **9** (m.p. 201-202°C) were obtained from an equimolar solution of **1b** and **1c** in MeOH.

Complex **10**: Violet mixed crystals of complex **10** (m.p. 145°C) were obtained from an equimolar solution of acids **1b** and **2d** in toluene. These crystals were found to be twinned.

Complex **11**: Black-violet crystals of complex **11**(m.p. 148°C) were obtained from an equimolar solution of 1,4-dinitrobenzene and N,N,N',N'-tetramethyl-*p*- phenylenediamine in CCl_4-hexane. These crystals were found to be twinned.

All the above complexes can also be prepared by thorough grinding of their respective components.[30] The X-Ray powder spectra of both the single crystalline and ground materials are identical. The complexation is very vigorous in the case of complex **11** where even mild rubbing of the starting materials leads to a quantitative solid state reaction.

2.4.3 X-Ray Crystallographic Studies on Acid Complexes

The data for the complexes, **1**, **2**, **4**, **8** and **9** were collected by Dr. T. Pilati, University of Milano, Italy while the data for complexes **5** and **6** were collected by, Dr. D.E. Zacharias, Fox Chase Cancer Centre, Philadelphia, U.S.A. and Dr.W.T. Robinson, University of Canterbury, Christchurch, New Zealand respectively. Complex **7** has already been reported from this laboratory.[31] The structure solution of all the complexes was carried out in this study with SHELXS86[32] and the refinements were carried out with SHELX76.[33] All non-hydrogen atoms were refined anisotropically and the final R-factors and other crystallographic information is presented in Appendix A-1. Tables of coordinates and thermal vibrational parameters are given Appendix A-2.

2.4.4 Semi-empirical Calculations

The AM1 approximation to molecular orbital theory was used in this study to evaluate the energies of the O-H...O and C-H...O hydrogen bonds in complex **1**.[19] All the calculations were carried out using the MOPAC program. The geometry of the O-H...O and C-H...O dimers in the crystal structure of complex **1** was the starting point in the optimisation. The C-H...O bond energy of the dimer was evaluated by subtracting the energies of the individual monomers. Cooperative effects in C-H...O bonds were evaluated by considering linear aggregates of **12**. Such aggregates are segments of the actual crystal structure which consists of a linear array of molecules (Figure 3). The neutron structural data of **12** were taken as input for the optimisation of linear C-H...O bonded molecular aggregates and upto five monomer units were considered to determine the magnitude of the cooperative effects.

2.4.5 CSD Studies

Screens -28, 153, 85 and 88 were set to eliminate organometallic entries and structures without coordinates or unmatched chemical and crystallographic connectivities. Entries with R-factors greater than 0.10 were also excluded to create a subsidiary IDX file of 2306 nitro compounds. All further 3D graphical searches for NO_2 recognition patterns I-V were made from this subsidiary file. For determining *bona fide* C-H...O interactions, C...O distances $3.0 \leq 4.0$Åand C-H...O angles of $100 \leq 180^o$ were considered. The motifs I-V are characterised by two C...O distances d_1 and d_2 and two C-H...O angles θ_1 and θ_2. For example, motif II can be defined by d_1 = C6...O2, d_2= C5...O9 and θ_1 = C6-H12-O2 and θ_2 = C5-H11-O9. Using such criteria, patterns such as IV and V may be distinguished.

There are 84 entries that contain both NO_2 and $N(CH_3)_2$ functional groups and of these, fifteen are duplicates and were not considered any further. For example, the structure of **12** has been determined as many as eight times by neutron and X-Ray methods but we have considered only the best structure here. The coordination of H atoms was specified to be either T3 or T4 to get sp^2 or sp^3 hybridised C atoms for these four patterns. Suffixes **a** and **b** are used in motifs II-V to distinguish sp^2 and sp^3 C-H groups.

References

1. (a) J.-M. Lehn, *Angew.Chem.Int.Ed.Engl.*, 1990, **29**, 1304.
   (b) D.J. Cram, *Angew.Chem.Int.Ed.Engl.*, 1986, **25**, 1039.
   (c) P.L. Anelli, P.R. Ashton, R. Ballardini, V. Balzani, M. Delgado, M.T. Gandolfi, T.T. Goodnow, A.E. Kaifer, D. Philp, M. Pietraszkiewicz, L. Prodi, M.V. Reddington, A.M.Z. Slawin, N. Spencer, J.F. Stoddart, C. Vicent and D.J. Williams, *J.Am.Chem.Soc.*, 1992, **114**, 193.
2. (a) G.M. Whitesides, *Angew.Chem.Int.Ed.Engl.*, 1990, **29**, 1209.
   (b) F.G. Tellado, S.J. Geib, S. Goswami and A.D. Hamilton, *J.Am.Chem. Soc.*, 1991, **113**, 9265.
3. G.R. Desiraju, *Crystal Engineering: The Design of Organic Solids*, Elsevier, Amsterdam, 1989.
4. (a) R. Taylor and O. Kennard, *Acc.Chem.Res.*, 1984, **17**, 320.
   (b) G.R. Desiraju, *Acc.Chem.Res.*, 1991, **24**, 290.
5. (a) C.V.K. Sharma, K. Panneerselvam, T. Pilati and G.R. Desiraju, *J.Chem.Soc.*, *Chem.Commun.*, 1992, 832.
   (b) K. Biradha, C.V.K. Sharma, K. Pannerselvam, L. Shimoni, H.L. Carrel, D.E. Zacharias and G.R. Desiraju, *J.Chem.Soc.*, *Chem.Commun.*, 1993, 1473.
   (c) T. Suzuki, H. Fujii and T. Miyashi, *J.Org.Chem.*, 1992, **57**, 6744.
6. C.V.K. Sharma, K. Panneerselvam, T. Pilati, and G.R. Desiraju, *J. Chem.Soc.*, *Perkin Trans.* 2, 1993, 2309.
7. G.R. Desiraju and C.V.K. Sharma, *J.Chem.Soc.*, *Chem.Commun.*, 1991, 1239.
8. G.A. Jeffrey and W. Saenger, *'Hydrogen Bonding in Biological Structures'*, Springer-Verlag, Berlin, 1991.
9. M.C. Etter and G.M. Frankenbach, *Chem. Mater.*, 1989, **1**, 10.
10. J.J. Dannenberg, *Chem.Mater.*, 1990, **2**, 635.
11. P. Seiler and J.D. Dunitz, *Helv. Chim. Acta*, 1989, **72**, 1125.

12. F.H. Allen, J.E. Davies, J.J. Galloy, O. Johnson, O. Kennard, C.F. Macrae and D.G. Watson, *J. Chem.Inf.Comp.Sci.*, 1991, **31**, 204.

13 (a) T. Steiner, S.A. Mason and W. Saenger, *J.Am.Chem.Soc.*, 1990, **112**, 6184.

(b) G. Gilli, F. Bellucci, V. Feretti and V. Bertolasi., *J.Am.Chem. Soc.*, 1989, **111**, 1023.

14. L. Turi and J.J. Dannenberg, *J.Phys.Chem.*, 1992, **96**, 5819.

15 T. Steiner and W. Saenger, *J.Am.Chem.Soc.*, 1992, **114**, 10146.

16. D.J. Williams, *Angew.Chem.Int.Ed.Engl.,* 1984, **23**, 690.

17. A. Filhol, G. Bravic, M. Rey-Lafon, M. Thomas, *Acta Crystallogr., Sect.* 1980, **B36**, 575.

18. B. Stolevik and P. Rademacher, *Acta Chem.Scand.,* 1969, **23**, 672.

19. M.J.S. Dewar, E.G. Zoebisch, E.F. Healy and J.J.P. Stewart, *J.Am.Chem. Soc.*, 1985, **107**, 3902.

20. L. Turi and J.J. Dannenberg, *J.Phy.Chem.*, 1993, **97**, 7899.

21. F.A. Cotton and R.L. Luck, *Inorg.Chem.,* 1989, **28**, 3210. For a recent discussion on hydrogen bonding see C.B. Aakeroy and K.R. Seddon, *Chem.Soc.Rev.,* 1993, 397.

22. M.J. Frisch, A.C. Scheiner, H.F. Schaefer and J.S. Brinkley, *J.Chem.Phys.*, 1985, **82**, 4194.

23. V.R. Pedireddi and G.R. Desiraju, *J.Chem.Soc.*, *Chem.Commun.*, 1992, 988.

24. V.R. Pedireddi, J.A.R.P Sarma and G.R. Desiraju, *J.Chem.Soc.*, *Perkin Trans.* 2, 1992, 311.

25. P.E. Eaton, R.G. Daniels, D. Casucci, G.T. Cunkle and P. Engel, *J.Org.Chem.*, 1987, **52**, 2100.

26. H. Plieninger, B. Schwarz, H. Jaggy, U. Huber-Patz, H. Rodewald, H. Irngartinger and K. Weinges, *Liebigs Ann.Chem.*, 1986, 1772.

27. P.E. O'Bannon, P.J. Carroll and W.P. Dailey, *Struct.Chem.*,

1990, **1**, 491.

28. M.G.B. Drew, B. Vickery and G.R. Willey, *Acta Crystallogr.*, 1984, **C40**, 304.
29. J.R. Johnson, *Org. Reactions,* Vol. I, 1978, pg. 210.
30. It has been shown that mechanical grinding is a superior method of obtaining quantitative yields of many organic donor-acceptor complexes. Naturally only polycrystalline material is obtained.

    (a) R.P. Rastogi, N.B. Singh, *J.Phys.Chem.,* 1966, **70**, 3315.

    (b) J.R. Scheffer, Y.F. Wong, A.O. Patil, D.Y. Curtin, I.C. Paul, *J.Am. Chem.Soc.,* 1985, **107**, 4898.

    (c). A.O. Patil, W.T. Pennington, G.R. Desiraju, D.Y. Curtin, and I.C. Paul, *Mol.Cryst.Liq.Cryst.,* 1986, **134**, 279.

    (d) M.C. Etter, G.M. Frankenbach, and J. Bernstein, *Tetrahedron Lett.,* 1989, **30**, 3617.
31. J.A.R.P. Sarma and G.R. Desiraju, *J. Chem. Soc., Perkin Trans.* 2, 1985, 1905.
32. G.M. Sheldrick, SHELXS86. in *Crystallographic Computing* 3; G.M. Sheldrick, C. Kruger and R. Goddard, Eds; Oxford University Press: Oxford, U.K., 1985, pp 175-189.
33. G.M. Sheldrick, SHELX76. *Program for Crystal Structure Determination*, University of Cambridge, England, 1976.

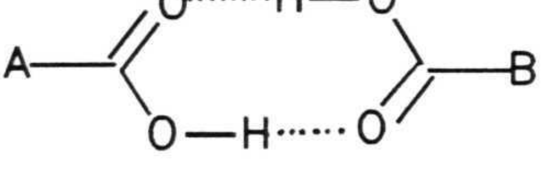
Chapter Three

Effects of C-H...O Hydrogen Bonding on O-H...O Hydrogen Bonded Networks: Some Anomalous Crystal Structures

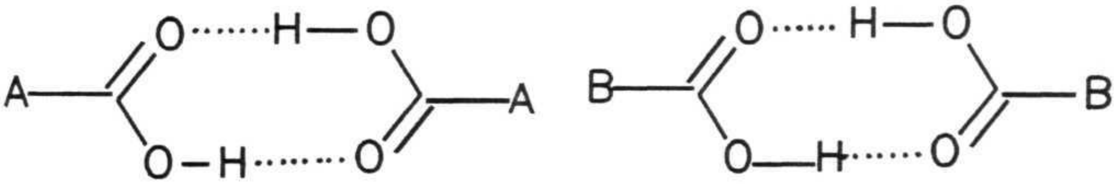
3.1 Introduction

The ever-growing demand for the construction of supermolecules[1] with high precision, that is with a control of secondary and tertiary structural features, has been largely unfulfilled, because such construction requires a subtle and simultaneous manipulation of strong and weak intermolecular interactions.[2] This is quite a difficult task, at least at present, as our knowledge of weak intermolecular interactions has not yet reached a stage where they may be used reliably for molecular recognition.[3]

In the preceding chapter we have seen how molecules organise themelves selectively using weak C-H...O hydrogen bonds. It is apparent from the earlier discussion that these weak interactions operate within the framework of strong hydrogen bonds.[3f] In other words, these interactions are formed in consonance with strong interactions and cannot compete with stronger hydrogen bonds in establishing stable crystal packings. But such an assumption need not always be valid. Sometimes, weak interactions can collectively dictate the details of supramolecular geometry and they may even determine the directional preferences of strong hydrogen bonds.



Extensive studies on conventional or strong O-H...O and N-H...O hydrogen bonds have led to the formulation of empirical rules concerning their preferential binding patterns for various functional groups.[2,4] For example, aromatic carboxylic acids (e.g., benzoic or cinnamic acids) crystallise as centrosymmetric O-H...O mediated dimers, but a 1:1 mixed crystal if obtained from a pair of acids, say A and B, with substituents of different electronegativities, contains only carboxy heterodimers AB.[4a,5] Such heterodimers are stable because of the variation in the proton donating and accepting capabilities of the two acids, which leads to the two hydrogen bonds in the ring being of unequal strengths. Such a structural motif is supposed to be robust and not perturbed by other interactions since it is formed in accordance with the principle that the strongest proton donor hydrogen bonds with the strongest proton acceptor followed by a matching of the next strongest proton donor and acceptor.[4–6]



Do all aromatic carboxylic acids form centrosymmetric dimers and do all such donor-acceptor acid complexes form heterodimers? In a study of several nitro and amino-substituted benzoic acids, **1a**-**1d**, and cinnamic acids, **2a**-**2f**, and their corresponding 1:1 complexes, **1**-**10**, it was noted that two anomalous structures were formed. These are respectively 3,5-dinitrocinnamic acid, **2b**, which forms a twofold axis related carboxyl dimer instead of the usual centrosymmetric dimer and the 1:1 complex, **9** (3,5-dinitrobenzoic acid, **1b** : 4-N,N-dimethylaminobenzoic acid, **1c**), where the structure is made up exclusively of homodimers AA and BB instead of AB heterodimers. Interestingly, a closely related complex of **9**, that is complex **21**, of 3,5-dinitrobenzoic acid, **1b** and 4-aminobenzoic acid, **1d,** forms a heterodimer and crystallises in a non-centrosymmetric space group.[5] These observations suggest that a consummate understanding of all crystal packing forces is required in the prediction of even strongly hydrogen bonded structures. In fact it was found that weak intermolecular interactions have to be considered in order to rationalise these unusual occurences. The $\pi...\pi$[7] and C-H...O[8] interactions are the possible weak interactions that can perturb the strong hydrogen bonds in these two instances. Indeed, the three types of interactions, O-H...O, C-H...O and $\pi...\pi$ require special attention in the area of molecular recognition because of their omnipresence in most organic and biological structures. Traditionally, these interactions have been studied independently and there are no collective studies of these interactions, in other words on how these three type of interactions co-adjust or coexist.[9] The main objective in this chapter is to study the interplay between O-H...O, C-H...O and $\pi...\pi$ interactions.

3.2 Results and Discussion

3.2.1 Crystal Structure of Acid 2b: A Carboxyl Dimer with a Twofold Axis

Acid **2b** crystallises as an O-H...O dimer wherein the hydrogen-bonded molecules are related not by the more common inversion center but by a twofold axis.[2] A close look at the crystal structure of acid **2b** reveals that this curious phenomenon occurs because of abundant C-H...O interactions which discriminate between energetically similar yet geometrically dissimilar O-H...O hydrogen bond patterns. The energy of the C-H...O interaction is just in the range where it can compete with conformational process in small molecules and with forces responsible for the tertiary structure in macromolecules.[10]

The eight membered carboxyl dimer ring of **2b** is reasonably planar, but because of the twofold symmetry, the 28° intramolecular twist between carboxy and aromatic groups leads to an inclination of 56° between the two aromatic rings in the dimer. Figure 1 provides a rationale for this observation. There is an extensive C-H...O bond network, (C...O, C-H...O, 3.19Å, 123°; 3.45Å, 152°; 3.40Å, 143°; 3.58Å, 151°; 3.64Å, 126°; 3.69Å, 160°) confirmed by the ordered carboxy group (C-O, 1.308(6), 1.226(6)). Acid **2b** is particularly well suited for the formation of these C-H...O bonds, because the alkenic H atoms of **2b** are acidic when compared to aliphatic H atoms.[11] Further the electron-withdrawing nature of the NO_2 group and cooperative effects[3f,12] may respectively enhance the acidity of the C-H group and basicity of the NO_2 group. So, C-H...O bonds dominate the structure and their directional requirements appear to be incompatible with an O-H...O inversion dimer. Simple calculations (MOPAC)[13] show that there is an energy difference of *ca.* 0.55 Kcal/mol between the all-planar conformation (which might have led to an inversion dimer) and a more energetic twisted conformation observed here. The total energy of the C-H...O bonds should be at least equal to this difference. The planarity and conformational flexibility of **2b** increases its C-H...O bond-forming ability in the crystal since rotations of the substituent groups to optimise C-H...O hydrogen bonds are facile.

In contrast to acid **2b**, 2,4-dinitrocinnamic acid, **2c**, crystallises as a normal inversion-symmetry O-H...O dimer. The 2-NO_2 group and the styryl moiety make an angle of 25° and 40° with the aromatic ring respectively. Here, the 2-NO_2 group does not participate effectively in C-H...O hydrogen bonding. Perhaps the conformational inflexibility caused by steric hindrance of the -$CH{=}CHCO_2H$ group results in such an inability to form C-H...O hydrogen bonds. However, the overall C-H...O interactions in this acid are equally good as in acid **2b** (3.26Å, 121°; 3.32Å, 129°; 3.43Å, 148°; 3.47Å, 136°; 3.47Å, 120°; 3.62Å, 158°; 3.62Å, 142°). These interactions suggest that the inherent intramolecular twist in acid **2c** may be conducive to making good C-H...O interactions leading to centrosymmetric carboxy dimers in

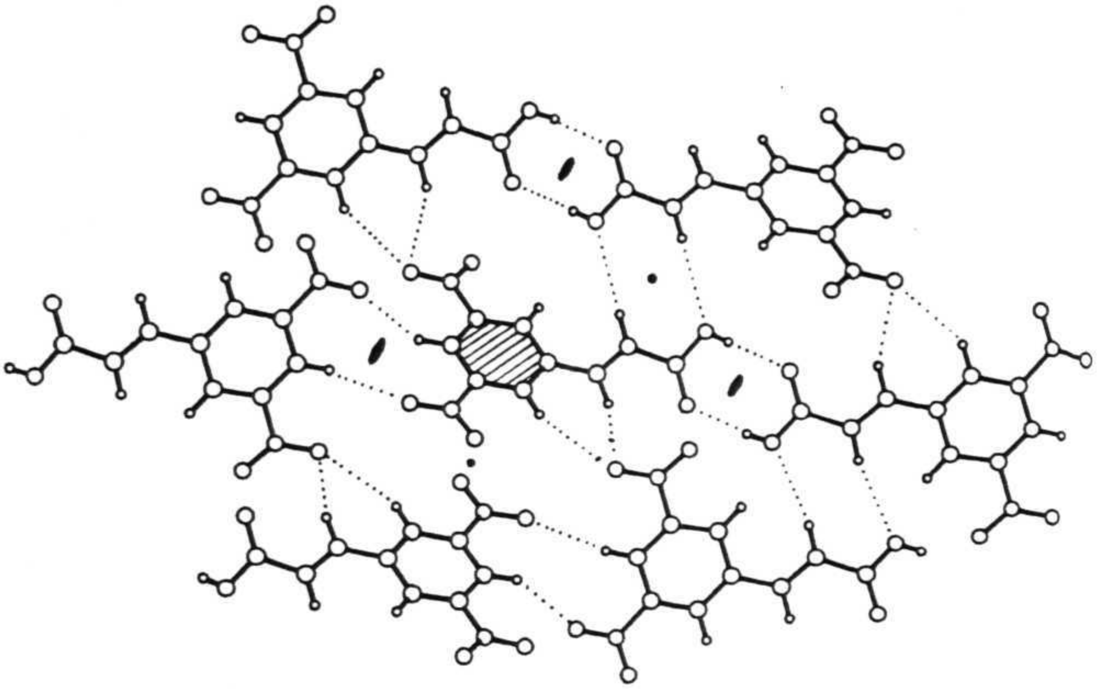
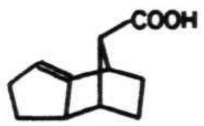


Figure 1. Crystal Structure of acid **2b** showing O-H...O and C-H...O hydrogen bonds. The reference molecule is shaded and is linked to its twofold axis related neighbours by O-H...O bonds and to its c-glide, inversion and other twofold related neighbours by C-H...O bonds.

its crystal structure (Figure 2). The molecular skeleton of acid **2c** is rigid and any intramolecular rotation requires high energy. So it is beyond the scope of C-H...O hydrogen bonds to cause any further twist in the intramolecular geometry of acid **2c**.



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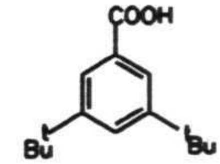
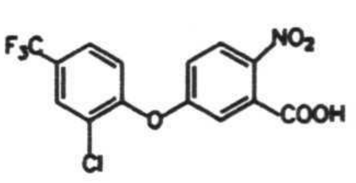
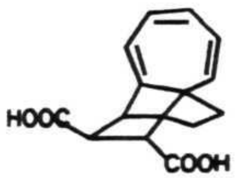


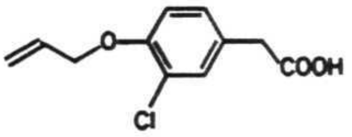
DTBUBZ



FIPXIL



DUGKEV



FICJAC

A more general CSD[14] search has also been carried out to examine the frequency of occurrence of a twofold axis in neutral carboxylic acid crystal structures. It was found that of a total of 2057 carboxylic acids in the CSD, 54 acids crystallise as carboxyl dimers in the space group C2/c. The majority of these acids contain a molecular twofold axis and/or dicarboxylic functionality. Acid dimers are usually related either by inversion centres or by psuedo-inversion centres. Five acids (DASDIK, DTBUBZ, DUGKEV, FICJAC and FIPXIL) which crystallise in C2/c were identified as having a twofold axis bisecting the carboxylic dimer ring with a significant twist between carboxyl dimer and the molecular skeleton (as in the compound under study in this work). Interestingly, all these acids have either no possibility or little possibility of having C-H...O hydrogen bonds in their crystal structures. It appears that steric reasons are associated with these geom-

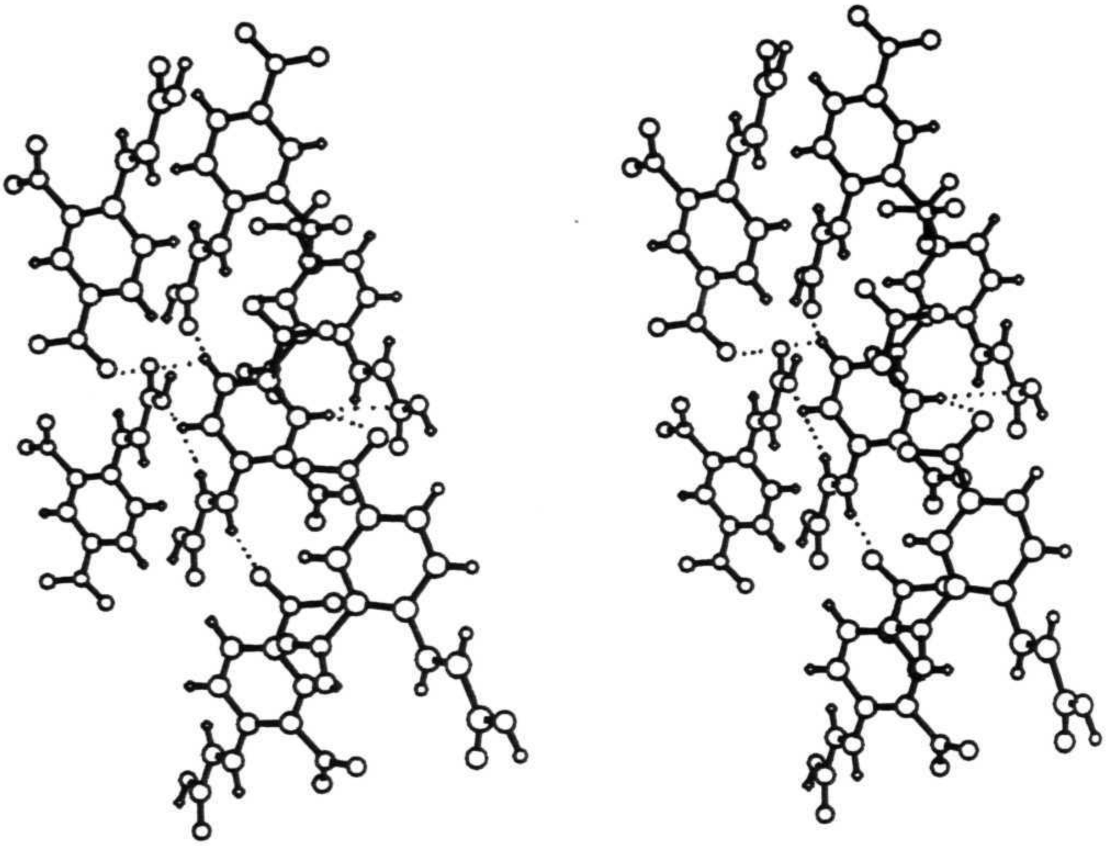


Figure 2. Stereoview of the crystal structure of acid **2c** showing C-H...O bonds.

etries. All these results indicate that C-H...O hydrogen bonds may be the main cause for a twofold axis observed in the crystal structure of acid **2b**.

As mentioned earlier, one of the NO_2 groups of the acid **2b** is also involved in a C-H...O self-recognition motif in its acid complexes (see Chapter 2, Figure 4b).[3f] To further investigate the C-H...O bond forming ability of the 3,5-dinitrocinnamoyl skeleton, the crystal structure of the corresponding methyl ester, **22** has been determined. The crystal structure of **22** contains an inversion dimer that is stablised by two types of bifurcated-acceptor C-H...O bonds, Figure 3;[15] the carbonyl O atom interacts with two alkene H atoms (C...O, 3.28Å, 3.70Å, C-H...O 168°, 148°) while the NO_2 O atom, interacts with two CH_3 H atoms albeit weakly (C...O 3.25Å, C-H...O 117°, 96°). These dimer units in turn form C-H...O bonds with surrounding dimers through other lateral C-H...O interactions leading to a planar structure along [100]. The crystal structure of **22** is, in effect, two-dimensional compared to that of the parent acid **2b** which is three-dimensional. The strength of the C-H...O bonded inversion dimer was approximated using AM1 molecular orbital calculations and found to be -8.20 Kcal/mole.[3a,16]

3.2.2 Crystal Structure of Complex 9 : A Homodimer

The crystal structures of acid complexes **1**-**10**, and **21**, consist of acid dimers which are themselves stacked so as to optimise $\pi...\pi$ donor-acceptor interactions (Figure 4). Therefore, two stacked heterodimers are related by an inversion centre (except in complex **21** which is non-centrosymmetric) while two stacked homodimers (complex **9**) are not crystallographically related, the inversion centres being located at the middle of each homodimer. It is to be mentioned here that the crystal structure of complex **3** has not been solved and that complex **10** (a heterodimer) forms twinned crystals for

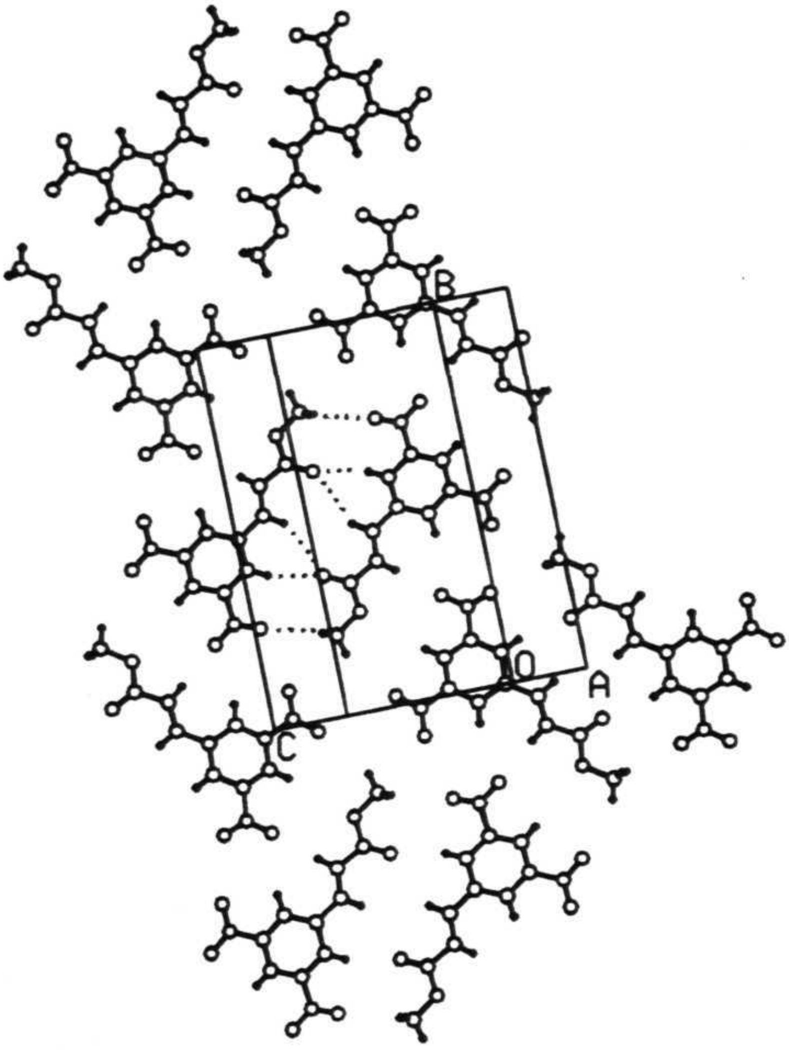


Figure 3. Crystal structure of ester **22** along [100] to show the planar structure.

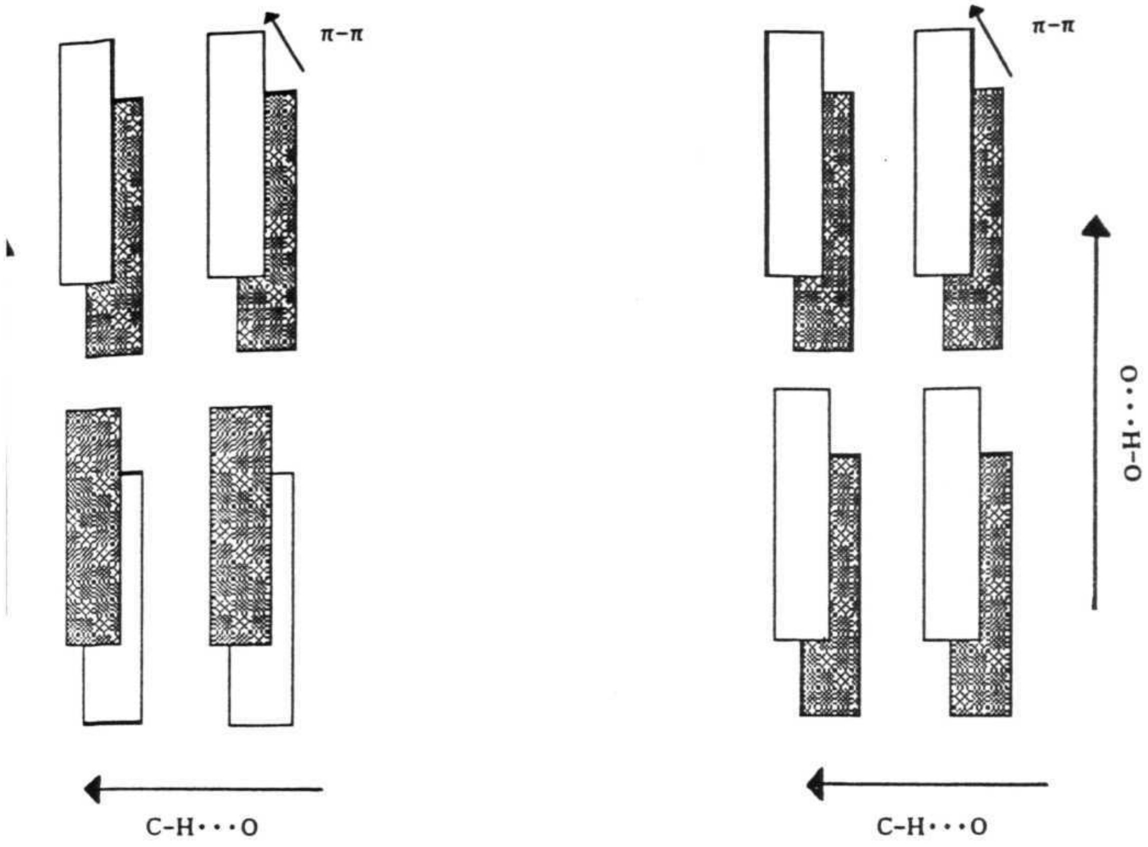


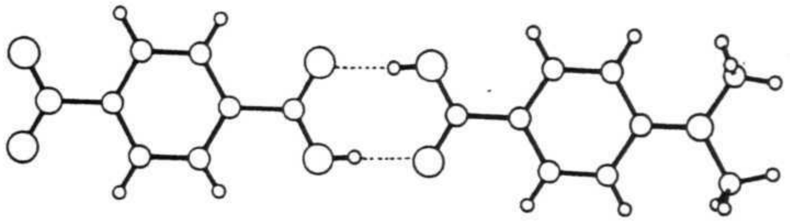
Figure 4. Schematic diagaram of carboxy hetero (left) and homo (right) dimers in the donor-acceptor complexes **1-8**, **21** and **9** showing the directional nature of the three interactions types (O-H...O, C-H...O and $\pi...\pi$) which are important in these complexes. Each donor monomer is represented by a blank rectangle while each acceptor monomer is represented by a shaded rectangle.

which only an approximate structure is available.

Inspection of the carboxy dimer motif in these ten structures (**1-10** and **21**) shows that except complex **9**, all the others contain the 'expected' heterodimer. The crystal stucture of **9**, however, contains dinitrobenzoic and dimethylaminobenzoic *homodimers* (Figure 5). This is an unusual hydrogen bond pattern and the absence of such homodimers in other systems was verified with the CSD. A total of 32 acid mixed crystals was obtained from the CSD, but none contain homodimers. AM1 calculations performed by Dannenberg show that the heterodimers AB for any given (aromatic) acid pair A and B are stabler than the either of the homodimers AA or BB by around 1.0 Kcal/mol.[17] These calculations were repeated on the acid pairs found in complexes **1-10** and very similar results were obtained. Even in complex **9**, the AM1 heterodimer energy obtained was -7.02 Kcal/mol while the two homodimer energies were -6.27 Kcal/mol (dinitro) and -6.15 Kcal/mol (dimethylamino). Though AM1 methods do not consider electronic correlation effects[18] and underestimate the hydrogen bond energy, their use in hydrogen bonded systems is well-documented and it is believed that the calculations permit a *relative* comparison of hydrogen bond energies. Therefore it may be concluded that the calculations of relative O-H...O bond energies are all reasonably accurate. Accordingly, the formation of homodimers in complex **9** is exceptional; *the stabilisation of heterodimer over homodimer to the extent of ca.* 1.0 *Kcal/mol must be compensated by other (weaker) interactions in the crystal if the homodimer is even to be obtained.*

Complex **9** is a good example of molecular recognition because from a mixture of heterodimers, homodimers and monomers in solution, the heterodimer:homodimer ratio being approximately 3:1 (assuming an energy difference of 0.8 Kcal/mole between hetero and homo dimers) only the minor component (homodimer) is obtained in the crystal. It is clear from the calculations and from structures **1-10** and **21** that the isolated heterodimer

1



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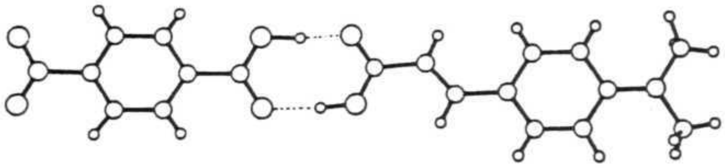

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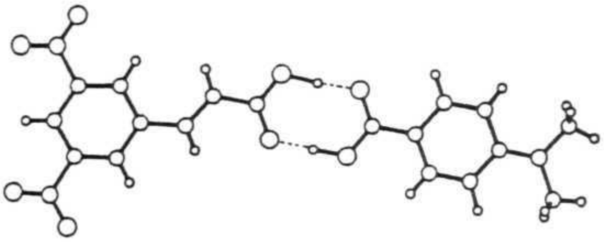

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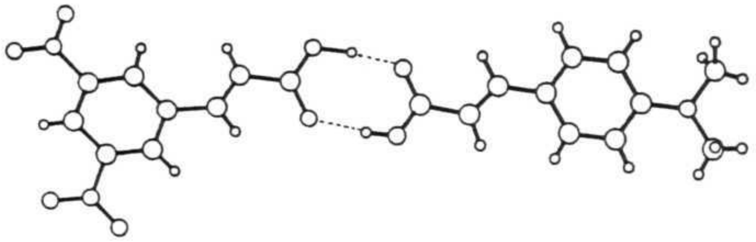

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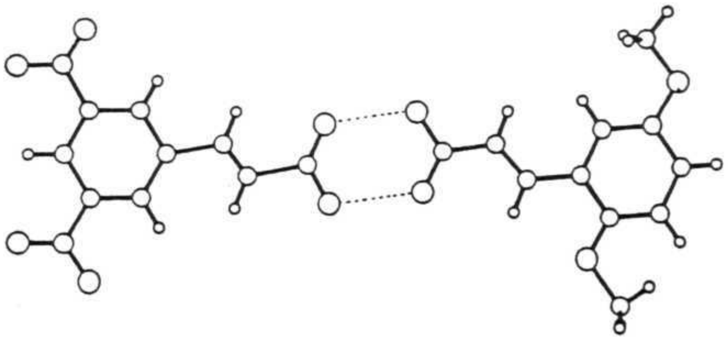

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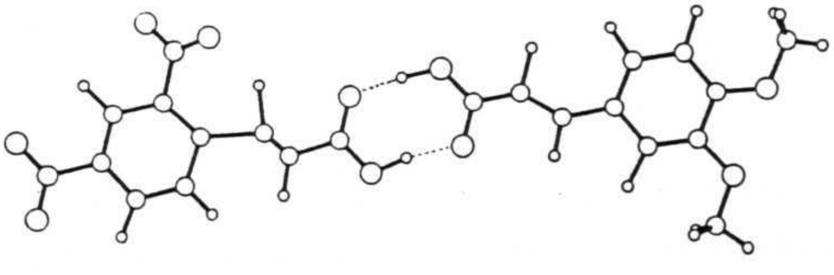

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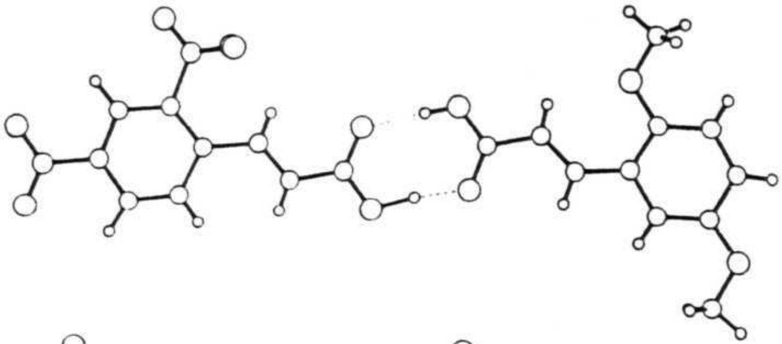

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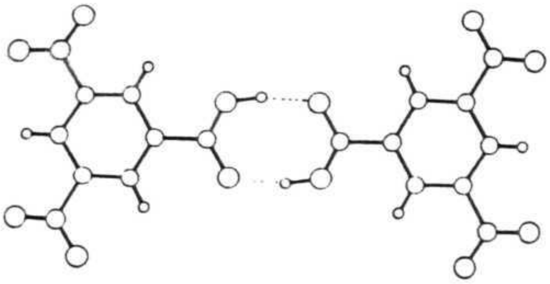

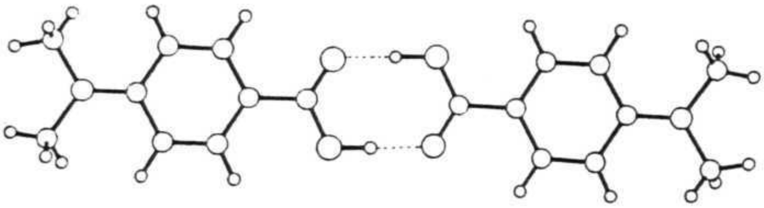

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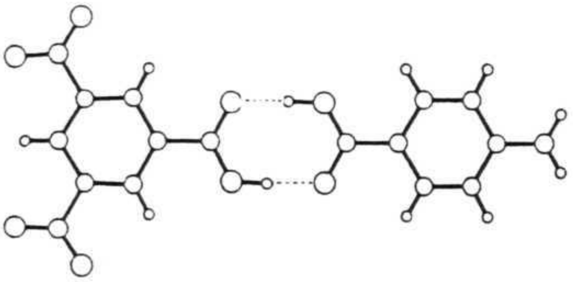


Figure **5** O-H...O dimers in donor-acceptor complexes **1**-**9** and **21**. Note that only complex **9** has homodimers **1b** - **1b**, **1c** - **1c** in the crystal structure, but that all the others form the more common hetero dimer. O-H...O bonds are shown as dashed line.

is stabler than the isolated homodimers. The occurrence of only homodimers in the crystal of **9**, obtained by either recrystallisation or grinding is therefore indicative of the importance of other factors.

Three weaker forces, van der Waals, C-H...O and $\pi...\pi$ interactions, were identified as possible perturbing factors which cause the tilt towards homodimer formation in **9**. It has been held by Hunter and Sanders[7a] that van der Waals or isotropic forces cannot in themselves determine the crystal packing of donor-acceptor complexes.[19] This is so because these forces are proportional to the extent of overlap between two stacked molecules. These ideas have already been detailed in Chapter 1. If these forces were structure-determining, the overlap between stacked molecules would be maximised. This is never so, because $\pi...\pi$ repulsions dominate at large overlaps. Thus, van der Waals forces are important only within the framework of the more electrostatic $\pi...\pi$ interactions. Therefore attention was shifted to C-H...O and $\pi...\pi$ interactions in complexes **1-10**. The C-H...O bonds in complexes **1-8** have been mentioned earlier in Sections 2.2.1 and 2.2.2. Complex **21** was found not to contain any characteristic C-H...O bonds because the NO_2 group of **1b** is involved, not surprisingly, in strong N-H...O hydrogen bonds with NH_2 group of **1d**. The C-H...O bonds in complex **9** are discussed here in some detail.

3.2.2.1 C-H...O Hydrogen Bonds in Complex 9

Unlike complexes **1-8** which display rich and distinctive C-H...O patterns, complex **9** contains only a few C-H...O bonds and that too of marginal significance. Figure 6 is a plot of C-H...O angle versus the H...O distance for all C-H...O bonds in structures **1-9** and **21**. In these plots, normalised H atom positions are used with the C-H distance taken to be 1.08Å. C-H...O bonds in complex **9** are shown as darkened circles. It is very clear from the plot that the C-H...O bonds in **9** are neither the shortest nor the most linear

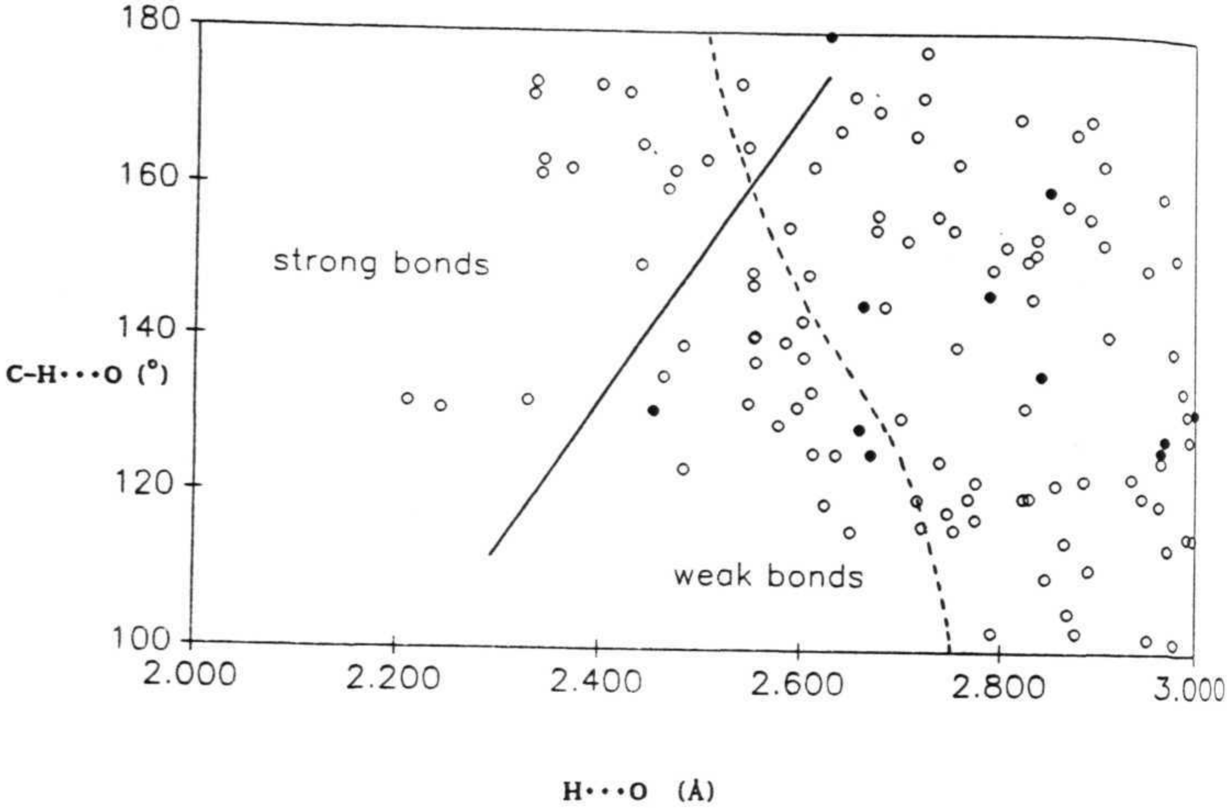


Figure 6. Scatter plot of H...O distance (normalised to 1.08Å) versus C-H...O angle for all C-H...O bonds in complexes **1-9** and **21**. Bonds in complex **9** are shown as dashed circles. It is clear from the figure that C-H...O bonds in complex **9** are weak either with our prescription (solid line) or with Saenger's[9b] (broken line). Note that excepting **9**, all other complexes have contributors in the strong bonds region.

in the group. The solid line in the plot appears to be a natural separation between regions containing strong and weak C-H...O bonds. The dashed line is drawn according to the prescription of Steiner and Saenger[8b] and makes allowance for elliptically-shaped H atoms. Whatever the type of demarcation, C-H...O contacts in complex **9** are feeble[20] and unlike in **1**-**8**, probably do not play a key role in the stabilisation of the structure. Could this observation correlate with the presence of homodimers in **9** and heterodimers in **1**-**8**?

Inspection of the molecular formulae of **1b** and **1c** suggests further probable reasons for the lack of C-H...O bonds in **9**. While **1b** has three acidic C-H protons, they are sterically inaccessible to O atoms. The only C-H...O pattern possible is the NO_2-$N(CH_3)_2$ recognition motif (Chapter 2, Figure 4a) which makes weak bonds of 3.59, 3.41, 3.71 and 3.68Å. Therefore H4 of acid **1b** which is the most acidic H atom in the system is blocked. Atoms H2 and H6 of acid **1b** are also blocked by the flanking substituents. Most critically, the absence of styryl H atoms which are invariably involved in C-H...O bonding in a large number of α,β-unsaturated carbonyl and nitro compounds[21] (Chapter 2, Figures 4b, 4c), means that there is just not enough C-H...O bond forming propensity here. In turn, it may be stated that the presence of such styryl H atoms as in acids **2a**-**2f** leads to distinctly favourable C-H...O bonding which causes layering or sheet-formation of molecules. This is depicted schematically in Figure 4. The structures of complexes **1**-**8** (especially cinnamic acid-containing complexes **4**-**8**) may be understood as being formed by a stacking of layers which are themselves composed of C-H...O networked O-H...O heterodimers. Conversely, complex **9**, which has only weak C-H...O bonds, has no layer structure. Figure 7 shows columns of stacked molecules which are inclined to one another at an angle of 23° to optimise a few weak C-H...O bonds and close-packing aromatic...aromatic herringbone interactions. *Thus, it is believed that it is*

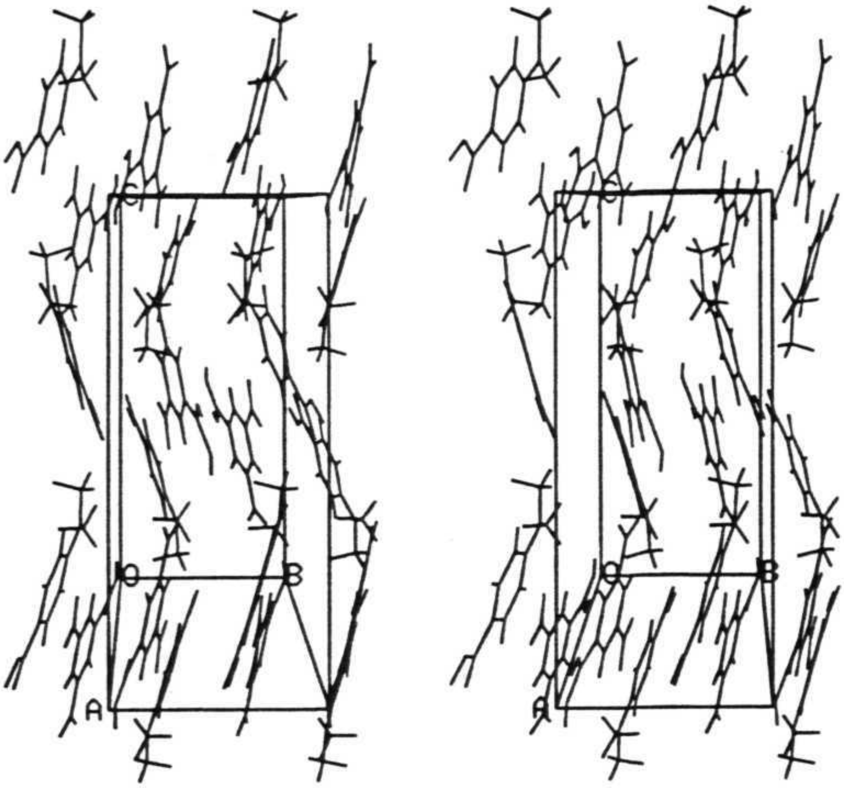
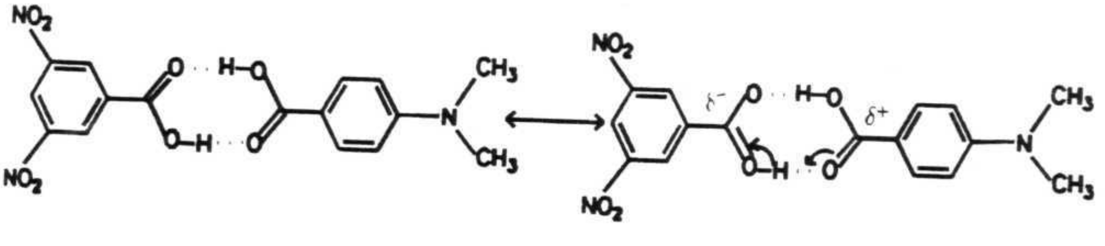


Figure 7. Stereoview of the crystal structure of complex **9**. It can be seen that the adjacent stacked columns of **1b** and **1c** make an angle of 23° indicating the stabilisation of stacks by herringbone interactions.

the lack of C-H...O *bond forming ability in complex* **9** *which causes it to adopt the anomalous homodimer structure.* This absence of C-H...O bonds compels one to consider the third variety of weak interactions in these structures, namely $\pi...\pi$ stacking.

3.2.2.2 Π...Π Stacking in Complex 9 and Elsewhere

Now let us consider the $\pi...\pi$ stacking interactions in the donor-acceptor complexes **1-9** and **21** and their possible role in stabilising the homodimer structure in **9** is considered. Hunter and Sanders have shown that the nature of these interactions is dependent on the intermolecular contacts between the relevant atoms rather than on the overall redox properties of the molecules. An attempt is made here to analyse the $\pi...\pi$ interactions according to this concept.



Scheme I

The electronic properties of atoms in carboxy homo- and heterodimers in complexes **1-9** and **21** are conveniently differentiated because the substituents on the aromatic rings are either powerful electron donors or acceptors. Let us consider complex **9**. The atoms in the aromatic ring and carboxyl group in the isolated **1b** molecule possess a partial (+) charge and correspondingly in **1c**, a partial (-) charge, because of the presence of -NO_2

and -$N(CH_3)_2$ groups respectively. If acids **1b** and **1c** were to form a heterodimer, there would be a flow of charge from **1c** to **1b** through the dimer ring as shown in Scheme I *via* resonance assisted hydrogen bonding.[22] As a result, the (+) and (-) charges in the aromatic rings of **1b** and **1c** will be diminished in the heterodimer as compared to the isolated monomers.

If, however, **1b** and **1c** were to form homodimers instead, as observed in reality, the (+) and (-) charges on the rings are enhanced. In other words, homodimer formation leads to a greater polarisation or charge separation in **1b** and **1c** molecules when compared to the isolated monomers. The AM1 charges obtained for homo- and heterodimers of **1b** and **1c** corroborate this statement but the magnitudes of all the charges are very small and the differences in charges for corresponding atoms between homo and heterodimers is less than 0.02 e. However, the *direction* of change in charge is always so as to support the hypothesis above. More satisfactory evidence for this hypothesis is obtained from the O-H...O bond lengths in homodimers and heterodimers of some of the acids in the study (Table 1). The crystal structure of the pure acid is a model for the homodimer to compare their carboxyl O...O distances with the corresponding heterodimers, when no homodimers are obtained in the acid complexes. Except acids **1b** and **1c**, all other acids form heterodimers. Table 1 shows that both the O...O distances in a heterodimer are always less than the O...O distance in either of the two corresponding homodimers. These figures argue convincingly for a net flow of charge across the hydrogen-bonded ring in heterodimers and conversely, for an accentuation of charge in a homodimer.

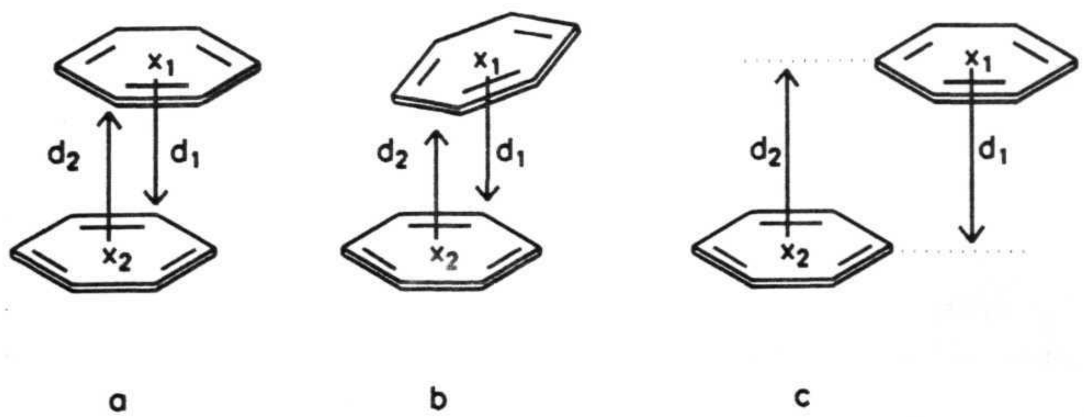
Table 1

O...O distances (Å) in the hydrogen-bonded rings in some of the pure acids and complexes in this study.

Compound	Pure	Complex[a]		
1a	2.660	2.632 (**1**)		
1b	2.636	2.655 (**9**)[b]	2.616 (**21**)	
1c	2.627	2.625 (**9**)[b]	2.608 (**4**)	2.606 (**5**)
1d	2.642	2.616 (**21**)		
2b	2.661	2.628 (**4**)	2.627 (**6**)	2.643 (**5**)
2c	2.657	2.632 (**7**)	2.638 (**8**)	
2f	2.632	2.619 (**7**)		

[a] Except **9** all the complexes are heterodimers and have O...O distances less than those found in pure acids. [b] Homodimers.

According to this argument, the polarisation of C and O atoms in the **1b**...**1b** and **1c**...**1c** homodimers will be greater than in the **1b**...**1c** heterodimer. So, if one considers stacking interactions, these should be more favourable for homodimers than for heterodimers (Figure 8). It is possible to verify the approximate strengths of these $\pi...\pi$ interactions in complexes **1**-**9** and **21** by examining the donor-acceptor aryl...aryl stacking distances.



Scheme II

There are many possible modes of aryl...aryl stacking (See, Sections 1.2.1 and 1.2.3). For example, the two aryl rings can interact each other with var-

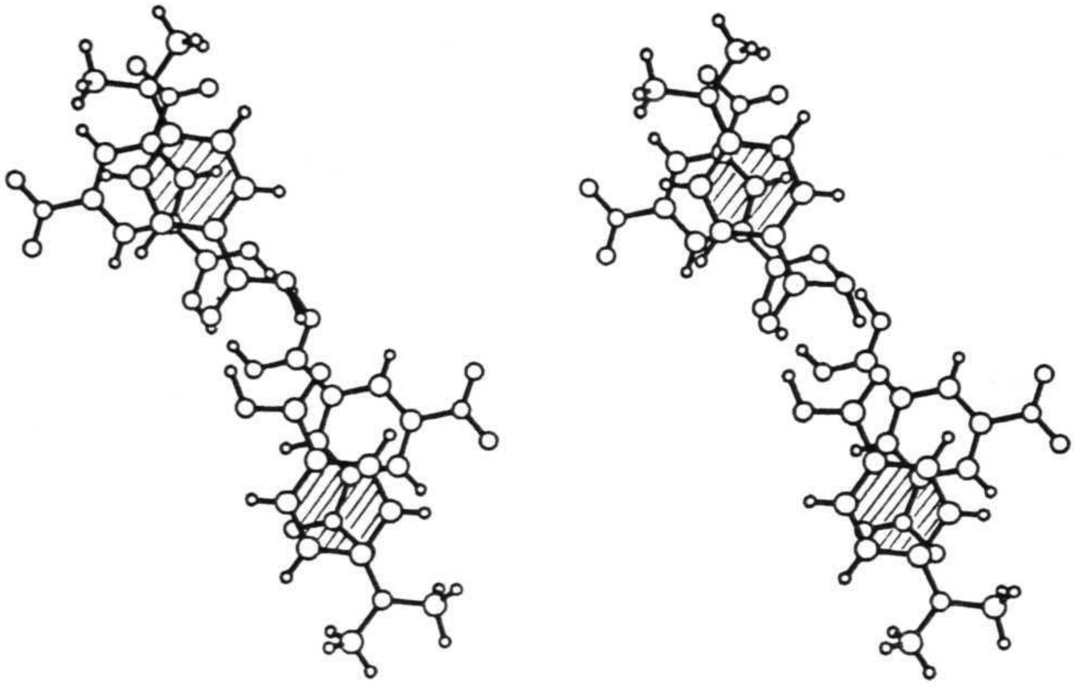


Figure 8. Stereoview of stacked homodimers of **1b** and **1c** in complex **9**. For clarity, homodimer **1c** is shaded. Interestingly these homodimers stack with the shortest aryl-aryl and carboxy-carboxy distances among all the complexes in this study.

ious offsets and perpendicular interplanar distances and simultaneouly may have different orientation angles ranging from 0 to 30° (Scheme II). Indeed, it is not possible to represent stacking interactions of aryl-aryl rings based on interplanar distance alone because aromatic rings with a short interplanar distance may well be separated with large offsets, in which case the overlapping between the rings would be almost negligible (Scheme II, c). In other cases, when the phenyl rings are non-parallel it is not possible to define the interplanar distance uniquely (Scheme II, b). Further, as the interplanar angle increases, the stacking interaction would be reduced and edge-face or herringbone interactions start operating. So in order to evaluate stacking interactions properly, one should consider all these possibilities. Probably the most complete way of representing stacking interactions is to consider both centroid-to-centroid ($X_1...X_2$) and mean-interplanar stacking distance, that is $(d_1+d_2)/2$. So an ideal stacking interaction (or overlapping) will have small centroid-to-centroid and mean-interplanar distances and any deviation from such an ideal position may be indicative of poorer stacking interactions.

Figure 9 is a scatterplot of centroid-to-centroid versus average perpendicular interplanar distances for the stacked aromatic rings in these complexes. It is clear from this figure that complex **9** is a striking outlier. The short interplanar and centroid-to-centroid distances in complex **9** (C...O, 3.38, 3.22, 3.41Å; C...C 3.38, 3.35, 3.40, 3.41, 3.42Å) are not found in any of the heterodimer structures **1**-**8** and **21** and show that the overlap of aromatic rings in **9** is very effective. Further, there is a significant overlap of the carboxyl hydrogen bonded rings (Figure 8), a structural feature which is absent in all the heterodimer structures studied here and one which argues convincingly in favour of enhanced atomic charges throughout the homodimer framework. *So it may be assumed that the combined aromatic and carboxyl* $\pi...\pi$*/electrostatic interactions obtained via overlap, are a critical*

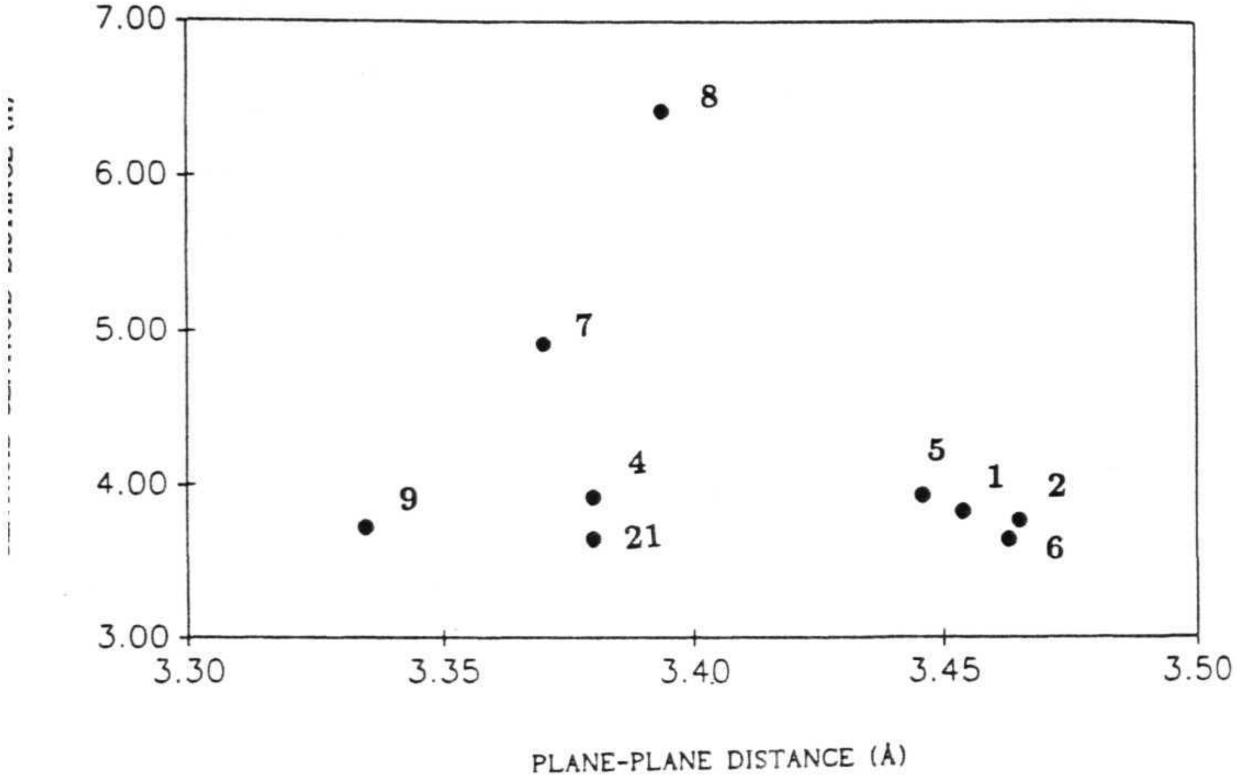


Figure 9. A graph between donor-acceptor aryl-aryl interplanar distances *versus* centroid-to-centroid distances. Complex **9** which forms homodimers is an outlier with a short interplanar distace. Note that complexes **4** and **21** with moderately short stacking distances do not have a good overlap between carboxy hetero dimers.

source of stabilisation of the homodimer structure in complex **9** *and that they are more than sufficient to compensate for the lack of* O-H...O *heterodimer stabilisation (ca.* 0.80 *Kcal/mol) and for the unsatisfactory* C-H...O *situation.*

3.2.2.3 A Possible Sequence for Crystallisation of Complex 9

In MeOH solution, component acid molecules are likely to exist as hydrogen bonded solvated monomers, heterodimers and homodimers. If it is assumed that in all cases the energy difference between heterodimers and homodimers in solution is around 0.80 Kcal/mol, it means that the heterodimer : homodimer ratio in solution is around 3:1. Indeed the energy difference between homodimer and heterodimer may be more than 0.8 Kcal in solution, as this energy difference more appropriately corresponds to gas phase carboxyl dimers. In solution, polarisation by the solvent may further enhance the energy gap between homodimers and heterodimers. Either type of dimer can form crystal nucleii by aggregation with other dimers laterally or along a stack. It is suggested that in the majority of cases **1**-**8**, crystal nucleii develop by a lateral organisation of O-H...O dimers *via* C-H...O bonding, the interaction of next importance (Figure 4). These lateral interactions are equally easy for hetero- and homodimers because of the presence of favourable features in the molecular structures of the monomers (styrenic H atoms). Accordingly, the more abundant heterodimers form crystal nucleii easier. These nucleii must also involve stacked molecules but the exact nature of this stacking is probably not critical, the growing nucleii already having obtained adequate stability from the O-H...O (hetero) and C-H...O interactions.

In the case of complex **9**, however, neither homodimers nor heterodimers can nucleate properly *via* lateral C-H...O bonds. Therefore both these types of dimers aggregate primarily *via* stacking interactions. In this event, the homodimers are distinctly favoured as detailed above. Growing homodimer stacks are formed in spite of an unfavourable heterodimer : homodimer ratio in solution and they aggregate *via* weak van der Waals forces to achieve close packing (Figure 7). The exclusive formation of the homodimer structure of **9** indicates that the stabilisation gained from $\pi...\pi$ interactions more than offsets the loss in O-H...O stability in avoiding the heterodimer alternative.

As crystallisation progresses, the heterodimer $\rightleftharpoons$ homodimer equilibrium in solution shifts towards homodimer. It is remarkable that very slight energetic preferences dictate an almost completely unequivocal crystallisation pathway. This, in general, has been observed by others and augurs well for future experiments in molecular recognition and crystal engineering.

3.3 Conclusions

C-H...O hydrogen bonds are the reason underlying the two anomalous crystal structures discussed in this Chapter. The presence of a carboxyl dimer bisected by the uncommon twofold axis in the crystal structure of acid **2b** is a result of a surfeit C-H...O hydrogen bonds, whilst the unusual carboxyl homodimers obtained in the crystal structue of complex **9** are a result of poor C-H...O hydrogen bonding. These examples indictate that weak C-H...O hydrogen bonds can dictate molecular geometry in certain favourable circumstances. More interestingly, a homodimer complex **9** is a good case study to examine stacking interactions *vis-a-via* weak and strong hydrogen bonding. These interactions which are sometimes in competition and sometimes in consonance are of great importance in biological molecules where the nature of the stacking may dictate the type of hydrogen bonding (Watson-Crick and Hoogsteen). The interplay between these two types of interactions has also been studied in the binding of Kemp's acid derivations with adenines.[23] However, these studies are involved with changes in the exposed surface area between stacked molecules whereas the present example considers mainly changes in the atomic charges in stacked molecules brought about by different kinds of hydrogen bonding. The assumption of charge transfer through hydrogen bonding involves a new perception in studies of hydrogen bonding and $\pi...\pi$ interactions.

The analysis of complexes **1**-**10** in this study addresses the following three points which are of current interest: (i) Weak C-H...O hydrogen bonds can control the crystal packing even in strongly hydrogen bonded compounds. (ii) O-H...O hydrogen bonds can act as channels for charge transfer and alter the polarisation of atoms. (iii) Hydrogen bonding interactions influence the nature of stacking interaction and vice versa.

The anomalous structures of acid **2b** and complex **9** shows that a strong interaction alone need not always dictate the crystal geometry if other weaker interactions are of special significance. These results caution one to keep track of weak interactions while designing novel structures of new materials and suggests that without a proper appreciation of both strong and weak interactions, the prediction and design of crystal structures may often turn out to be an elusive objective.

3.4 Experimental Section

3.4.1 Synthesis

The preparation of acids **1b** and **1c** has been described in Section 2.4.1, while *trans*-3,5-dinitromethylcinnamate, **22** (m.p. 160°C) was prepared by reacting 3,5-dinitrocinnamic acid with diazomethane in dry ether at 0°C. NMR, ($CDCl_3$), δ 9.1 (m, 1Hδ),δ 8.7 (m, 2H),δ 7.8 (d, 1H), δ 6.7 (d, 1H), δ 3.8 (s, 3H). Crystallisation of all the acid complexes has been discussed in Chapter 2. Complex **21** has been described elsewhere.[5]

3.4.2 X-Ray Crystallographic Studies

Crystal data for acids **1b** and **1c** was collected by Prof. W.T. Robinson, University of Canterbury, New Zealand and the structure was determined in using SHELXTL. Crystal data for ester **22** was collected by Dr. T. Pilati, University of Milano, Italy. The crystal structure solution of **22** was carried out in this study with the program SHELX86[24] and the refinements were carried out with the program SHELXL93.[25] All non-H atoms were refined anisotropically and the final R-factors and other crystallographic information of acids **1b**, **1c** and ester **22** are presented in Appendix B-1. Tables of coordinates and thermal vibrational parameters are given in Appendix B-2.

3.4.3 CSD Study

All the carboxylic acids were retrieved from the CSD (Version 5.07) using the 3D graphics option. Screens -28, -55, 153 and 85 were set to eliminate metal containing and charged organic compounds, structures without coordinates or unmatched chemical and crystallographic connectivities. A distance of 3.20Åwas specified for O...O atoms between carboxyl groups for obtaining hydrogen bonded carboxylic dimers. Further, acids crystallising the space group C2/c were retrieved and closely inspected.

References

1. (a) J,-M. Lehn, *Angew.Chem., Int.Ed.Engl.*, 1990, **29**, 1304.
   (b) D.J. Cram, *Angew.Chem., Int.Ed.Engl.*, 1986, 1039.
   (c) G.M. Whitesides, *Angew.Chem., Int.Ed.Engl.*, 1990, **29**, 1209.
   (d) J. Rebek, *Angew.Chem., Int.Ed.Engl.*, 1990, **29**, 245.
   (e) F.G. Tellado, S.J. Geib, S. Goswami and A.D. Hamilton, *J. Am. Chem.Soc.*, 1991, **113**, 9265.
   (f) F. Vogtle, R. Berscheid and W. Schnick, *J.Chem.Soc., Chem.Commun.*, 1991, 414.
   (g) S.B. Copp, S. Subramanian and M.J. Zaworotko, *J.Am.Chem.Soc.*, 1992, **114**, 8719.
   (h) L.E. Orgel, *Nature*, 1992, **358**, 203.
2. G.R. Desiraju, *Crystal Engineering. The Design of Organic Solids.* Elsevier, Amsterdam, 1989.
3. (a) C.V.K. Sharma, K. Panneerselvam, T. Pilati and G.R. Desiraju, *J. Chem.Soc., Chem.Commun.*, 1992, 832.
   (b) K. Biradha, C.V.K. Sharma, K. Panneerselvam, L. Shimoni, H.L. Carrell, D.E. Zacharias and G.R. Desiraju, *J.Chem.Soc., Chem. Commun.,* 1993,1473.
   (c) D.S. Reddy, K. Panneerselvam, T. Pilati and G.R. Desiraju, *J.Chem.Soc., Chem.Commun.*, 1993, 661.
   (d) D.S. Reddy, B.S. Goud, K. Panneerselvam and G.R. Desiraju, *J.Chem. Soc., Chem.Commun.*, 1993, 663.
   (e) D.S. Reddy, D.C. Craig, A.D. Rae and G.R. Desiraju, *J.Chem.Soc., Chem.Commun.,* 1993, 1737.
   (f) C.V.K. Sharma and G.R. Desiraju, *J.Chem.Soc. Perkin Trans.* 2, 1994, 2309.
4. (a) M.C. Etter, *Acc.Chem.Res.*, 1990, **23**, 120.
   (b) M.C. Etter and D.A. Adsmond, *J.Chem.Soc., Chem.Commun.*, 1990,

589.

5. M.C. Etter and G.M. Frankenbach, *Chem.Mater.*, 1989, **1**, 10.

6. See, However, Z. Berkovitch-Yellin, L. Leiserowitz, *J.Am.Chem.Soc.*, 1983, **105**, 765.

7. (a) C.A. Hunter and J.K.M. Sanders, *J.Am.Chem.Soc.*, 1990, **112**, 5525.
   (b) D. Philip and J.F. Stoddart, *Syn Lett.*, 1991, 445.
   (c) R. Berscheld, M. Nieger and F. Vogtle, *J.Chem.Soc., Chem.Commun.*, 1991, 1364.
   (d) A.R. VanDoorn, M. Bor, S. Harkema, J. VanEirdeu, W. Verboom and D.N. Reinhoudt, *J.Org.Chem.*, 1991, **56**, 2371.

8. (a) G.R. Desiraju, *Acc.Chem.Res.*, 1991, **24**, 290.
   (b) T. Steiner and W. Saenger, *J.Am.Chem.Soc.*, 1992, **114**, 10146.

9. Strong hydrogen bonding and stacking have previously been considered jointly (reference 23) but it is believed that the present work is the first where both strong and weak hydrogen bonds are considered along with stacking interactions. In any case these previous studies dealt with phenomena in solution.

10. K.A. Thomas, G.M. Smith, T.B. Thomas and R.J. Feldmann, *Proc. Natl. Acad. Sci.*, USA, 1982, **79**, 4843.

11. G.R. Desiraju, *J.Chem.Soc., Chem.Commun.*, 1990, 454,

12. R. Taylor and O. Kennard, *Acc.Chem.Res.*, 1984, **17**, 320.

13. M.J.S. Dewar, E.G. Zoebisch, E.F. Healy and J.J.P. Stewart, *J.Am. Chem.Soc.*, 1985, **107**, 3902.

14. F.H. Allen, J.E. Davies, J.J. Galloy, O. Johnson, O. Kennard, C.F. Macrae and D.G. Watson, *J.Chem.Inf.Comp.Sci.*, 1991, **31**, 204.

15. G.A. Jeffrey and W. Saenger, '*Hydrogen Bonding in Biological Structures*' Springer-Verlag, Berlin, 1991.

16. C.V.K. Sharma, K. Panneerselvam, T. Pilati and G.R. Desiraju, *Acta Crystallogr.*, 1994, **C**, 000.

17. J.J. Dannenberg, *Chem.Mater.*, 1990, **2**, 635.
18. M.J. Frisch, A.C. Scheiner, H.F. Schaefer and J.S. Brinkley, *J.Chem.Phys.*, 1985, **82**, 4194.
19. However, van der Waals forces can distort N-H...O hydrogen bond pattern in other cases as is seen in the unusual crystal structure of adipamide., A.T. Hagler, L. Leiserowitz, *J.Am.Chem.Soc.*, 1978, **100**, 5879.
20. Further evidence for the weakness of the C-H...O bonds in complex **9** is provided by the disordered carboxyl group in acid **1b**. Complexes **1** -**8** however contain ordered carboxyl groups.
21. (a) V.R. Pedireddi and G.R. Desiraju, *J.Chem.Soc., Chem.Commun.*, 1992,988.

    (b) V.R. Pedireddi, J.A.R.P. Sarma and G.R. Desiraju, *J.Chem.Soc., Perkin Trans* 2, 1992, 311.
22. G. Gilli, F. Bellucci, V. Ferretti and V. Bertolasi, *J.Am.Chem.Soc.*, 1989, **111**, 1023.
23. (a) K. Williams, B. Askew, P. Ballester, C. Bubr, K.S. Jeong, S. Jones and J. Rebek, *J.Am.Chem.Soc.*, 1989, **111**, 1090.

    (b) S. Goswami and A.D. Hamilton, *J.Am.Chem.Soc.*, 1989, **111**, 3425.
24. G.M. Sheldrick, SHELXS86. in *Crystallographic Computing* 3; G.M. Sheldrick, C. Kruger and R. Goddard, Eds; Oxford University Press: Oxford, U.K., 1985, pp 175-189.
25. G.M. Sheldrick, (1993) SHELXL. An Intergrated System for Solving, Refining and Displaying Crystal Structures from Diffraction Data, University of Cottingen, Germany.

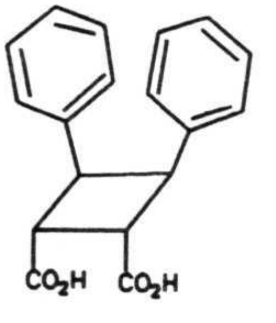
Chapter Four

Engineered Topochemical Synthesis and a Study of Host-Guest Complexation Properties

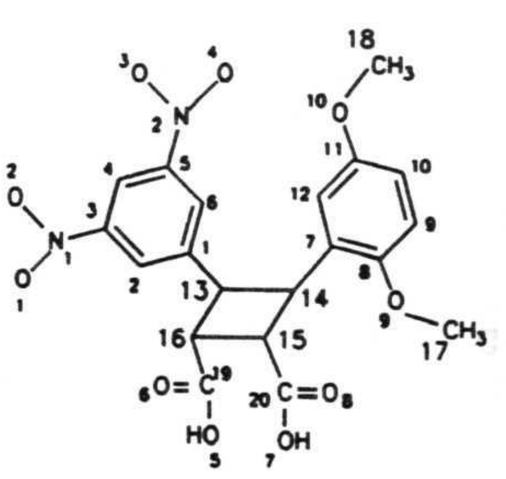
4.1 Introduction

Solid state organic chemistry has the unique feature of adopting various concepts, strategies and techniques in a single study. It links synthesis, structure and properties to obtain a clearer understanding of organic solids. Such an understanding in turn provides insight into many observed chemical, physical and biological processes such as molecular recognition,[1] crystal engineering[2] and supramolecular function.[3]

Molecular assembly and architecture of a wide and sophisticated variety of organic supermolecules often requires the synthesis of novel building-block molecules with desired information sites.[3] Such molecules may on occasion be difficult to synthesise conventionally. A case in point are ß-truxinic acids such as **23** which are problematic to make in solution but not so in the solid state.[4] It has been found that unsymmetrical ß-truxinic acids such as **24** clathrate guest molecules selectively.[5] These unsymmetrical derivatives are unusual and must in principle be prepared *via* solid state 2+2 cycloaddition reactions of cinnamic acid molecular complexes.

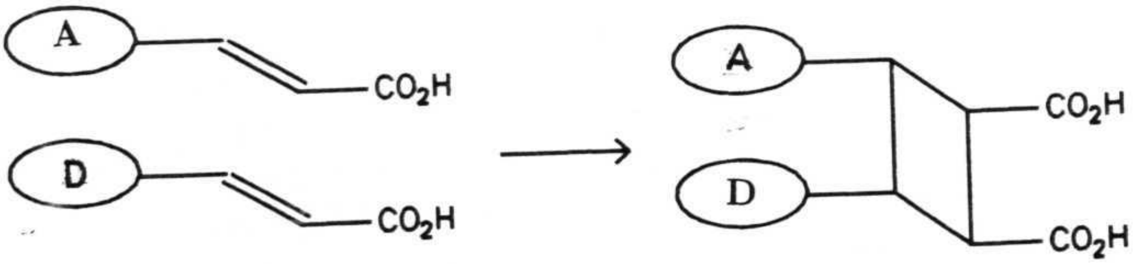


23



24

The engineered topochemical synthesis of diacid **24** is discussed in this chapter and it has been shown that this system is a model to study several interesting molecular and supramolecular properties. The methodology adopted here for the solid state synthesis is to use donor-acceptor $\pi ... \pi$ interactions to bring together to within the topochemical threshold distance, two 'potentially reactive' alkenic double bonds from two electronically distinctive cinnamic acids. This is shown in Scheme I from which it is clear that the product cyclobutane will have donor and acceptor groups in a cofacial relationship leading to cleft formation; this feature can be exploited for the selective binding of simple aromatic compounds. Further, the proximity of the donor and acceptor phenyl rings in **24** makes it a good model compound for the study of intramolecular charge tranfer.[6,7] Additionally, the rigid parallel orientation of phenyl groups with respect to the connecting central C-C single bond is a prerequisite for the phenomenon of Through Bond Coupling (TBC)[6,8] and the consequent C-C bond elongation provides a good opportunity to study this phenomenon also. X-Ray crystallography, semi-empirical calculations, electronic spectroscopy and the CSD[9] have been used to study the above properties of diacid **24**.

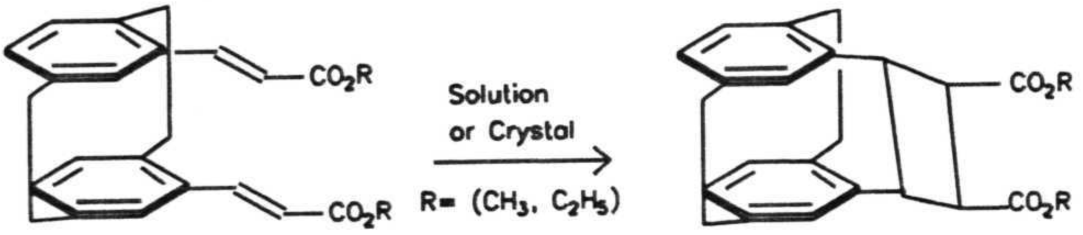


Scheme I

4.2 Results and Discussion

4.2.1 Crystal Engineering: The 2+2 Cycloaddition Reaction

It was shown that the 1:1 charge transfer complex **7** of 2,4-dinitrocinnamic acid (**2c**) and 3,4-dimethoxycinnamic acid (**2f**) is not photoreactive in the solid state despite the favourable disposition of the two 'potentially reactive' double bonds of the donor and acceptor molecules namely a mean double bond centre-centre distance of 3.80 Å.[10] Subsequently, another 1:1 cinnamic acid charge transfer complex **8** was prepared using the same acceptor **2c** and a different donor, 2,5-dimethoxycinnamic acid, **2e**. This dimer was also found to be photostable. This unexpected lack of reactivity of acid **2c** complexes confirms the earlier suggestion that the nitro groups in **2c** suppress the reactivity of the alkenes towards $\pi\pi^*$ mediated reactions due to the easier accessibility of the $n\pi^*$ level, which provides a pathway for the excited $\pi\pi^*$ electrons to the ground state through radiationless decay without any net chemical reaction.[10] The lack of reactivity of complexes **7** and **8** towards solid state 2+2 cycloaddition suggested that it would be more appropriate to use 3,5-dinitrocinnamic acid **2b** as the acceptor component in the molecular complex selected for the solid state reaction. Unlike in acid **2c,** the excited $\pi\pi^*$ electrons in acid **2b** cannot access the $n\pi^*$ state because the 1,3,5-substitution pattern precludes the resonance required for the $\pi\pi^* --> n\pi^*$ energy transfer or in other words, the nitro groups of **2b** act essentially as inductive groups only. Accordingly complexes **2b** with 2,5-dimethoxycinnamic acid, **2e** (**6**) and of **2b** with 3,4-dimethoxycinnamic acid, **2c** (**25**), were prepared. As expected, these two complexes are photoreactive in the solid state and this observation is in accord with the mechanism proposed for the photostability of complexes of acid **2b**. The crystal structure of complex **6** has been determined (see Chapter 2) and the centre-centre distance between the two potentially reactive double bonds is 3.54Å, which is within the 4.2Åthreshold distance for solid state photochemical reactivity.[4] This is shown in Figure 1. The crystal structure of **25** has not been solved. The photochemical product obtained upon irradiation of complex **6**, that is 3-(3',5'-dinitrophenyl)-4-(2',5'-dimethoxyphenyl)cyclobutane-1-2-dicarbo-xylic acid (**24**) has been separated and the structure confirmed by X-Ray crystallography. A strategy that is close to the present solid state reaction was reported recently, wherein the appropriately substituted [2.2] paracyclophane derivatives undergo a 2+2 cycloaddition either in solution or in the solid state to yield 100% cyclobutane derivatives (Scheme II).[11]



Scheme II

4.2.2 Molecular Properties of Diacid 24

4.2.2.1 Molecular Structure

An ORTEP[12] view of diacid **24** is shown in Figure 2. Diacid **24** has two cofacial phenyl rings, with a mean-interplanar distance of 3.77Å(for a definition see Section 3.2.2.2), a centroid-centroid distance 4.37Åand an interplanar angle of 59.2°, These two phenyl rings have a slightly skewed conformation with the torsion angle, C1-C13-C14-C7, being 16.7°, The closest distance between the two phenyl rings is C1...C7, 3.00Å. There are

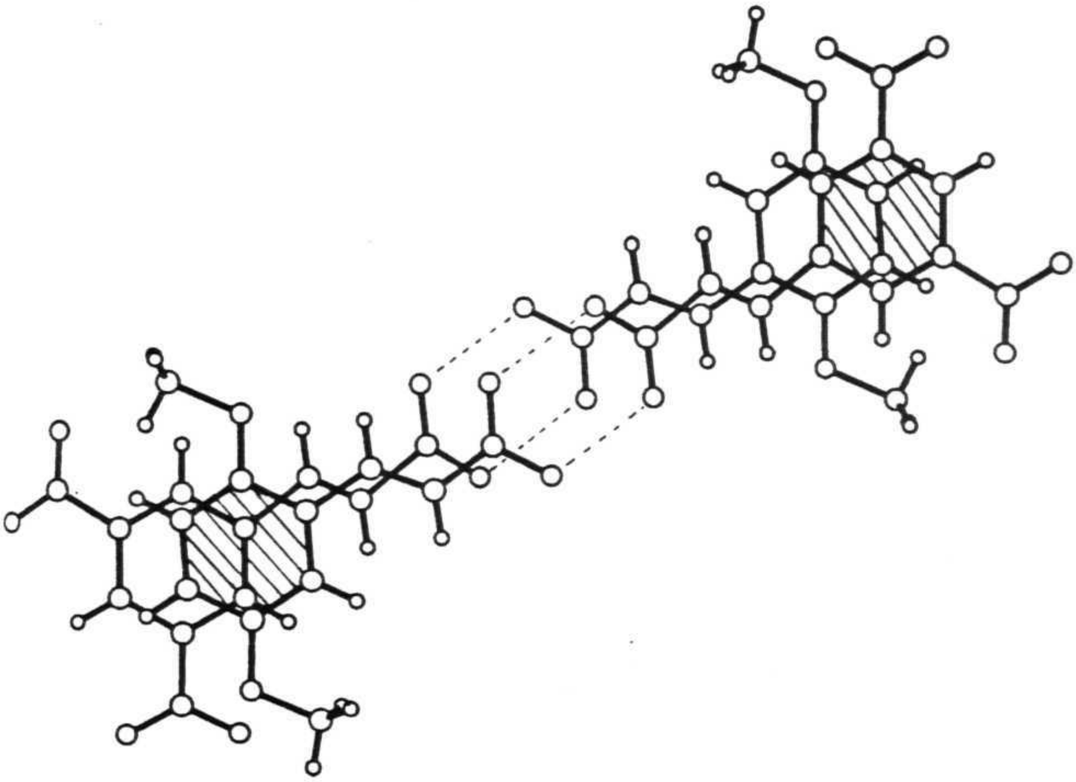


Figure 1. Molecules **2b** and **2e** in complex **6**, related by O-H...O hydrogen bonding and $\pi ... \pi$ stacking. Diacid **24** is formed by 2+2 cycloaddition of neighbouring stacked molecules. O-H...O Hydrogen bonds are shown as dashed lines.

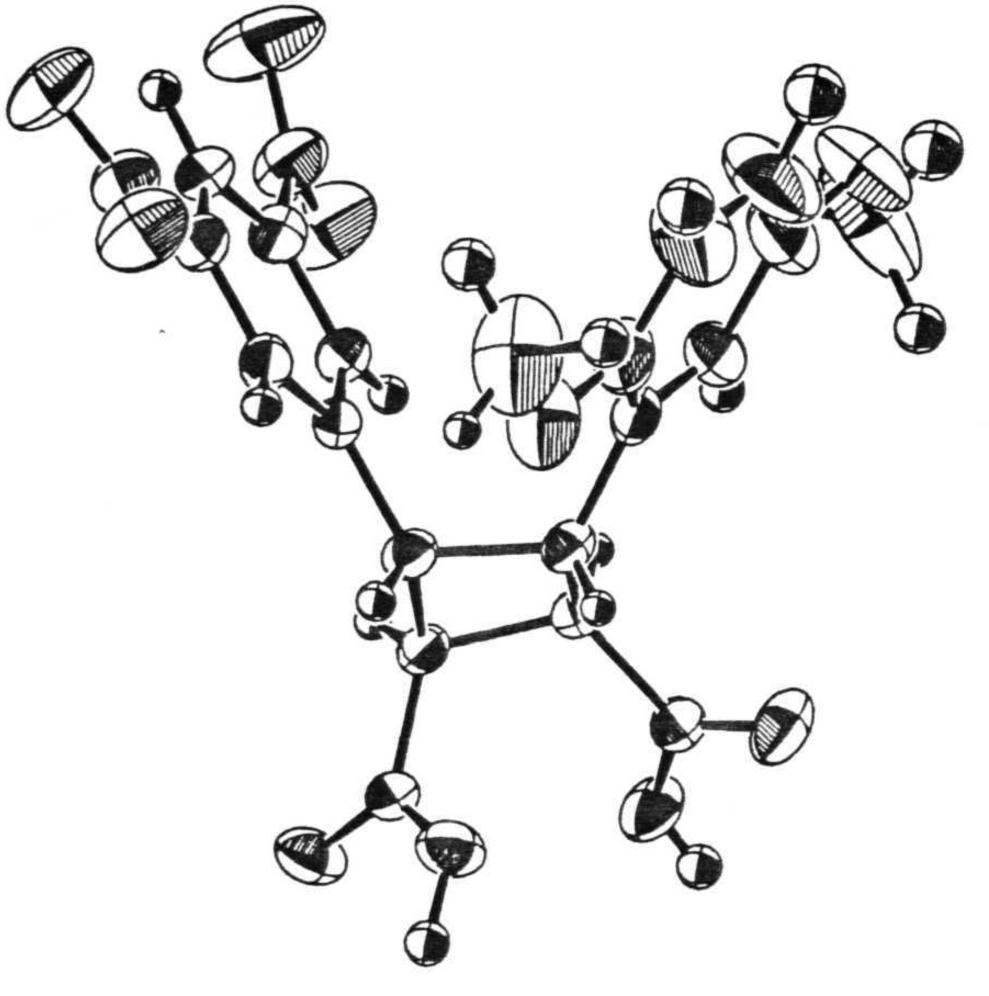


Figure 2. ORTEP diagram of the molecule of **24.** The toluene and water molecules are not shown.

two intramolecular nonbonded C-H...O contacts[13] between the H(6) atom of the dinitrophenyl group and the O(9) atom of the dimethoxyphenyl group (C...O, 3.23Å; $\theta = 104^o$) and between the carboxyl oxygen atom O(5) and the diagonally located H(14) atom of the cyclobutane ring (C...O, 3.20Å and $\theta = 102^o$). The AM1[14] optimised structure of diacid **24** also results in two C-H...O interactions, but these are different from those observed in the crystal structure. In the crystal the cyclobutane ring is puckered with a torsion angle of 11.4° but the ring is planar in the AM1 optimised geometry with a torsion angle of 1.4°. The carboxyl groups of **24** are not involved in intramolecular O-H...O hydrogen bonding though they are adjacent. Instead both of them form intermolecular hydrogen bonded dimers (Figure 6a). The two carboxyl groups are partially disordered with the two C-O distances being 1.246 and 1.272 Å in one group and 1.241 and 1.272 Å in the other. Acid **24** clathrates both water and toluene molecules. The water molecule (not shown in Figure 2) is disordered and occupies a special position (1/2, 1/2, 0) in the crystal. The two H atoms of the water molecules were found from difference Fourier maps. The H-O distances are 0.74 and 1.17 Å with the H-O-H angle being 102.6°. The disordered toluene molecule is located on another inversion centre at (1/2, 0, 1/2) and hence the asymmetric unit contains only half a toluene molecule (omitted in Figure 2 for clarity).

4.2.2.2 Charge Transfer

An interesting feature in the molecular structure of **24** is the cofacial disposition of aromatic donor and acceptor groups. Such an arrangement permits intramolecular charge transfer,[6,7] the presence of which is ascertained by electronic spectroscopy. The UV spectrum of diacid **24** in MeOH (4 X 10^{-5} M) was compared with those of the model compounds, 1,3-dinitrobenzene and 1,4-dimethoxybenzene in the same solvent. The UV spectrum of **24** is red-shifted and broadened compared to the combined 1:1

spectrum of a mixture of the model compounds (Figure 3). A residual absorption near 310 nm was also noticed in the spectrum of **24**. This band is ascribed to intramolecular charge transfer. UV spectra of **24** recorded in MeCN and CH_2Cl_2 also showed similar features clearly indicating the presence of intramolecular charge transfer. As seen in Figure 3, the absorption maxima at 227 nm and 288 nm are 3 and 2 nm red shifted, compared to the composite spectrum of the model compounds. The ^1H NMR shifts ($CDCl_3$) of the two aryl moieties in **24** also suggest mutual shielding and therefore the presence of a molecular conformation which can sustain intramolecular charge transfer. The nitro aromatic protons of **24** are shifted upfield to δ 8.35 and 8.63 compared to the values of δ 8.78 and 9.10 in 1,3-dinitrobenzene and similarly the aliphatic and methoxy aromatic protons in **24** are shifted upfield to δ 3.60, 3.70 and 6.60 compared to the values of δ 3.81 and 6.9 in 1,4-dimethoxybenzene. The slight variations in the upfield shifts of the different protons also suggest the importance of skewed conformations of **24** in solution. The mean interplanar distance of the two phenyl rings 3.77Å, obtained from the crystal structure also indicates the existence of intramolecular charge transfer. This distance is slightly higher than the AM1 or MNDO optimised values of 3.64 and 3.62 Å, because of the presence in the crystal structure of the toluene guest molecule which is involved in intermolecular charge transfer with the dinitrophenyl ring of **24.**

4.2.2.3 Through Bond Coupling (TBC) and C-C Bond Elongation

Diacid **24** is a good example to study the phenomenon of TBC which arises when multiple π orbitals are parallel to a σ bond which is elongated as a result.[15] The σ bond length can be diminished by Through Space Coupling (TSC) which opposes the TBC effect. The TBC in diphenylethanes will be a maximum if the two phenyl groups connected to the σ bond are in a

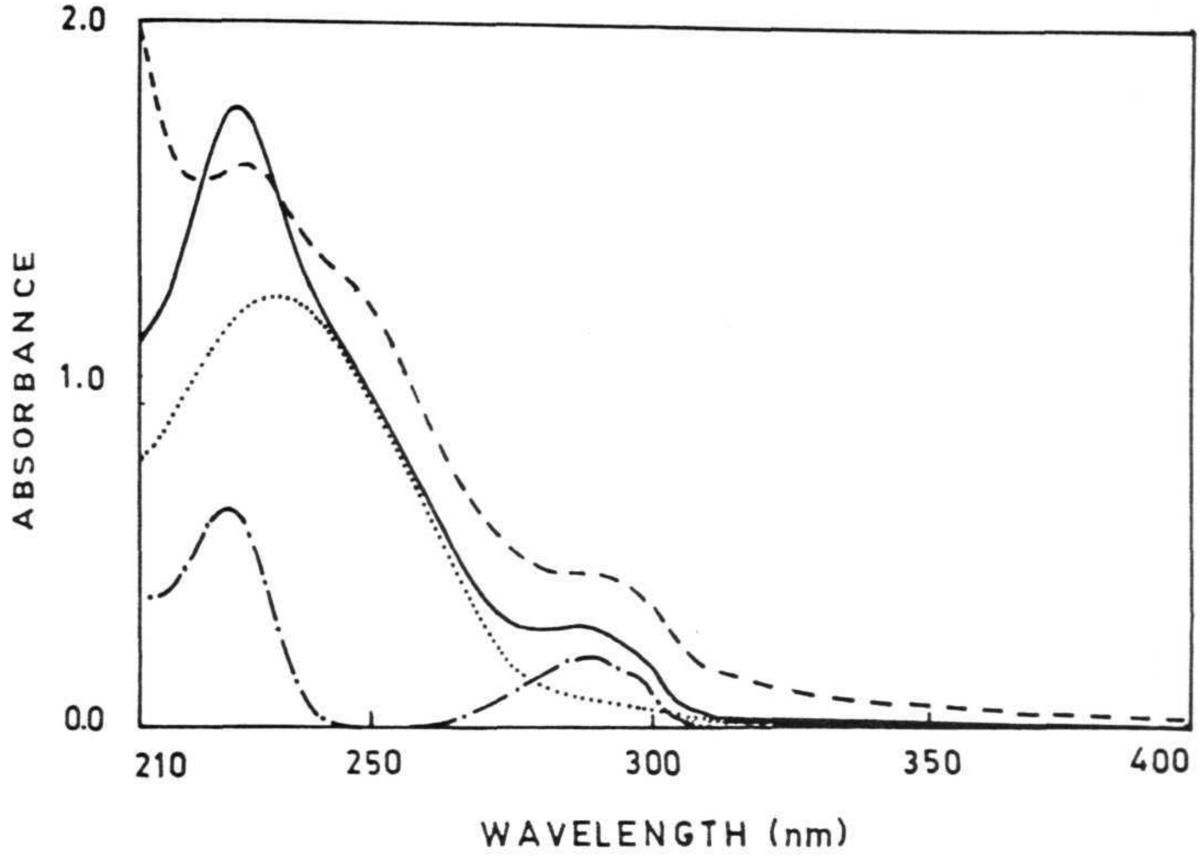


Figure 3. Electronic absorption spectra of **24** (—) and the model compounds 1,3-dinitrobenzene (....) and 1,4-dimethoxybenzene (-.-.-) in MeOH (4×10^{-5}M). Spectrum (- - -) is a composite of the 1,3-dinitrobenzene and 1,4-dimethoxybenzene spectra.

trans disposition and parallel to each other, because the TSC would then be negligible and the maximum number of π orbitals can mix with σ^* orbitals. Steric constraints and a rigid molecular framework accentuate the TBC effect.[6] Substitution at the sp^3 centres may also affect the magnitude of TBC.[15a] A study of the C-C bond lengthening may reveal the process of C-C bond cleavage which is synthetically important and an estimate of the energy required for such a process.[6]

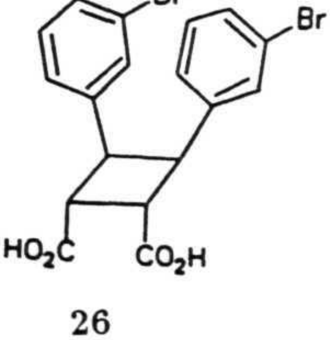
In the present example, we noticed a slight elongation in the C13-C14 (hereafter called the central C-C bond) bond length 1.566Å, compared to the 'normal' bond length between C(sp^3)-C(sp^3) atoms 1.537Å.[16] Other related structures have significantly elongated central C-C bonds. Earlier studies on indanoindane (KINCUF) which resembles **24** closely both electronically and structurally show an elongation of the C-C bond to 1.614 Ådue to TBC.[6] Two other truxinic acids, 3,4-bis(3$'$-bromophenyl) cyclobutane-1,2-dicarboxylic acid, **26** and 3,4-bis(3$'$-chlorophenyl) cyclobutane-1,2-dicarboxylic acid, **27** are reported in the literature[17] as having elongated central C-C bond lengths of 1.573 and 1.575 Å. Some other simple cyclobutanes which are not part of a larger rigid molecular framework such as BAHNIH[18] (1.604Å), CMCNCB[19] (1.606Å), SAJJAO[20] (1.594Å) and SIKROT[21] (1.585 Å) also have elongated central C-C bonds. We carried out molecular mechanics and semi-empirical MNDO and AM1 calculations to find out the effect of substituents on the central C-C bond length in diacids **23**, **24, 26** and **27**.[14] The central C-C bond lengths, interplanar distances and some of the torsion and interplanar angles of the phenyl groups obtained by experiment, molecular mechanics and semi-empirical methods are given in Table 1.

Table 1

Selected intramolecular angles and distances in cyclobutanes **23**, **24**, **26** and **27** obtained from experiment and calculation to probe the effect of TBC on central C-C bond elongation.

		Phenyl - Phenyl			
	Central C-C Distance[a](Å)	Torsion Angle[b](°)	Interplanar Angle(°)	interplanar Distance(Å)	Centroid-Centroid Distance(Å)
23					
Crystal[c]	—	—	—	—	—
MMX	1.553	18.94	56.9	3.33	4.62
MNDO	1.573	13.79	116.8	3.43	4.85
AM1	1.561	8.6	53.1	2.94	4.62
24					
Crystal	1.566	-16.7	59.2	3.77	4.37
MMX	1.556	17.3	54.1	3.12	4.80
MNDO	1.576	-8.9	63.1	3.62	4.83
AM1	1.565	-5.9	113.9	3.64	4.42
26					
Crystal	1.575	20.5	61.2	3.82	4.44
MMX	1.555	23.2	58.1	3.58	4.42
MNDO	1.576	9.1	63.9	3.82	4.65
AM1	1.566	12.0	61.8	3.72	4.41
27					
Crystal	1.573	20.8	61.1	3.81	4.45
MMX	1.556	21.1	58.1	3.58	4.41
MNDO	1.577	10.4	116.9	3.75	4.67
AM1	1.568	7.7	60.6	3.61	4.37

a C13-C14, **b** C1-C13-C14-C17, **c** crystal structure not solved.



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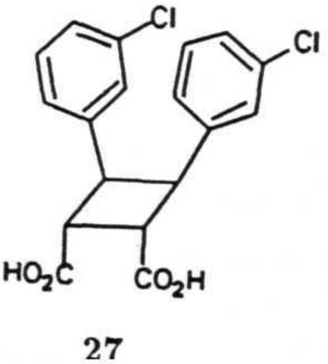
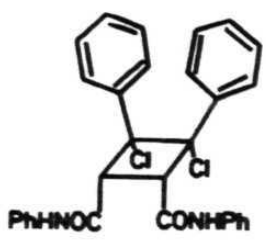
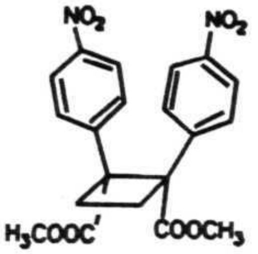


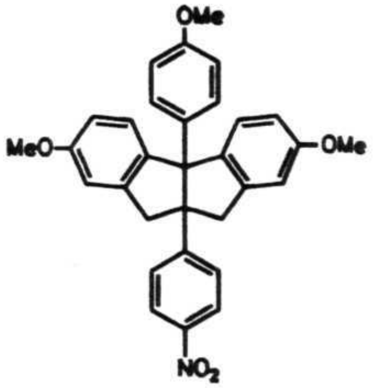
27



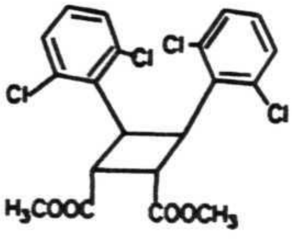
BAHNIH



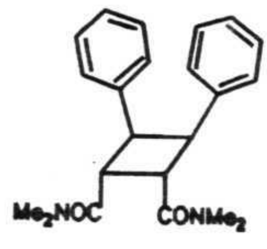
CMCNCB



KINCUF



SAJJAO



SIKROT

Table 1 shows that the central C-C bond lengths and molecular geometry are not reproduced consistently in all the three structures by the semi-empirical methods.[22] However, the semi-empirical central C-C bond lengths are slightly increased compared to the lengths obtained *via* molecular mechanics which does not consider electronic effects. Such differences between molecular mechanics and semiempirical values indicate the presence of TBC. Variations of the substitution patterns in the phenyl rings showed no significant effect on the central C-C bond lengths in either of the semi-empirical methods. So the reason for the relatively slight elongation of the central C-C bond in **24** compared to molecules **23**, **26**, and **27** is not clear. However, it may be reasonable to assume that TSC is greater in **24** than in other related cyclobutanes due to the strong intramolecular charge transfer interaction between adjacent phenyl rings or because of the location of the guest molecule toluene in the cleft formed by the two phenyl groups.

Further, a more general CSD study on all crystal structures that contain the 1,2-diphenylethane fragment was carried out (see Experimental Section 4.4.3). TBC is insensitive to rotation around the central C13-C14 bond,[8] whereas rotation around C1-C13 and C7-C14 will diminish the interaction between σ and π orbitals reducing the TBC effect. This CSD study is also helpful to distinguish between steric and electronic effects on the central C-C bond elongation. If steric effects were to play an important role in bond lengthening, there should not be any correlation between the C-C bond lengths and the relative orientation of phenyl rings (parallel arrangement of π orbitals). On the other hand if any such correlation is found, it is an indication of TBC. Though the torsion angle C1-C13-C14-C7 has no direct role to play in these systems, it can indirectly affect the TBC. This is so because at lower torsion angles $(0 - 45^\circ)$ the phenyl groups must be parallel while at higher torsion angles $(45 - 90^\circ)$ the phenyl groups need not be parallel. Finally, as the torsion angle increases further $(90 - 180^o)$ the phenyl groups will be free to take up any orientation whatsoever. In order to visualise the effect of torsion angle on interplanar angle more clearly, three scatterplots were drawn for C-C bond lengths versus interplanar angle of phenyl groups for three different ranges of torsion angles (Figure 4).

At smaller torsional angles (Figure 4a) most of the C-C bond lengths are long, 1.57-1.64 Åbecause the interplanar angles must also be small and the TBC effect increases. In Figure 4b where the phenyl groups have rotational freedom (torsion angle $45 - 90^o$), the interplanar angles are randomly distributed. When the interplanar angles are large (70-110^o) not much lengthening of the central C-C bond (1.52-1.57 Å) is noticed as would be expected. In this intermediate range of torsion angles, the larger interplanar angles between phenyl groups will be stabilised by herringbone interactions and the possibility of TBC appears to be remote. Figure 4b also indicates that

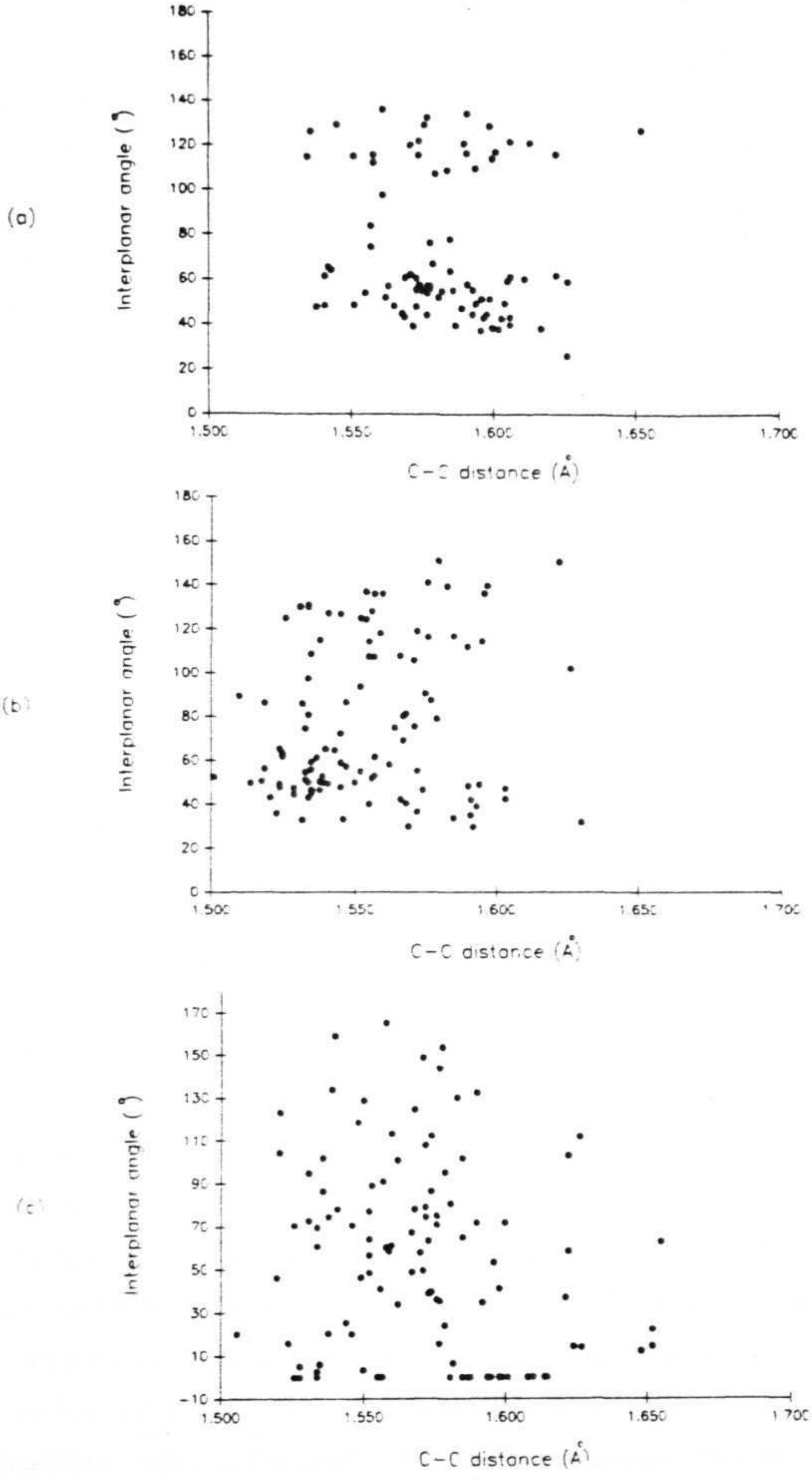


Figure 4. Scatterplots of phenyl-phenyl interplanar angle versus central C-C bond distance in 1,2-diphenylethanes retrieved from the CSD with small (**a**),

small interplanar angles (0-60^o and 120-180^o) are crucial for C-C bond lengthening. Long central C-C bond lengths occur only when the interplanar angles are small. At higher torsion angles (Figure 4c) there is minimal interaction between phenyl rings which exist in all mutual orientations. So the C-C bond lengths have all values in the range, 1.53-1.65Åand satisfyingly, the longer lengths ($>$ 1.60Å) are associated with smaller interplanar angles. Surprisingly, scatterplot **4c** shows a small cluster of points with short bond lengths, 1.52-1.56 Åand small interplanar angles ($<$ 30^o). This subset requires further analysis. However, in an overall sense, plots **4a-4c** emphasise the importance of smaller interplanar angles for effective TBC.

4.2.3 Supramolecular Properties

Weber and co-workers have shown that several three and four membered ring compounds with phenyl and other bulky substituents are good and highly selective host materials for the formation of inclusion compounds.[23] The cavity size (between two phenyl groups) and electronic properties of diacid **24** makes it a specific host for simple aromatics because these molecules can simultaneously satisfy the requirements of size, shape, $\pi ... \pi$ and herringbone interactions which are necessary for binding with the host. So we selected benzene, toluene, *p*-xylene, nitrobenzene, 1,4-dinitrobenzene and anisole as possible guests for complexation with **24**. We were successful in obtaining crystals of the host-guest complex between **24** and toluene from 5:1 MeOH-toluene. After the X-ray analysis it was found that the **24** crystal also includes a water molecule, with both the toluene and water molecules being disordered. Crystals of the nitrobenzene complex of **24** obtained from CH_2Cl_2 were of a quality too poor for X-Ray work.

4.2.3.1 Diacid 24: A Supramolecular Host

As shown in Figure 5 two inversion-related molecules of **24** surround the toluene molecule and form the supramolecular cavity. The toluene molecule is disordered around the same inversion centre, effectively appearing like a molecule of *p*-xylene. In this way, the cavity size and shape matches the guest and also optimises $\pi...\pi$ interactions. Figure 5 also shows that the toluene molecule is sandwiched between the two dinitrophenyl moieties of **24** with a stacking distance of 3.25 Å, a centroid-centroid distance of 4.6 Åand a dihedral angle of 16^o, while simultaneously making an angle of 74^o with the 2,5-dimethoxyphenyl moieties of **24** with a 5.76Åcentroid-centroid distance. The electron-rich toluene molecule stacks with the electron deficient dinitrophenyl rings and has herringbone (C-H...π) type interactions with the electron rich dimethoxyphenyl rings of **24**. Knowing these binding features, one may predict that *p*-xylene will bind like toluene, while nitrobenzene a molecule of roughly the same size and shape would be nearly parallel to the dimethoxyphenyl rings and inclined in a herringbone fashion to the dinitrophenyl rings.

The water molecule which is included along with toluene in crystalline **24** is not involved in any significant hydrogen bonding (water, O_w...O 3.50 Å, C-H...O_w, 3.77, 136°). Despite the presence of a sizable number of O atoms in the molecule, the water molecule merely occupies the channels formed by the carboxylic dimers (Figure 6a). The related diacids **26** and **27** (Figure 6b) also form similar channels and these channels are filled by disordered acetic acid and/or water molecules (not located exactly).[17] Acids **26** and **27** also do not show any significant hydrogen bonding with the included molecules (O_w...O 3.00Å, 2.95Å). It seems that the solvent inclusion phenomenon is common to many other β-truxinic acids.[24] This observation raises the significant question as to whether water can act as a space filler in crystals without being involved in any specific hydrogen bonding even in

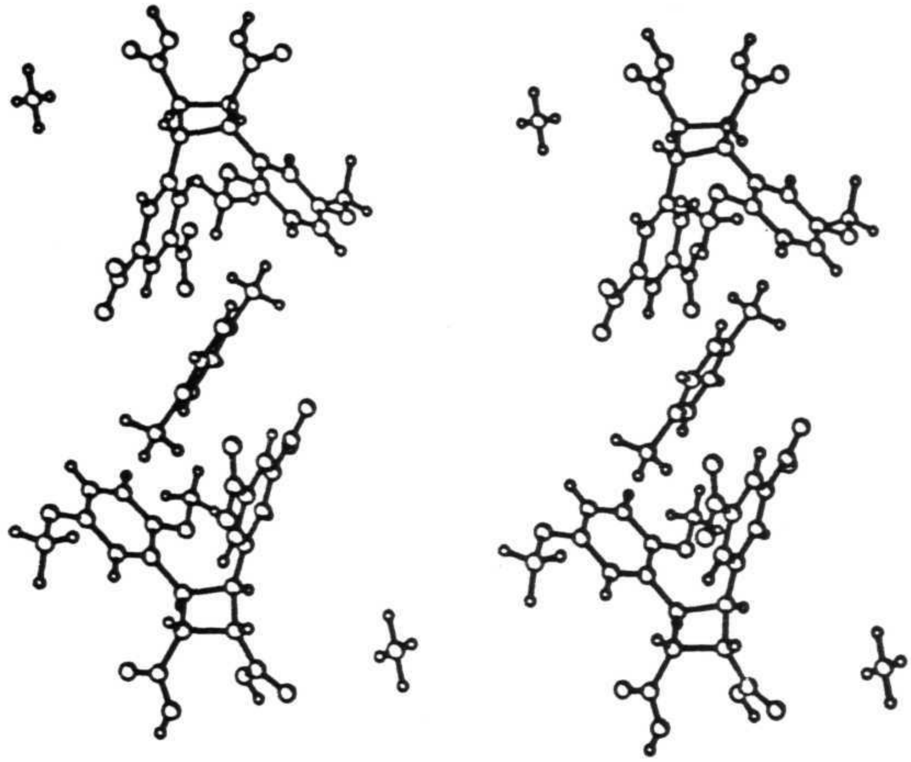


Figure 5. Stereoview of the guest-molecule induced supramolecular cage of **24**. Notice the orientation of the toluene guest *vis-a-vis* the dinitrophenyl and the dimethoxyphenyl rings of the host. The water molecule is also shown.

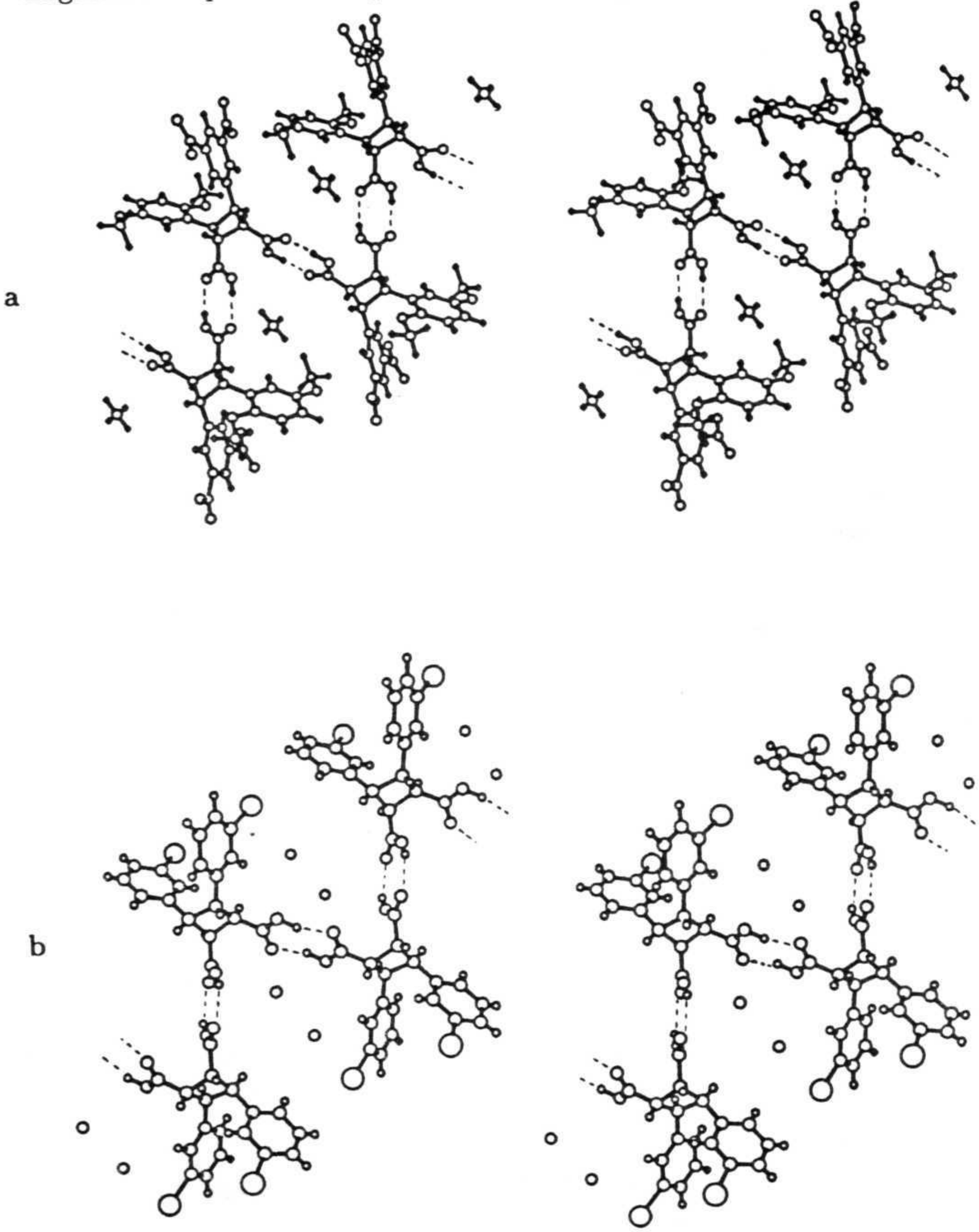


Figure 6. Stereoviews of the divergent supermolecules formed by the zig-zag hydrogen bonded chains of carboxy dimers in some cyclobutane-1,2- dicarboxylic acids: (**a**) a disordered water molecule in the cavity of **24**; (**b**) two disordered water molecules (H atoms not shown) in the cavity of **26** (or **27**).

the presence of hetero-atom containing host molecules.[25]

The crystal structure of **24** is also interesting because it has two distinct supramolecular cages, polar and apolar. The polar cavity is occupied by water molecules (Figure 6a) and the apolar cavity by toluene molecules (Figure 5). The polar cavity is induced by the mutual recognition of carboxyl groups which form hydrogen bonded dimers and the apolar cavity is induced by the guest. The supramolecular assembly of carboxyl dimers is divergent forming a zig-zag hydrogen bonded chain as shown in Figure 6a. The apolar convergently assembled supermolecule is formed when two molecules of **24** encapsulate the toluene molecule (Figure 5). The divergent polar supramolecular assembly and the clathration of water (acetic acid) molecules in it is also found in two other truxinic acids **26** and **27** (Figure 6b). But these two truxinic acids do not have a convergent supramolecular cage. The phenyl rings in diacids **26** and **27** are close-packed with a phenyl ring protruding into the cleft of the adjacent molecule without forming a cage (Figure 7). On the other hand, the guest molecules in **24** occupy the clefts between two phenyl rings and hold two **24** molecules together. This may be termed a guest-induced supramolecular cage. Another example of this type of guest induced cavity is the 6:1 complex of 1,3-cyclohexanedione (mono enol form) and benzene, where the benzene molecule is surrounded by six hydrogen bonded molecules of the 1,3-diketone (Figure 8).[26] It should be mentioned here that when 1,3-cyclohexanedione is recrystallised in the absence of benzene, a divergent linear hydrogen bonded chain is formed (still the mono enol form). These examples highlight the fact that one can design convergent supermolecules (or supramolecular cages) of different sizes by varying the host to guest molecular ratio based on the geometrical and directional properties of the host and guest.

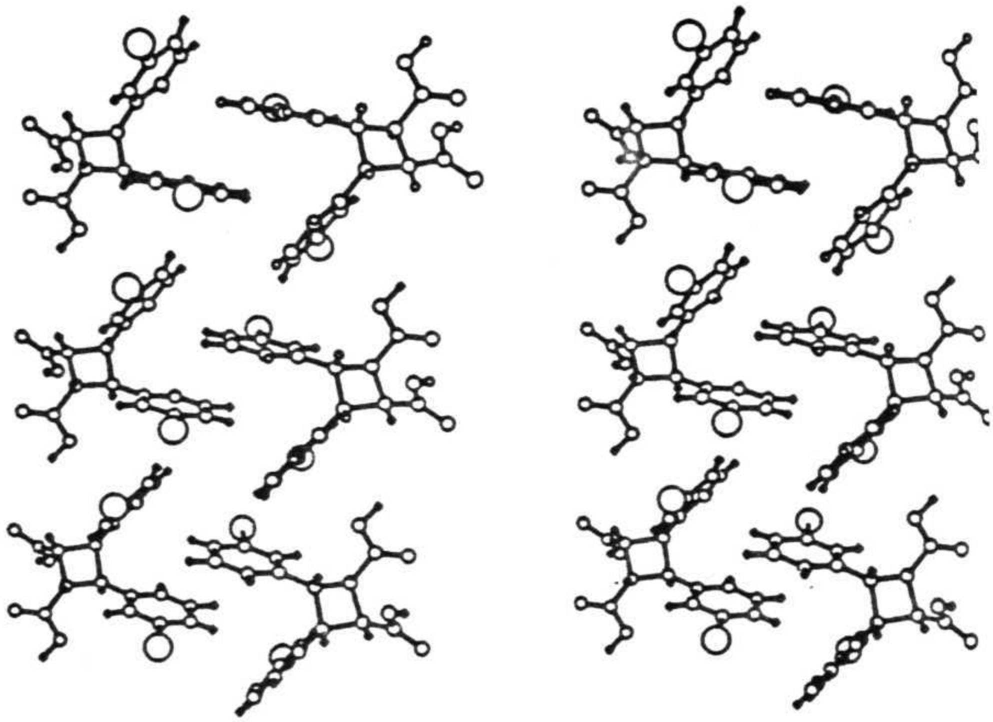


Figure 7. Stereoview of the crystal structure of diacid **26** (or **27**) with p rings protruding into the cavity formed by adjacent molecules. Compar with Figure 5.

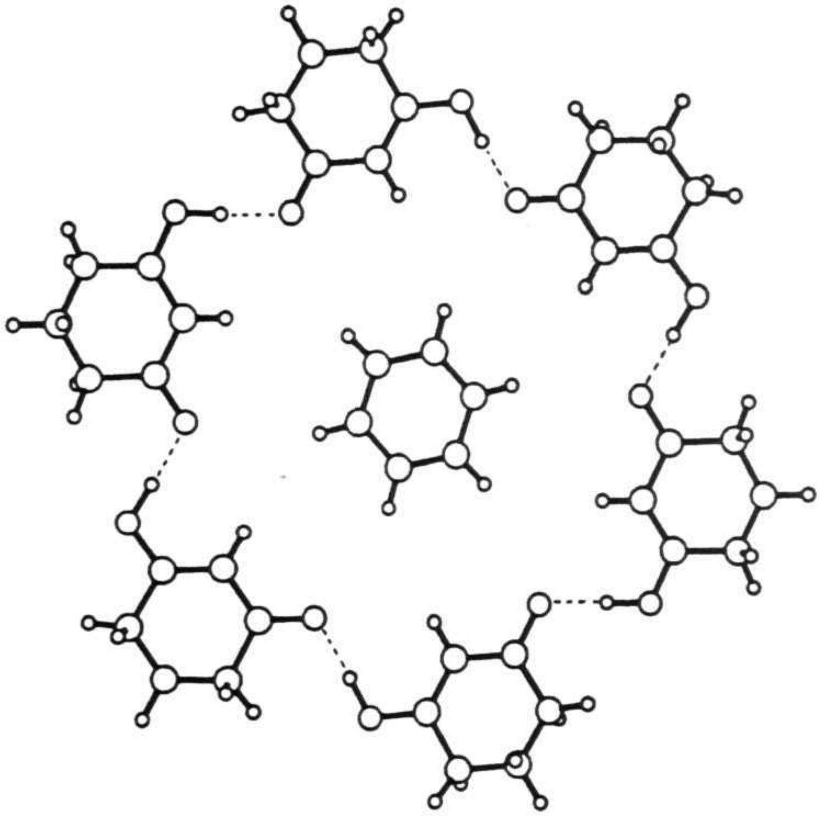


Figure 8. Benzene guest molecule in the cavity of the hydrogen bonded hexamer of the mono enol form of 1,3-cyclohexanedione. O-H...O Hydrogen bonds are shown as dashed lines.

4.2.3.2 A General Study on Binding Properties of Toluene, Benzene and Water

The observations made in the crystal structure of **24** prompted a further study, to search the CSD for other solvates of benzene, toluene and water, to investigate more thoroughly the nature of their interaction with the host and especially to ascertain the importance of these solvents as space fillers in the host network. Benzene and toluene solvates, retrieved from the CSD, may also provide an opportunity to estimate the importance of electrostatic and van der Waals forces in crystal packing in general.[27] The easiest way of approximating the significance of van der Waals interactions in such solvates is to distinguish the hosts as aromatic and non-aromatic, because non-aromatic clathrates of benzene and toluene can only be stabilised by van der Waals interactions. Of a total of 31 toluene clathrates with $R < 0.10$, toluene is clathrated by 26 aromatic and 5 non-aromatic compounds, while of a total of 177 benzene clathrates with $R < 0.10$ benzene is clathrated by 132 aromatic and 45 non-aromatic compounds. The higher percentage of non-aromatic clathrates for benzene (34%) as compared to toluene (19%), suggests that the more symmetrical and non-polar molecule is more suited to a space-filling role. We also examined the stacking interactions in these two groups of solvates; often the guest molecules are found to stack with electron-withdrawing aromatic rings rather than with electron-donating aromatic rings. In the latter case, T-shaped geometries and herringbone interactions (C-H...π) seem to be preferred. The kind of selective binding of the toluene molecule observed in **24** is also observed in the benzene solvates of 1-(mesityl-2-sulfonyl)-3-nitro- 1,2,4-triazole (BEZBEN)[28] and bis(N-pentaflurophenyl)-tetraphenyl- cyclodisilazane (DUZLIT)[29](Figure 9).

A total of 2437 organic hydrates was retrieved from the CSD; these hits were further classified as neutral two residue compounds (1479), neutral three residue compounds (151), neutral four residue compounds (2) and

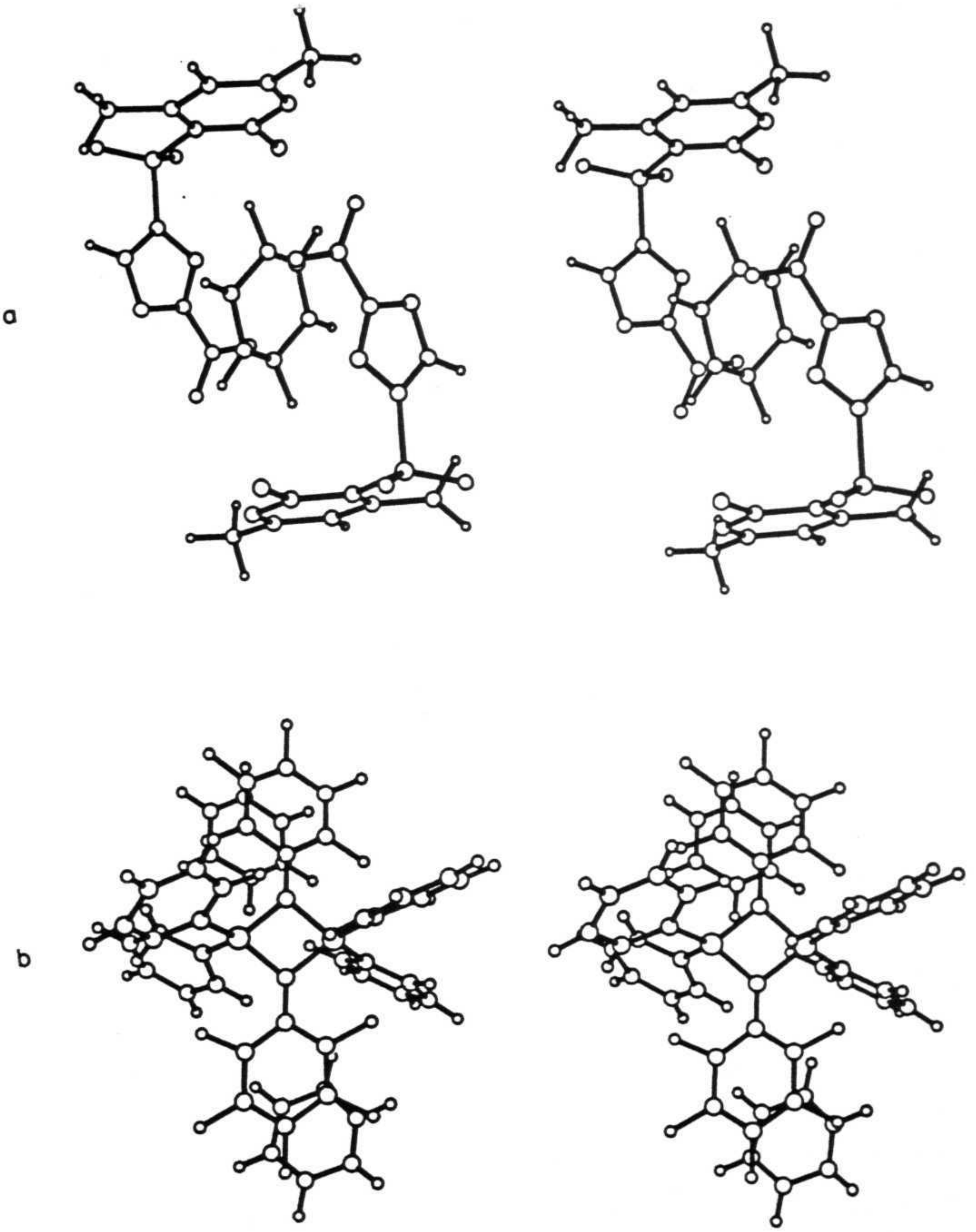
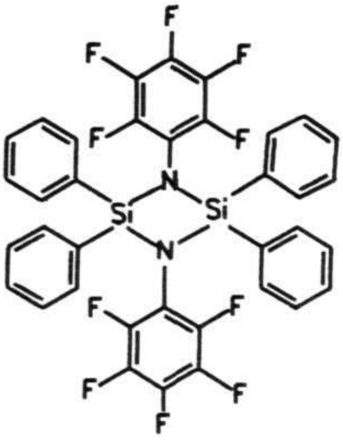
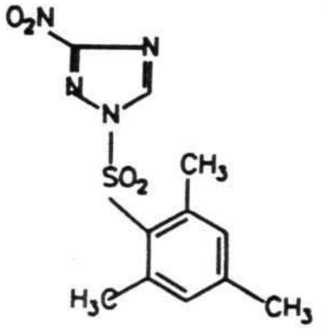


Figure 9. Benzene solvates satisfying stacking and herringbone interactions with the host molecules: (**a**) BEZBEN ; (**b**) DUZLIT. Compare the similarity of (**a**) with Figure 5.



DUZLIT



BEZBEN

crystals containing charged molecules (805). Of these, we considered possible hydrogen bonding in the neutral two and three residue compounds. It is interesting to note here that water is the most favoured choice for the third residue in three residue neutral organic compounds. Of the 176 neutral three residue compounds in the CSD, as many as 151 compounds contain water as one of the residues, i.e, there are only 25 neutral three residue compounds that do not contain water. What is more significant is that amongst these 151 hydrates, the water molecule is involved in hydrogen bonding in only 46% of the cases. In contrast, for the 1479 two residue hydrates, water is involved in hydrogen bonding in 66% of the cases. There is no evidence of hydrogen bonding in the remaining compounds even when the $O_w ... (N, O)$ threshold distance was increased from 3.20Åto 3.50Å. Additionally, the percentage of hydrogen bonds in both cases were evaluated by imposing more rigorous restrictions such as eliminating all disordered molecules and reducing the R-factor to be below 0.075. Even so, the trends are similar but the percentage of hydrogen bonded compounds increased as expected for two residue compounds to 72%(786) and for 3 residue compounds to 58%(85). These results indicate that the highly polar water molecule can also act as a very good space filler often being disordered when fulfilling this role. To provide crystal stability, it may occupy polar or apolar cavities without necessarily participating in strong hydrogen bonding. Water may act as a space filler because its small size allows it to fit easily into small voids created during the crystallisation process.[30] Solvent inclusion may therefore be one of the factors that affects the crystallisation process. It is pertinent to record here that water was not added to the recrystallising solution of **24** in 5:1 MeOH-toluene but on the other hand, no attempt was made to carry out the recrystallisation under strictly anhydrous conditions. It is reasonable to assume that certain molecules cannot crystallise if their shape is awkward and/or the intermolecular interactions are incompatible with close packing. Crystallisation of such compounds may be facilitated by the presence of a particular solvent which is capable of being clathrated effectively.

4.3 Conclusions

The solid state reaction reported here reveals that the principles of crystal engineering may be used to synthesise new compounds such as **24** for a study of molecular and supramolecular properties. The CSD study on 1,2-diphenylethanes provides unambiguous crystallographic evidence for the presence of TBC.[6] The selective binding of an aromatic compound in the cavity formed by four phenyl groups (from two molecules) reveals an interesting feature in the binding process, namely that by varying substituents on the phenyl groups one can fine-tune the orientation of the guests precisely. This example also highlights the superior selective binding features in the solid state where non-directional, van der Waals and directional $\pi...\pi$ and C-H...π interactions are perfectly matched.[2,31,32] Further, the concept of guest-induced supramolecular cages may open up a new perception in host-guest complexes. The unusual absence of hydrogen bonding of the included water molecules in the **24** crystal is an observation which seems to contradict chemical intuition especially in compounds where there is a lot of scope for hydrogen bonding. The CSD survey of hydrogen bonding in hydrates shows that the highly polar water molecule is not only good at forming hydrogen bonds but is also a good space filler, in other words it provides thermodynamic stability to the crystal without invoking its potential hydrogen bonding functions. The CSD search also hints that the symmetrical, non-polar benzene molecule is more suited for a space-filling role rather than the toluene molecule. Finally it is suggested that the 'correct' solvent for crystallisation may be obtained by optimising clathration effects in certain cases.

4.4 Experimental Section

4.4.1 Synthesis

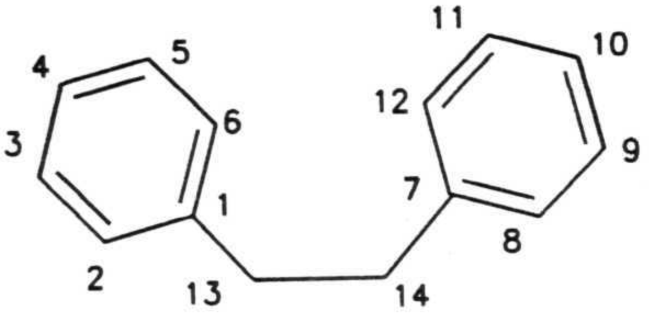
The 1:1 mixed crystals of **25**[5] (m.p. 158°C) were obtained from EtOH, or by simple solid state grinding of the constituent acids (see Experimental Section 2.4.1 for the preparation of 3,5-dinitrocinnamic acid). Powdered, crystalline complexes **6**, **7**, **8** and **25** were coated thinly between glass plates separately and were irradiated in sunlight at *ca.* 25-30°C. Complexes **7**[10] and **8** showed no reactivity at all even after irradiation for two to three months. Complexes **6** and **25**, however, yielded the corresponding truxinic acids in *ca.* 60% yield after 5 days. Material obtained by grinding might just as easily have been used for these solid state reactions and there is no need to prepare single crystals of the complex by solution recrystallisation in order to carry out the solid state reaction. We irradiated both recrystallised and ground single crystals of complexes **6** and **25** and an intimately ground 1:1 physical mixture of the respective acids but the final products (i.e, the unsymmetrical β truxinic acids) were obtained in similar yields in either case. The reaction products were separated by column chromatography (silicagel, 3:2 hexane-EtOAc). The topochemical product obtained exclusively from **6** is $3-(3',5'$-dinitrophenyl)-4-(2',5'-dimethoxyphenyl)cyclobutane-1,2-dicarboxylic acid,

$C_{20}H_{18}N_2O_{10}$, **24**. NMR($^2H_6$-acetone): δ 3.6(s,3H); 3.7(s,3H); 4.2, 4.7(m, 4H); 6.6(m, 2H), 6.9(d,1H). 8.35(d, 2H), 8.65(dd, 1H), MS: (m/z,%) 446 M^+ (2%), ($M-H_2O$), 428(30%), ($M-NO_2$), 400(25%), ($C_{11}H_{12}O_4$), 208(100%), ($C_{11}H_{12}O_4-H_2O$), 190(40%), ($C_{11}H_{12}O_4$-OMe) 177(50%). Crystals suitable for X-Ray analysis were obtained by slow evaporation from a solution of **24** in 5:1 MeOH-toluene. These crystals ($210^{\circ}C$) are deep yellow and have a composition $(C_{20}H_{18}N_2O_{10}):(C_7H_8)_{0.5}:(H_2O)_{0.5}$.

4.4.2 X-Ray Crystallography

The data for diacid **24** were collected by Dr. H.L. Carrell, Fox Chase Cancer Center, Philadelphia. The structure of diacid **24** was solved by Direct Methods (SHELXS86)[33] and the refinement was carried out with the programme SHELX76.[34] The toluene and water molecules were found to be disordered about centres of inversion. All H atoms were located from difference Fourier maps except the hydrogen atoms in the toluene molecule. All non-H atoms were refined anisotropically and H atoms were refined isotropically barring the disordered H atoms in the toluene and water. All the relevant crystallographic information is given in Appendix C-1. The atomic coordinates and thermal parameters are given in Appendix C-2.

4.4.3 Database Studies



Scheme III

The CSD (version 5.01, 109861 entries)[9] was searched for 1,2-diphenyl ethane derivatives to study the C13-C14 bond elongation and for benzene, toluene and water inclusion compounds to examine the nature of solvent binding. Details of the questions framed for these two distinct problems are briefly discussed.

All 1,2-diphenylethanes (Scheme III) were retrieved from the CSD using the 3D graphics option (Table 2). The atoms C13 and C14 were specified to be tetrahedral. The commands NOLN (nolinks) and NOCY (nocyclic routes) were specified for the two phenyl rings so as to retain some chemical similarity and to preserve the rotational degrees of freedom around C13-C14, C1-C13 and C7-C14. Such commands would then exclude compounds such as the cyclophanes, 1,2-(dinaphthyl)ethane and so on. Screens -28, 35, 153, 85 and 89 were set to eliminate organometallic and disordered structures and also those entries containing no coordinates or where chemical and crystallographic connectivities are not matched. Entries where the R-factor is greater than 0.075 would also be excluded. All 1,2-diphenylcyclopropanes were identified and eliminated manually, because these were found to be structurally quite distinct from those compounds in which TBC was observed. The numbering scheme shown above and in Table 2 is used in the text to represent the specific bond lengths and torsion angles in all the diphenylethanes discussed irrespective of the numbering scheme used in the original crystallographic papers.

Solvates containing benzene, toluene and water were obtained using the screens -28, 153, 85, 88 to create a subsidiary IDX file which was then searched for further classification and subsequent tests. For calculating hydrogen bond distances in the hydrates, it was specified that the O_w...RR distance (RR=N, O; water O atom and O or N atom of the host compound) should be between 2.50Åand 3.20Å. This distance which is longer than the normal hydrogen bond distance of 2.80Åwas used in order that some weak hydrogen bonds would not be missed. Any compound that has at least one hydrogen bond (hit) that satisfies the above relaxed distance criterion was considered to display hydrogen bonding with the water molecule. While calculating the percentage of hydrogen bonds in these hydrates, only unique hits were considered; in other words, duplicate structures were excluded.

Table 2

Sample CSD question generated by the Graphics 3D option for 1,2-diphenylethane derivatives.

```
SCREEN -28 153 85 89 35
T1 *CONN
NFRAG 1
AT1 C 3
AT2 C 2
AT3 C 2
AT4 C 2
AT5 C 2
AT6 C 2
AT7 C 3
AT8 C 2
AT9 C 2
AT10 C 2
AT11 C 2
AT12 C 2
AT13 C T4
AT14 C T4
BO 1 2 5
BO 2 3 5
BO 3 4 5
BO 4 5 5
BO 5 6 5
BO 1 6 5
BO 7 8 5
BO 8 9 5
BO 9 10 5
BO 10 11 5
BO 11 12 5
BO 7 12 5
BO 1 13 1
BO 13 14 1
BO 7 14 1
NOCR 2 3 4 5 6 8 9 10 11 12
NOLN
GEOM
DEFINE TOR 1 13 14 7
SELECT TOR -45 45
DEFINE C-C 13 14
SELECT C-C 1.5 1.7
SETUP P1 1 2 3 4 5 6
SETUP P2 7 8 9 10 11 12
DEFINE P1P2 P1 P2
SCAT C-C P1-P2
NFRAG -99
END
QUEST T1
```

References

1. (a) G.M. Whitesides, *Angew.Chem.Int.Ed.Engl.*, 1990, **29**, 1209.
   (b) J. Yang, E. Fan, S.J. Geib and A.D. Hamilton, *J.Am.Chem.Soc.*, 1993, **115**, 5314.
   (c) P.R. Ashton, A.S. Reder, N. Spencer and J.F. Stoddart, *J.Am. Chem.Soc.*, 1993, **115**, 5286.
   (d) J. Rebek, *Angew.Chem.Int.Ed.Engl.*, 1990, **29**, 245.
   (e) S.B. Copp, S. Subramaninan and M.J. Zaworotko, *J.Am.Chem.Soc.*, 1992, **114,** 8719.
   (f) J.E. Kickham, S.J. Loeb and S.J. Murphy, *J.Am.Chem.Soc.*, 1993, **115**, 7031.
   (g). M.C. Etter, Z. Urbanczyk-Lipkowska, M. Zia-Ebrahimi and T.W. Panunto, *J.Am.Chem.Soc.*, 1990, **112**, 8415.
   (h) C.V.K. Sharma, K. Panneerselvam, T. Pilati and G.R. Desiraju, *J. Chem.Soc., Chem.Commun.*, 1992, 832.
   (i) K. Biradha, C.V.K. Sharma, K. Panneerselvam, L. Shimoni, H.L. Carrell, D.E. Zacharias and G.R. Desiraju, *J.Chem.Soc., Chem.Commun,* 1993, 1473.
2. G.R. Desiraju, *Crystal Engineering. The Design of Organic Solids,* Elsevier, Amsterdam, 1989.
3. (a) J.-M. Lehn, *Angew.Chem.Int.Ed.Engl.*, 1990, **28**, 1304.
   (b) J.L. Atwood, G.W. Orr, S.G. Bott and K.D. Robinson, *Angew.Chem.Int. Ed.Engl.*, 1993, **32**, 1093.
   (c) C.T. Seto and G.M. Whitesides, *J.Am.Chem.Soc.*, 1993, **115**, 905.
   (d) P.L. Anelli, P.R. Ashton, R. Ballardini, V. Balzani, M. Delgado, M.T. Gandolfi, T.T. Goodnow, A.E. Kaifer, D. Philp, M. Pietraszkiewicz, L. Prodi, M.V. Reddington, A.M.Z. Slawin, N. Spencer, J.F. Stoddart, C. Vicent and D.J. Williams, *J.Am.Chem. Soc.*, 1992, **114**, 193.

(e) D.S. Reddy, K. Panneerselvam, T. Pilati and G.R. Desiraju, *J.Chen Soc., Chem.Commun.*, 1993, 661.

(f) D.S. Reddy, B.S. Goud, K. Panneerselvam and G.R. Desiraju, *J.Che Soc., Chem.Commun.*, 1993, 663.

4. M.D. Cohen, G.M. Schmidt and F.I. Sonntag, *J.Chem.Soc.*, 1964, 2000
5. G.R. Desiraju and C.V.K. Sharma, *J.Chem.Soc., Chem.Commun.*, 1991, 1239.
6. G.M. Anstead, R. Srinivasan, C.S. Peterson, S.R. Wilson and J.A. Katzenellenbogen, *J.Am.Chem.Soc.*, 1991, **113**, 1378.
7. (a) T. Nakazawa and I. Murata, *J.Am.Chem.Soc.*, 1977, **99**, 1996.

   (b) M. Stobbe, S. Kirchmeyer, G. Adiwidjaja and A.de Meijere, *Angeu Chem.Int.Ed.Engl.*, 1986, **25**, 171.

   (c) P. Maslak and A. Chopra, *J.Am.Chem.Soc.*, 1993, **115**, 9331.
8. R. Hoffmann, *Acc.Chem.Res.*, 1971, **4**, 1.
9. F.H. Allen, J.E. Davies, J.J. Galloy, O. Johnson, O. Kennard, C.F. Macrae and D.G.Watson, *J.Chem.Inf.Comp.Sci.*, 1991, **31**, 204.
10. J.A.R.P. Sarma and G.R. Desiraju, *J.Chem.Soc., Perkin Trans. 2*, 1985, 1905.
11. H. Greiving, H. Hopf, P.G. Jones, P. Bubenitschek, J.P. Desvergne and H. Bouas-Laurent, *J.Chem.Soc., Chem.Commun.*, 1994 1075.
12. C.K. Johnson, (1976) ORTEPII. Report ORNL-5138. Oak Ridge National Laboratory, Tennessee, USA.
13. (a) F. Takusagawa, T.F. Koetzle, T. Srikrishnan and R. Parthasarathy *Acta.Crystallogr.*, 1979, **B35**, 1388.

    (b) M.C. Etter and T.W. Panunto, *J.Am.Chem.Soc.*, 1988, **110**, 5896.

    (c) T. Steiner and W. Saenger, *J.Am.Chem.Soc.*, 1992, **114**, 10146.

    (d) For a discussion of intramolecular C-H...N interactions see: R.L. Harlow, C. Li and M.P. Sammes, *J.Chem.Soc., Chem.Commun.*, 1984, 819.; C. Avendano, M. Espada, B. Ocana, S. Garcia-Granda, R.M. Diaz, B. Tejerina, F. Gomez-Beltran, A. Martinez and J. Elguero, *J. Chem.Soc., Perkin Trans* 2., 1993, 1547.

14. M.J.S. Dewar, E.G. Zoebisch, E.F. Healy and J.J.P. Stewart, *J. Am. Chem.Soc.*, 1985, **107**, 3902.
15. (a) D.A. Dougherty, H.B. Schlegel and K. Mislow, *Tetrahedron,* 1978, **34**, 1441.

    (b) X. Zhou, R. Liu and N.L. Allinger, *J.Am.Chem.Soc.* 1993, **115**, 7525. 16. (a) L.E. Sutton, Ed., *Chem.Soc., Spec.Publ.,* No.18, 1965, 514.

    (b) F.H. Allen, *Acta Crystallogr.*, 1981, **B37**, 890.
17. S. Kanao, S. Kashino and M.Haisa, *Acta Crystallogr.,* 1990, **C46**, 2439.
18. M. Ciechanowicz-Rutkowska, A. Konsur, S. Duraj, A. Kolasa, L.L. Ledibea, and W. Zankowska-Janinska, *Tetrahedron,* 1981, **37**, 3503.
19. P. Carr, J.L. Finney, P.F. Lindley and G.T. Detitta, *Acta. Crystallogr., Sect,* 1977, **B33**, 1022.
20. D.A. Ben-Efraim and R. Arad-Yellin, *Tetrahedron,* 1988, 44, 6175.
21. S. Caccamese and F.R. Fronczek, *Tetrahedron,* 1990, **46**, 7841.
22. However it seems that there is no conclusive evidence on the efficacy of either AM1 or MNDO approximation methods in evaluating TBC, as reference 6 of this paper states that while AM1 outperfoms MNDO for calculating TBC, the MNDO method seems to work well for many other cases. See for example, E. Osawa, K. Kanenmatsu in *Molecular Structure and Energetics* Vol 3., Studies of Organic Molecules J.F. Liebman, A.Greenberg, Eds; VCH; New York 1986, pp 329.

    23. (a) E. Weber, M. Hecker, I. Csoregh and M. Czugler, *J. Am. Chem. Soc,* 1989, **111**, 7866.

    (b) I. Csoregh, M. Czugler, K. Kalman, E. Weber and M. Hecker, *Bull. Chem.Soc.Jpn.,* 1991, **64**, 2539.
24. F.Nakanishi, H.Nakanishi, M.Tsuchiya and M.Hasegawa, *Bull.Chem.*

Soc.Jpn, 1976, **49**, 3096.

25. G.A. Jeffrey and W. Saenger, *'Hydrogen Bonding in Biological Structures'*, Springer-Verlag, Berlin, 1991.
26. M.C. Etter, Z. Urbanczyk-Lipkowska, D.A. Jahn and J.S. Frye, *J. Am.Chem.Soc*, 1986, **108**, 5871. For a discussion on co-operative hydrogen bonding and stabilisation energies of 1,3-diketone aggregates and their 6:1 benzene complex see, L. Turi and J.J. Dannenberg, *J.Phys. Chem.*, 1992, **96**, 5819.
27. (a) C.A. Hunter and J.K.M. Sanders, *J.Am.Chem.Soc.*, **1990**, 112, 5525. (b) S.B. Ferguson, E.M. Sanford, E.M. Seward and F. Diederich, *J.Am. Chem.Soc.*, 1991, **113**, 5410.

    (c) G. Klebe and F. Diederich, *Phil. Trans. R.Soc.Lond.* A., 1993, **335**, 37.
28. R. Kuroda, M.R. Sanderson, S. Neidle and C.B. Reese, *J.Chem. Soc., Perkin. Trans.* 2, 1982, 617.
29. P. Clare, D.B. Sowerby and I. Haidul, *J.Organomet.Chem.*, 1986, **310**, 161. 30. However it is possible that water is involved in weak intermolecular interactions such as C-H...O, O-H...π and O-H...C in compounds which do not show strong hydrogen bonding. See for example, M.A. Viswamitra, R. Radhakrishnan, J. Bandekar and G.R. Desiraju, *J. Am. Chem. Soc.*, 1993, **115**, 4868.
31. T. Suzuki, H. Fujii and T. Miyashi, *J.Org.Chem.*, 1992, **57**, 6744.
32. C.V.K. Sharma, K. Panneerselvam, T. Pilati and G.R. Desiraju, *J.Chem.Soc., Perkin Trans* 2, 1993, 2209.
33. G.M. Sheldrick, 'SHELX86', in *Crystallographic Computing 3*; G.M. Sheldrick, C.Kruger, R.Goddard, Eds; Oxford University Press: Oxford, U.K., 1985; pp 175-189
34. G.M. Sheldrick 'SHELX 76', Programme for Crystal Structure Determination, University of Cambridge, England, 1976.

Appendices

Table 2.1

Crystallographic Details for Complexes **1 – 9***

	1	**2**	**4**	**5**
Formula	$C_{16}H_{16}N_2O_6$	$C_{18}H_{18}N_2O_6$	$C_{18}H_{17}N_3O_8$	$C_{20}H_{19}$
Mol wt	334.31	358.35	403.36	429.39
Crystal system	Monoclinic	Triclinic	Triclinic	Triclini
Space group	$P2_1/c$	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$
a/Å	15.181(3)	7.389(2)	7.974(1)	8.422(4
b/Å	7.126(1)	9.470(2)	8.342(1)	15.854(
c/Å	14.258(3)	13.175(3)	15.045(1)	7.623(3
$\alpha/^o$	90	86.35(2)	85.32(1)	85.20(3
$\beta/^o$	93.81(2)	88.86(2)	85.95(1)	102.76(
$\gamma/^o$	90	67.84(2)	67.60(1)	91.73(3)
Cell vol, $Å^3$	1539.0	852.2	921.3	989.2
Z	4	2	2	2
F(000)	696	376	420	448
D_{calcd}, $g.cm^{-3}$	1.443	1.397	1.454	1.442
λ , Å	0.7107	0.7107	0.7107	0.7107
μ , cm^{-1}	0.70	0.99	0.74	.72
Crystal size, mm	.25 × .20 × .10	.2 × .1 × .2	.1 × .25 × .34	.4 × .5 ×
Diffractometer	P3	CAD4	P3	P3
Radiation	MoKα	MoKα	MoKα	MoKα
2θ range/^{o}	2-50	2-50	2-50	2-50
h	-17 to 17	-9 to 9	-9 to 9	-10 to 1
k	0 to 8	-12 to 12	-9 to 9	-20 to 2
l	0 to 16	0 to 16	0 to 17	0 to 9
Total reflctn	2139	3921	3234	4804
Non-zero reflctn	1438	1905	1725	2173
σ-level	3.0	3.0	3.0	3.0
R	0.038	0.048	0.040	0.050
R_w	0.038	0.048	0.041	0.053
Min e $Å^{-3}$	-0.18	-0.27	-0.21	-0.24
Max e $Å^{-3}$	0.11	0.17	0.17	0.32

* Crystal structure of complex **3** is not solved, crystal structure of compl
7 is reported elsewhere.

Table 2.1 (contd...)

	6	**8**	**9**
Formula	$C_{20}H_{18}N_2O_{10}$	$C_{20}H_{18}N_2O_{10}$	$C_{16}H_{15}N_3O_8$
Mol wt	446.38	446.38	377.32
Crystal system	Orthorhombic	Triclinic	Monoclinic
Space group	Pbca	P$\bar{1}$	P2$_1$/c
a/Å	16.859(10)	9.008(3)	14.442(2)
b/Å	17.277(10)	10.088(3)	6.969(3)
c/Å	13.993(6)	11.874(2)	16.952(2)
$\alpha/^o$	90	97.51(2)	90
$\beta/^o$	90	97.51(2)	99.58(1)
$\gamma/^o$	90	103.17(3)	90
Cell vol, Å^3	4075.8	1027.1	1682.4
Z	8	2	4
F(000)	1856	464	784
D$_{calcd}$, g.cm $^{-3}$	1.455	1.443	1.489
λ, Å	0.7107	0.7107	0.7107
μ , cm^{-1}	0.12	0.75	0.78
Crystal size, mm	.2 × .3 × .25	.13 × .23 × .35	.4 × .19 × .3
Diffractometer	Nicolet R3m	P3	P3
Radiation	MoKα	MoKα	MoKα
2θ range/^{o}	2-45	2-50	2-50
h	0 to 18	-10 to 10	-14 to 14
k	0 to 18	-12 to 12	0 to 9
l	0 to 15	0 to 14	0 to 17
Total reflctn	3144	3603	2781
Non-zero reflctn	852	1561	1635
σ -level	3.0	3.0	3.0
R	0.114	0.046	0.040
R$_w$	0.160	0.044	0.041
min e Å^{-3}	-0.38	-0.26	-0.15
max e Å^{-3}	0.40	0.16	0.17

Table 2.2

Fractional co-ordinates and equivalent thermal parameters for complex **1** (e.s.d's are in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
Molecule A				
C(1)	0.0751(2)	0.3233(3)	0.2108(2)	0.040(2)
C(2)	0.1564(2)	0.2476(4)	0.1928(2)	0.047(2)
C(3)	0.2238(2)	0.2424(4)	0.2626(2)	0.048(2)
C(4)	0.2081(2)	0.3146(4)	0.3492(2)	0.045(2)
C(5)	0.1277(2)	0.3869(4)	0.3699(2)	0.049(2)
C(6)	0.0610(2)	0.3904(4)	0.2998(2)	0.046(2)
C(7)	0.0037(2)	0.3328(4)	0.1346(2)	0.044(2)
N(1)	0.2812(2)	0.3153(4)	0.4229(2)	0.058(2)
O(1)	0.0184(2)	0.2616(3)	0.0560(2)	0.064(1)
O(2)	-0.0679(1)	0.4097(3)	0.1517(1)	0.057(1)
O(3)	0.3502(2)	0.2377(3)	0.4063(2)	0.077(2)
O(4)	0.2694(2)	0.3949(4)	0.4970(2)	0.082(2)
H(2)	0.164(2)	0.206(3)	0.137(2)	0.046(8)
H(3)	0.280(2)	0.189(4)	0.249(2)	0.063(8)
H(5)	0.120(2)	0.437(4)	0.433(2)	0.079(10)
H(6)	0.006(2)	0.437(3)	0.312(2)	0.046(7)
H(O1)	-0.026(4)	0.268(8)	0.016(5)	0.052(19)*
H(O2)	-0.107(4)	0.408(8)	0.109(4)	0.045(18)*
Molecule B				
C(1)	-0.2529(2)	0.3433(4)	-0.1343(2)	0.040(2)
C(2)	-0.3316(2)	0.4387(4)	-0.1249(2)	0.043(2)
C(3)	-0.3978(2)	0.4403(4)	-0.1949(2)	0.042(2)
C(4)	-0.3885(2)	0.3418(4)	-0.2795(2)	0.040(2)
C(5)	-0.3082(2)	0.2493(4)	-0.2897(2)	0.045(2)
C(6)	-0.2427(2)	0.2508(4)	-0.2189(2)	0.046(2)
C(7)	-0.1825(2)	0.3432(4)	-0.0600(2)	0.045(2)
C(8)	-0.5359(2)	0.4410(6)	-0.3391(3)	0.062(2)
C(9)	-0.4431(3)	0.2468(6)	-0.4376(2)	0.061(2)
N(1)	-0.4562(1)	0.3346(3)	-0.3479(2)	0.048(1)
O(1)	-0.1948(1)	0.4276(3)	0.0170(1)	0.061(1)
O(2)	-0.1107(2)	0.2597(3)	-0.0739(2)	0.067(2)

Table 2.2 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
Molecule B				
H(2)	-0.336(1)	0.510(3)	-0.069(2)	0.049(8)
H(3)	-0.450(2)	0.514(3)	-0.188(2)	0.052(8)
H(5)	-0.300(1)	0.185(3)	-0.343(2)	0.043(7)
H(6)	-0.190(2)	0.181(4)	-0.226(2)	0.058(8)
H(81)	-0.581(2)	0.407(4)	-0.388(2)	0.067(9)
H(82)	-0.523(2)	0.570(5)	-0.340(2)	0.079(12)
H(83)	-0.563(2)	0.404(4)	-0.278(2)	0.086(11)
H(91)	-0.502(2)	0.254(4)	-0.476(2)	0.066(9)
H(92)	-0.426(2)	0.111(6)	-0.429(2)	0.109(14)
H(93)	-0.398(2)	0.306(5)	-0.472(2)	0.091(12)
H(O1)	-0.149(4)	0.422(7)	0.058(4)	0.044(17)*
H(O2)	-0.071(5)	0.249(9)	-0.041(5)	0.063(23)

* Fractional occupancy 0.5

Table 2.3

Fractional co-ordinates and equivalent thermal parameters for complex 2 (e.s.d's are in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
Molecule A				
C(1)	0.2595(4)	-0.4272(3)	0.1920(2)	0.045(2)
C(2)	0.3433(4)	-0.5693(3)	0.1519(2)	0.050(2)
C(3)	0.3526(4)	-0.7003(3)	0.2081(2)	0.058(2)
C(4)	0.2779(4)	-0.6855(3)	0.3041(2)	0.056(2)
C(5)	0.1918(4)	-0.5467(4)	0.3463(2)	0.061(2)
C(6)	0.1825(4)	-0.4164(3)	0.2894(2)	0.061(2)
C(7)	0.2529(4)	-0.2876(3)	0.1320(2)	0.046(2)
N(1)	0.2887(4)	-0.8240(4)	0.3668(2)	0.082(2)
O(1)	0.3107(3)	-0.2963(2)	0.0412(1)	0.058(2)
O(2)	0.1880(3)	-0.1632(2)	0.1762(1)	0.067(1)
O(3)	0.3640(4)	-0.9475(3)	0.3282(2)	0.112(2)
O(4)	0.2253(4)	-0.8083(3)	0.4523(2)	0.117(2)
H(2)	0.396(3)	-0.572(3)	0.087(2)	0.05(1)
H(3)	0.415(4)	-0.805(3)	0.185(2)	0.09(1)

Table 2.3 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
H(5)	0.140(3)	-0.539(3)	0.411(2)	0.06(1)
H(6)	0.121(3)	-0.322(3)	0.313(2)	0.05(1)
H(02)	0.178(6)	-0.058(6)	0.128(4)	0.19(2)
Molecule B				
C(1)	0.2713(4)	0.3835(3)	-0.2111(2)	0.048(2)
C(2)	0.1983(4)	0.5240(3)	-0.1672(2)	0.053(2)
C(3)	0.1847(4)	0.6578(3)	-0.2195(2)	0.050(2)
C(4)	0.2452(3)	0.6583(3)	-0.3214(2)	0.044(2)
C(5)	0.3158(4)	0.5171(3)	-0.3656(2)	0.059(2)
C(6)	0.3290(4)	0.3846(3)	-0.3114(2)	0.053(2)
C(7)	0.2841(4)	0.2399(3)	-0.1565(2)	0.051(2)
C(8)	0.2209(4)	0.2250(4)	-0.0645(2)	0.059(2)
C(9)	0.2324(4)	0.0799(3)	-0.0138(2)	0.053(2)
C(10)	0.2788(7)	0.7923(4)	-0.4812(3)	0.073(2)
C(11)	0.1547(6)	0.9370(4)	-0.3281(3)	0.067(2)
N(1)	0.2379(3)	0.7907(2)	-0.3734(2)	0.052(1)
O(1)	0.1652(3)	0.0836(2)	0.0744(2)	0.077(1)
O(2)	0.3096(3)	-0.0441(2)	-0.0599(1)	0.064(1)
H(2)	0.154(3)	0.532(3)	-0.103(2)	0.06(1)
H(3)	0.132(3)	0.750(3)	-0.189(2)	0.04(1)
H(5)	0.355(3)	0.509(3)	-0.436(2)	0.07(1)
H(6)	0.386(3)	0.288(3)	-0.342(2)	0.06(1)
H(7)	0.351(4)	0.141(3)	-0.193(2)	0.07(1)
H(8)	0.157(4)	0.314(3)	-0.027(2)	0.08(1)
H(101)	0.407(5)	0.715(4)	-0.492(3)	0.11(1)
H(102)	0.186(5)	0.765(4)	-0.518(2)	0.11(1)
H(103)	0.276(5)	0.885(5)	-0.507(3)	0.13(2)
H(111)	0.222(5)	0.934(4)	-0.257(3)	0.14(1)
H(112)	0.017(5)	0.969(4)	-0.314(3)	0.12(2)
H(113)	0.176(5)	1.012(4)	-0.372(3)	0.11(1)
H(02)	0.309(5)	-0.142(5)	-0.026(3)	0.16(2)

Table 2.4

Fractional co-ordinates and equivalent thermal parameters for complex **4** (e.s.d's are in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
Molecule A				
C(1)	-0.3986(3)	0.6261(3)	-0.1311(2)	0.041(2)
C(2)	-0.4818(4)	0.6063(4)	-0.2053(2)	0.047(2)
C(3)	-0.5588(4)	0.7460(3)	-0.2652(2)	0.046(2)
C(4)	-0.5570(4)	0.9072(4)	-0.2544(2)	0.049(2)
C(5)	-0.4779(4)	0.9251(3)	-0.1798(2)	0.048(2)
C(6)	-0.3987(4)	0.7900(3)	-0.1183(2)	0.048(2)
C(7)	-0.3145(4)	0.4755(4)	-0.0696(2)	0.048(2)
C(8)	-0.2190(4)	0.4640(4)	-0.0003(2)	0.054(2)
C(9)	-0.1441(4)	0.3020(4)	0.0546(2)	0.052(2)
N(1)	-0.6456(3)	0.7223(4)	-0.3434(2)	0.063(2)
N(2)	-0.4816(4)	1.0982(3)	-0.1648(2)	0.071(2)
O(1)	-0.6520(4)	0.5818(3)	-0.3512(2)	0.098(2)
O(2)	-0.7060(4)	0.8457(3)	-0.3969(2)	0.092(2)
O(3)	-0.4401(4)	1.1227(3)	-0.0925(2)	0.113(2)
O(4)	-0.5272(4)	1.2097(3)	-0.2256(2)	0.102(2)
O(5)	-0.0500(3)	0.3016(3)	0.1199(2)	0.084(2)
O(6)	-0.1755(3)	0.1721(3)	0.0378(1)	0.064(1)
H(2)	-0.484(4)	0.499(4)	-0.214(2)	0.06(1)
H(4)	-0.611(4)	0.999(4)	-0.297(2)	0.08(1)
H(6)	-0.346(4)	0.810(3)	-0.067(2)	0.06(1)
H(7)	-0.331(3)	0.380(4)	-0.083(2)	0.05(1)
H(8)	-0.199(4)	0.559(4)	0.018(2)	0.07(1)
H(O5)	-0.009(7)	0.168(7)	0.167(3)	0.19(2)
Molecule B				
C(1)	0.0586(4)	-0.2631(3)	0.2730(2)	0.049(2)
C(2)	0.1505(4)	-0.2720(4)	0.3498(2)	0.061(2)
C(3)	0.2007(4)	-0.4167(4)	0.4078(2)	0.059(2)
C(4)	0.1616(4)	-0.5618(3)	0.3911(2)	0.047(2)
C(5)	0.0674(4)	-0.5514(4)	0.3144(2)	0.051(2)
C(6)	0.0171(4)	-0.4050(4)	0.2574(2)	0.049(2)
C(7)	0.0102(4)	-0.1105(4)	0.2111(2)	0.051(2)

Table 2.4 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
Molecule B				
C(8)	0.1731(8)	-0.8559(5)	0.4289(3)	0.076(3)
C(9)	0.3068(7)	-0.7189(6)	0.5281(3)	0.072(2)
N(1)	0.2169(3)	-0.7090(3)	0.4463(2)	0.061(1)
O(1)	-0.0764(3)	-0.1106(3)	0.1422(1)	0.061(1)
O(2)	0.0519(3)	0.0170(3)	0.2253(1)	0.077(1)
H(2)	0.182(4)	-0.174(4)	0.363(2)	0.07(1)
H(3)	0.264(4)	-0.415(4)	0.457(2)	0.07(1)
H(5)	0.032(3)	-0.645(3)	0.300(2)	0.05(1)
H(6)	-0.043(4)	-0.398(3)	0.208(2)	0.05(1)
H(81)	0.227(5)	-0.952(6)	0.468(3)	0.13(2)
H(82)	0.218(5)	-0.899(5)	0.372(3)	0.11(2)
H(83)	0.047(6)	-0.827(5)	0.435(3)	0.13(2)
H(91)	0.336(6)	-0.832(6)	0.554(3)	0.15(2)
H(92)	0.240(7)	-0.659(6)	0.573(3)	0.15(2)
H(93)	0.413(6)	-0.687(5)	0.519(3)	0.13(2)
H(O1)	-0.118(6)	0.012(6)	0.094(3)	0.15(2)

Table 2.5

Fractional co-ordinates and equivalent thermal parameters for complex 5 (e.s.d's are in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
Molecule A				
C(1)	-0.4721(3)	-0.2720(2)	0.0133(4)	0.037(2)
C(2)	-0.3087(4)	-0.2834(2)	0.0128(4)	0.040(2)
C(3)	-0.1971(4)	-0.2214(2)	0.0759(4)	0.039(2)
C(4)	-0.2381(4)	-0.1484(2)	0.1383(4)	0.042(2)
C(5)	-0.3993(4)	-0.1379(2)	0.1343(4)	0.039(2)
C(6)	-0.5166(3)	-0.1981(2)	0.0753(4)	0.039(2)
C(7)	-0.6018(3)	-0.3327(2)	-0.0512(4)	0.040(2)
C(8)	-0.5957(4)	-0.4041(2)	-0.1259(4)	0.044(2)
C(9)	-0.7474(4)	-0.4522(2)	-0.1865(5)	0.049(2)

Table 2.5 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
N(1)	-0.0244(3)	-0.2334(2)	0.0745(4)	0.052(2)
N(2)	-0.4500(4)	-0.0592(2)	0.1948(4)	0.054(2)
O(1)	0.0108(3)	-0.2943(2)	0.0044(4)	0.071(2)
O(2)	0.0744(3)	-0.1810(2)	0.1423(4)	0.076(2)
O(3)	-0.3445(3)	-0.0089(2)	0.2572(4)	0.080(2)
O(4)	-0.5943(3)	-0.0479(2)	0.1790(4)	0.082(2)
O(5)	-0.7372(3)	-0.5251(1)	-0.2429(3)	0.062(2)
O(6)	-0.8793(3)	-0.4192(2)	-0.1881(4)	0.086(2)
H(2)	-0.268(4)	-0.331(2)	-0.020(4)	0.04(1)
H(4)	-0.164(4)	-0.108(2)	0.182(4)	0.05(1)
H(6)	-0.624(3)	-0.192(2)	0.083(4)	0.03(1)
H(7)	-0.705(3)	-0.318(2)	-0.039(3)	0.03(1)
H(8)	-0.503(4)	-0.428(2)	-0.141(4)	0.05(1)
H(O5)	-0.854(8)	-0.562(4)	-0.271(8)	0.21(2)
Molecule B				
C(1)	0.5098(4)	0.2731(2)	0.4979(4)	0.043(2)
C(2)	0.3574(4)	0.3058(2)	0.4926(4)	0.047(2)
C(3)	0.2159(4)	0.2607(2)	0.4363(5)	0.049(2)
C(4)	0.2208(4)	0.1790(2)	0.3802(4)	0.042(2)
C(5)	0.3736(4)	0.1452(2)	0.3858(4)	0.044(2)
C(6)	0.5127(4)	0.1916(2)	0.4427(4)	0.046(3)
C(7)	0.6619(4)	0.3190(2)	0.5558(4)	0.050(2)
C(8)	0.6801(4)	0.3937(2)	0.6217(5)	0.056(2)
C(9)	0.8402(5)	0.4356(2)	0.6722(5)	0.054(2)
C(10)	-0.0753(4)	0.1629(2)	0.3437(6)	0.069(2)
C(11)	0.0854(4)	0.0473(2)	0.2729(6)	0.075(2)
N(1)	0.0780(3)	0.1340(2)	0.3192(4)	0.061(2)
O(1)	0.8382(3)	0.5062(2)	0.7392(4)	0.087(2)
O(2)	0.9675(3)	0.4027(2)	0.6493(4)	0.068(2)

Table 2.5 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
Molecule B				
H(2)	0.344(4)	0.359(2)	0.534(4)	0.06(1)
H(3)	0.119(4)	0.285(2)	0.440(4)	0.05(1)
H(5)	0.380(4)	0.088(2)	0.350(4)	0.07(1)
H(6)	0.617(4)	0.165(2)	0.454(4)	0.06(1)
H(7)	0.770(5)	0.294(2)	0.559(5)	0.08(1)
H(8)	0.584(4)	0.425(2)	0.645(5)	0.07(1)
H(101)	-0.077(6)	0.158(3)	0.497(7)	0.16(2)
H(102)	-0.089(5)	0.216(2)	0.294(5)	0.08(1)
H(103)	-0.154(5)	0.129(3)	0.301(5)	0.09(1)
H(111)	0.148(5)	0.044(3)	0.192(6)	0.09(2)
H(112)	-0.008(6)	0.028(3)	0.240(6)	0.10(2)
H(113)	0.146(8)	0.007(4)	0.400(8)	0.18(3)
H(O1)	0.931(7)	0.537(4)	0.767(7)	0.19(2)

Table 2.6

Fractional co-ordinates and equivalent thermal parameters for complex **6** (e.s.d's are in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
Molecule A				
C(1)*	0.6894(5)	-0.2847(7)	0.2048(8)	0.049(6)
C(2)*	0.6536(5)	-0.3570(7)	0.1940(8)	0.039(5)
C(3)*	0.6966(5)	-0.4242(7)	0.2133(8)	0.052(6)
C(4)*	0.7752(5)	-0.4192(7)	0.2434(8)	0.034(5)
C(5)*	0.8111(5)	-0.3469(7)	0.2542(8)	0.049(6)
C(6)*	0.7681(5)	-0.2797(7)	0.2349(8)	0.056(6)
C(7)*	0.6527(14)	-0.2008(13)	0.1888(16)	0.089(8)
C(8)*	0.5886(14)	-0.1979(13)	0.1718(16)	0.097(8)
C(9)*	0.5518(13)	-0.1090(12)	0.1535(17)	0.066(8)

Table 2.6 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
N(1)	0.6616(12)	-0.4993(10)	0.2020(13)	0.062(13)
N(2)	0.8939(8)	-0.3385(9)	0.2827(11)	0.036(12)
O(1)	0.4816(8)	-0.1152(7)	0.1334(10)	0.077(10)
O(2)	0.5920(8)	-0.0496(8)	0.1549(11)	0.037(10)
O(3)	0.5919(9)	-0.4994(8)	0.1726(11)	0.076(12)
O(4)	0.6993(8)	-0.5568(9)	0.2230(10)	0.067(11)
O(5)	0.9262(7)	-0.3978(7)	0.3141(10)	0.068(10)
O(6)	0.9258(9)	-0.2770(7)	0.2744(15)	0.135(15)
H(2)*	0.5994(5)	-0.3604(7)	0.1733(8)	–
H(4)*	0.8048(5)	-0.4654(7)	0.2567(8)	–
H(6)*	0.7928(5)	-0.2299(7)	0.2424(8)	–
H(7)*	0.6847(14)	-0.1550(13)	0.1935(16)	–
H(8)*	0.5561(14)	-0.2435(13)	0.1679(16)	–
Molecule B				
C(1)*	0.3016(5)	0.2426(7)	0.0434(8)	0.041(5)
C(2)*	0.3421(5)	0.3121(7)	0.0573(8)	0.035(5)
C(3)*	0.3025(5)	0.3824(7)	0.0463(8)	0.059(6)
C(4)*	0.2223(5)	0.3832(7)	0.0215(8)	0.057(6)
C(5)*	0.1819(5)	0.3137(7)	0.0076(8)	0.060(6)
C(6)*	0.2215(5)	0.2434(7)	0.0186(8)	0.080(7)
C(7)*	0.3438(11)	0.1670(10)	0.0581(13)	0.051(6)
C(8)*	0.4188(11)	0.1578(10)	0.0799(13)	0.051(6)
C(9)*	0.4550(10)	0.0822(11)	0.0947(13)	0.030(5)
C(10)	0.1037(11)	0.1784(15)	-0.0361(19)	0.065(20)
C(11)	0.4239(15)	0.4517(17)	0.0702(22)	0.150(28)
O(1)	0.4164(7)	0.0196(7)	0.0962(9)	0.049(8)
O(2)	0.5325(7)	0.0832(7)	0.1088(10)	0.056(9)
O(3)	0.1879(7)	0.1751(7)	0.0081(11)	0.074(10)
O(4)	0.3381(9)	0.4556(7)	0.0510(10)	0.098(12)

Table 2.6 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
Molecule B				
H(2)*	0.3973(5)	0.3116(7)	0.0744(8)	–
H(4)*	0.1951(5)	0.4316(7)	0.0139(8)	–
H(5)*	0.1267(5)	0.3142(7)	-0.0095(8)	–
H(7)*	0.3127(11)	0.1208(10)	0.0508(13)	–
H(8)*	0.4514(11)	0.2030(10)	0.0866(13)	–
H(101)*	0.0900(11)	0.1565(14)	-0.0970(19)	–
H(102)*	0.1041(11)	0.2338(14)	-0.0409(19)	–
H(103)*	0.0653(11)	0.1628(14)	0.0107(19)	–
H(111)*	0.4410(15)	0.5046(17)	0.0729(22)	–
H(112)*	0.4522(15)	0.4252(17)	0.0203(22)	–
H(113)*	0.4345(15)	0.4269(17)	0.1303(22)	–

* fixed geometrically and refined isotropically

Table 2.7

Fractional co-ordinates and equivalent thermal parameters for complex **8** (e.s.d's are in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
Molecule A				
C(1)	-0.1969(5)	0.2783(4)	0.6531(3)	0.057(3)
C(2)	-0.2700(5)	0.3748(4)	0.6991(3)	0.052(3)
C(3)	-0.3172(5)	0.3774(5)	0.8056(4)	0.058(3)
C(4)	-0.2927(5)	0.2741(4)	0.8662(3)	0.059(3)
C(5)	-0.2206(6)	0.1774(5)	0.8264(4)	0.080(4)
C(6)	-0.1731(6)	0.1810(5)	0.7228(4)	0.083(4)
C(7)	-0.1415(6)	0.2766(5)	0.5424(4)	0.076(3)
C(8)	-0.0742(6)	0.1891(5)	0.4945(4)	0.065(3)
C(9)	-0.0251(5)	0.1970(5)	0.3837(4)	0.073(3)
N(1)	-0.3076(5)	0.4821(4)	0.6331(4)	0.089(3)
N(2)	-0.3486(5)	0.2719(5)	0.9766(3)	0.080(4)
O(11)*	-0.3422(8)	0.4475(7)	0.5264(5)	0.097(5)
O(12)@	-0.2054(17)	0.5221(11)	0.5689(11)	0.114(10)
O(2)	-0.3449(5)	0.5742(4)	0.6813(3)	0.137(3)

Table 2.7 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
Molecule A				
O(3)	-0.3405(5)	0.1739(5)	1.0242(3)	0.134(3)
O(4)	-0.4004(5)	0.3648(4)	1.0149(3)	0.116(3)
O(5)	0.0483(4)	0.1100(3)	0.3472(3)	0.078(2)
O(6)	-0.0513(5)	0.2859(4)	0.3281(3)	0.148(3)
H(3)	-0.371(5)	0.444(4)	0.838(4)	0.09(2)
H(5)	-0.218(5)	0.106(5)	0.875(4)	0.12(2)
H(6)	-0.125(5)	0.115(4)	0.697(3)	0.07(1)
H(7)	-0.165(7)	0.336(6)	0.502(5)	0.15(3)
H(8)	-0.065(5)	0.116(4)	0.525(4)	0.08(1)
H(O5)	0.081(7)	0.125(6)	0.255(6)	0.16(2)
Molecule B				
C(1)	0.2778(4)	0.1540(4)	-0.1837(3)	0.050(3)
C(2)	0.2683(5)	0.2511(4)	-0.2574(4)	0.054(3)
C(3)	0.3205(5)	0.2368(5)	-0.3616(4)	0.059(3)
C(4)	0.3836(5)	0.1295(4)	-0.3943(4)	0.059(3)
C(5)	0.3981(5)	0.0337(4)	-0.3213(3)	0.057(3)
C(6)	0.3440(5)	0.0457(4)	-0.2193(4)	0.056(3)
C(7)	0.2224(5)	0.1568(4)	-0.0738(4)	0.057(3)
C(8)	0.1548(6)	0.2419(5)	-0.0197(4)	0.069(3)
C(9)	0.1021(5)	0.2230(5)	0.0892(4)	0.064(3)
C(10)	0.2262(9)	0.4732(6)	-0.2763(5)	0.086(4)
C(11)	0.4851(9)	-0.1669(7)	-0.2871(6)	0.092(5)
O(1)	0.0311(5)	0.3120(4)	0.1270(3)	0.108(3)
O(2)	0.1240(4)	0.1283(3)	0.1415(3)	0.080(2)
O(3)	0.2054(4)	0.3564(3)	-0.2196(2)	0.081(2)
O(4)	0.4662(4)	-0.0673(3)	-0.3606(2)	0.079(2)
H(3)	0.313(4)	0.300(4)	-0.406(3)	0.06(1)
H(4)	0.423(4)	0.117(4)	-0.467(3)	0.06(1)
H(6)	0.345(4)	-0.017(4)	-0.174(3)	0.05(1)
H(7)	0.236(4)	0.085(3)	-0.039(3)	0.05(1)

Table 2.7 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
Molecule B				
H(3)	0.313(4)	0.300(4)	-0.406(3)	0.06(1)
H(4)	0.423(4)	0.117(4)	-0.467(3)	0.06(1)
H(6)	0.345(4)	-0.017(4)	-0.174(3)	0.05(1)
H(7)	0.236(4)	0.085(3)	-0.039(3)	0.05(1)
H(8)	0.131(4)	0.311(4)	-0.047(3)	0.06(1)
H(101)	0.344(7)	0.511(5)	-0.278(4)	0.13(2)
H(102)	0.171(6)	0.450(5)	-0.364(5)	0.12(2)
H(103)	0.183(4)	0.534(4)	-0.228(3)	0.07(1)
H(111)	0.534(4)	-0.224(4)	-0.336(3)	0.08(1)
H(112)	0.548(6)	-0.121(5)	-0.213(4)	0.10(2)
H(113)	0.381(6)	-0.215(5)	-0.272(4)	0.11(2)
H(O1)	0.002(6)	0.302(6)	0.196(5)	0.14(2)

* occupancy 0.65 @ occupancy 0.35

Table 2.8

Fractional co-ordinates and equivalent thermal parameters for complex **9** (e.s.d's are in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
Molecule A				
C(1)	0.1946(2)	-0.1438(4)	-0.0720(2)	0.041(2)
C(2)	0.2795(2)	-0.1618(4)	-0.0205(2)	0.047(2)
C(3)	0.3575(2)	-0.2146(4)	-0.0514(2)	0.049(2)
C(4)	0.3556(2)	-0.2513(4)	-0.1313(2)	0.050(2)
C(5)	0.2705(2)	-0.2346(4)	-0.1805(2)	0.045(2)
C(6)	0.1902(2)	-0.1823(4)	-0.1525(2)	0.043(2)
C(7)	0.1091(2)	-0.0832(4)	-0.0408(2)	0.043(2)
N(1)	0.4477(2)	-0.2348(5)	0.0025(2)	0.080(2)
N(2)	0.2661(2)	-0.2757(4)	-0.2662(2)	0.060(2)
O(1)	0.4498(2)	-0.2149(7)	0.0722(2)	0.148(3)
O(2)	0.5166(2)	-0.2722(5)	-0.0254(2)	0.125(2)
O(3)	0.1909(2)	-0.2544(4)	-0.3098(1)	0.086(2)
O(4)	0.3373(2)	-0.3298(4)	-0.2889(1)	0.085(2)

Table 2.8 (contd...)

Atom	x/a	y/b	z/c	U_{eq}
Molecule A				
O(5)	0.1192(1)	-0.0207(3)	0.0296(1)	0.059(2)
O(6)	0.0315(2)	-0.0951(3)	-0.0871(1)	0.061(1)
H(2)	0.283(2)	-0.137(4)	0.034(2)	0.05(1)
H(4)	0.411(2)	-0.288(4)	-0.151(2)	0.05(1)
H(6)	0.135(2)	-0.167(4)	-0.189(2)	0.05(1)
H(O5)*	0.067(6)	-0.024(13)	0.060(5)	0.11(3)
H(O6)*	-0.021(7)	-0.072(14)	-0.068(5)	0.11(3)
Molecule B				
C(1)	0.1414(2)	0.3473(4)	-0.1274(2)	0.044(2)
C(2)	0.2374(2)	0.3262(4)	-0.1011(2)	0.043(2)
C(3)	0.2967(2)	0.2704(4)	-0.1517(2)	0.042(2)
C(4)	0.2631(2)	0.2292(4)	-0.2326(2)	0.044(2)
C(5)	0.1658(2)	0.2491(5)	-0.2585(2)	0.054(2)
C(6)	0.1078(2)	0.3057(5)	-0.2073(2)	0.056(2)
C(7)	0.0806(2)	0.4116(4)	-0.0723(2)	0.050(2)
C(8)	0.2894(4)	0.1597(9)	-0.3688(2)	0.085(3)
C(9)	0.4214(3)	0.1666(8)	-0.2587(3)	0.072(3)
N(1)	0.3210(2)	0.1689(4)	-0.2834(1)	0.054(2)
O(1)	-0.0093(2)	0.4138(4)	-0.1012(1)	0.073(2)
O(2)	0.1109(1)	0.4643(3)	-0.0035(1)	0.062(1)
H(2)	0.261(2)	0.353(4)	-0.044(2)	0.05(1)
H(3)	0.359(2)	0.257(3)	-0.132(1)	0.03(1)
H(5)	0.140(2)	0.225(4)	-0.315(2)	0.07(1)
H(6)	0.042(2)	0.314(4)	-0.228(2)	0.07(1)
H(81)	0.266(4)	0.301(7)	-0.389(3)	0.16(2)
H(82)	0.336(3)	0.119(7)	-0.398(3)	0.15(2)
H(83)	0.241(3)	0.088(7)	-0.379(3)	0.13(2)
H(91)	0.444(3)	0.299(7)	-0.251(3)	0.13(2)
H(92)	0.438(3)	0.098(6)	-0.212(2)	0.11(2)
H(93)	0.452(3)	0.099(6)	-0.303(2)	0.13(2)
H(O1)	-0.051(3)	0.462(6)	-0.061(2)	0.13(2)

* occupancy 0.5

Table 2.9

Final anisotropic thermal vibrational parameters (Å^2) for non-H atoms in complex **1** (e.s.d's are in parentheses).

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
Molecule A						
C(1)	0.039(2)	0.040(1)	0.039(1)	0.005(1)	0.002(1)	-0.004(1)
C(2)	0.046(2)	0.054(2)	0.042(2)	0.002(2)	0.005(2)	0.002(1)
C(3)	0.038(2)	0.052(2)	0.053(2)	0.009(2)	0.003(1)	0.002(1)
C(4)	0.042(2)	0.044(2)	0.048(2)	0.012(1)	-0.006(1)	-0.005(1)
C(5)	0.049(2)	0.055(2)	0.041(2)	0.001(1)	-0.001(1)	-0.001(1)
C(6)	0.040(2)	0.051(2)	0.047	-0.000(1)	0.004(1)	0.004(1)
C(7)	0.041(2)	0.048(2)	0.043(2)	0.004(1)	-0.001(1)	-0.001(1)
N(1)	0.050(2)	0.063(2)	0.059(2)	0.016(1)	-0.010(1)	-0.010(1)
O(1)	0.052(1)	0.099(2)	0.042(1)	-0.011(1)	-0.002(1)	0.016(1)
O(2)	0.044(1)	0.078(2)	0.048(1)	-0.007(1)	-0.005(1)	0.015(1)
O(3)	0.047(1)	0.101(2)	0.082(2)	0.013(1)	-0.014(1)	0.008(1)
O(4)	0.077(2)	0.112(2)	0.057(1)	-0.011(1)	-0.018(1)	-0.004(1)
Molecule B						
C(1)	0.041(2)	0.042(2)	0.038(2)	0.002(1)	0.004(1)	-0.003(1)
C(2)	0.045(2)	0.044(2)	0.040(2)	-0.005(1)	0.007(1)	-0.001(1)
C(3)	0.038(2)	0.045(2)	0.042(2)	-0.004(1)	0.006(1)	0.002(1)
C(4)	0.040(2)	0.038(2)	0.041(1)	0.004(1)	0.003(1)	-0.003(1)
C(5)	0.045(2)	0.049(2)	0.040(2)	-0.008(1)	0.006(1)	0.003(1)
C(6)	0.040(2)	0.047(2)	0.050(2)	0.002(1)	0.007(1)	0.004(1)
C(7)	0.043(2)	0.050(2)	0.041(2)	0.003(1)	0.004(1)	0.001(1)
C(8)	0.055(2)	0.071(3)	0.059(2)	-0.004(2)	-0.015(2)	0.011(2)
C(9)	0.064(2)	0.076(3)	0.042(2)	-0.009(2)	-0.002(2)	-0.002(2)
N(1)	0.045(1)	0.057(1)	0.041(1)	-0.006(1)	-0.001(1)	0.005(1)
O(1)	0.054(1)	0.087(2)	0.042(1)	-0.010(1)	-0.004(1)	0.008(1)
O(2)	0.047(1)	0.093(2)	0.060(2)	-0.006(1)	-0.005(1)	0.019(1)

Table 2.10

Final anisotropic thermal vibrational parameters (Å^2) for non-H atoms in complex **2** (e.s.d's are in parentheses).

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
Molecule A						
C(1)	0.042(1)	0.047(1)	0.045(1)	0.003(1)	-0.001(1)	-0.021(1)
C(2)	0.053(2)	0.047(2)	0.048(2)	-0.000(1)	0.003(1)	-0.022(1)
C(3)	0.058(2)	0.049(2)	0.066(2)	0.001(1)	-0.003(1)	-0.024(1)
C(4)	0.055(2)	0.052(2)	0.060(2)	0.010(1)	-0.005(1)	-0.029(1)
C(5)	0.059(2)	0.079(2)	0.045(2)	0.006(2)	0.003(1)	-0.035(2)
C(6)	0.059(2)	0.054(2)	0.047(2)	-0.003(1)	0.006(1)	-0.023(1)
C(7)	0.045(1)	0.043(1)	0.050(2)	-0.002(1)	0.000(1)	-0.018(1)
N(1)	0.090(2)	0.073(2)	0.083(2)	0.025(2)	-0.010(2)	-0.048(2)
O(1)	0.079(1)	0.052(1)	0.042(1)	-0.002(1)	0.011(1)	-0.026(1)
O(2)	0.092(1)	0.043(1)	0.066(1)	-0.008(1)	0.020(1)	-0.024(1)
O(3)	0.153(2)	0.065(2)	0.119(2)	0.018(1)	0.004(2)	-0.050(2)
O(4)	0.152(2)	0.119(2)	0.082(2)	0.032(2)	0.010(2)	-0.074(2)
Molecule B						
C(1)	0.045(2)	0.045(2)	0.052(2)	0.001(1)	-0.000(1)	-0.018(1)
C(2)	0.056(2)	0.064(2)	0.040(2)	0.003(1)	0.003(1)	-0.028(1)
C(3)	0.055(2)	0.046(2)	0.049(2)	-0.006(1)	0.004(1)	-0.018(1)
C(4)	0.043(2)	0.044(1)	0.044(1)	0.004(1)	-0.001(1)	-0.016(1)
C(5)	0.056(2)	0.050(2)	0.042(2)	-0.002(1)	0.007(1)	-0.019(1)
C(6)	0.057(2)	0.044(2)	0.059(2)	-0.000(1)	0.005(1)	-0.021(1)
C(7)	0.048(2)	0.053(2)	0.051(2)	-0.002(1)	0.001(1)	-0.020(1)
C(8)	0.063(2)	0.054(2)	0.060(2)	-0.006(1)	0.004(1)	-0.024(1)
C(9)	0.055(1)	0.043(2)	0.062(2)	0.003(1)	-0.002(1)	-0.021(1)
C(10)	0.112(3)	0.055(2)	0.053(2)	0.007(2)	0.009(2)	-0.028(2)
C(11)	0.090(3)	0.043(2)	0.068(2)	-0.005(1)	0.004(2)	-0.019(2)
N(1)	0.069(2)	0.041(1)	0.046(1)	0.001(1)	0.006(1)	-0.018(1)
O(1)	0.112(1)	0.054(1)	0.066(1)	-0.003(1)	0.030(1)	-0.030(1)
O(2)	0.084(1)	0.050(1)	0.059(1)	0.001(1)	0.013(1)	-0.026(1)

Table 2.11

Final anisotropic thermal vibrational parameters (Å^2) for non-H atoms in complex **4** (e.s.d's are in parentheses).

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
Molecule A						
C(1)	0.044(2)	0.037(1)	0.044(2)	0.001(1)	0.000(1)	-0.014(1)
C(2)	0.049(2)	0.041(2)	0.050(2)	-0.002(1)	-0.002(1)	-0.017(1)
C(3)	0.047(2)	0.046(2)	0.047(2)	0.003(1)	-0.006(1)	-0.017(1)
C(4)	0.049(2)	0.046(2)	0.053(2)	0.009(1)	-0.006(1)	-0.014(1)
C(5)	0.052(2)	0.038(1)	0.055(2)	0.000(1)	-0.001(1)	-0.021(1)
C(6)	0.053(2)	0.045(2)	0.046(2)	0.001(2)	-0.007(1)	-0.020(1)
C(7)	0.055(2)	0.040(2)	0.049(2)	0.001(1)	-0.002(1)	-0.017(1)
C(8)	0.057(2)	0.046(2)	0.059(2)	0.006(1)	-0.011(2)	-0.022(1)
C(9)	0.051(2)	0.052(2)	0.052(2)	0.010(1)	-0.007(1)	-0.022(1)
N(1)	0.064(2)	0.069(2)	0.056(2)	0.001(1)	-0.017(1)	-0.027(1)
N(2)	0.086(2)	0.043(2)	0.085(2)	0.005(2)	-0.015(2)	-0.031(1)
O(1)	0.122(2)	0.082(2)	0.091(2)	-0.003(1)	-0.048(1)	-0.049(2)
O(2)	0.115(2)	0.092(2)	0.069(2)	0.026(1)	-0.046(1)	-0.040(1)
O(3)	0.178(3)	0.072(2)	0.089(2)	-0.010(1)	-0.030(2)	-0.066(2)
O(4)	0.131(2)	0.053(1)	0.122(2)	0.032(1)	-0.047(2)	-0.045(1)
O(5)	0.093(2)	0.072(2)	0.089(2)	0.029(1)	-0.049(1)	-0.044(1)
O(6)	0.085(2)	0.048(1)	0.059(1)	0.010(1)	-0.020(1)	-0.024(1)
Molecule B						
C(1)	0.053(2)	0.049(2)	0.046(2)	0.006(1)	-0.006(1)	-0.018(1)
C(2)	0.075(2)	0.049(2)	0.060(2)	0.002(2)	-0.014(2)	-0.028(2)
C(3)	0.071(2)	0.053(2)	0.052(2)	0.003(1)	-0.018(2)	-0.025(2)
C(4)	0.051(2)	0.048(2)	0.042(2)	0.002(1)	-0.004(1)	-0.018(1)
C(5)	0.056(2)	0.047(2)	0.049(2)	0.001(1)	-0.006(1)	-0.021(1)
C(6)	0.051(2)	0.054(2)	0.043(2)	0.002(1)	-0.008(2)	-0.018(1)
C(7)	0.053(2)	0.047(2)	0.051(2)	0.004(1)	-0.004(1)	-0.015(1)
C(8)	0.106(4)	0.052(2)	0.072(3)	0.010(2)	-0.020(3)	-0.034(2)
C(9)	0.093(3)	0.070(2)	0.052(2)	0.010(2)	-0.021(2)	-0.028(2)
N(1)	0.085(2)	0.052(1)	0.047(1)	0.012(1)	-0.022(1)	-0.028(1)
O(1)	0.076(1)	0.057(1)	0.051(1)	0.011(1)	-0.014(1)	-0.018(1)
O(2)	0.099(2)	0.055(1)	0.077(2)	0.020(1)	-0.028(1)	-0.037(1)

Table 2.12

Final anisotropic thermal vibrational parameters ($\AA^2$) for non-H atoms in complex **5** (e.s.d's are in parentheses).						
Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
Molecule A						
C(1)	0.034(2)	0.040(2)	0.036(2)	-0.004(1)	0.009(1)	-0.003(1)
C(2)	0.041(2)	0.038(2)	0.040(2)	-0.007(1)	0.012(1)	0.002(1)
C(3)	0.032(2)	0.044(2)	0.041(2)	-0.003(1)	0.008(1)	-0.001(1)
C(4)	0.039(2)	0.040(2)	0.046(2)	-0.008(1)	0.008(1)	-0.009(1)
C(5)	0.041(2)	0.035(2)	0.042(2)	-0.007(1)	0.009(1)	-0.000(1)
C(6)	0.032(2)	0.041(2)	0.046(2)	-0.007(1)	0.011(1)	0.000(1)
C(7)	0.030(2)	0.044(2)	0.047(2)	-0.012(2)	0.008(1)	-0.005(1)
C(8)	0.040(2)	0.043(2)	0.049(2)	-0.008(2)	0.007(1)	-0.002(1)
C(9)	0.050(2)	0.043(2)	0.053(2)	-0.015(2)	0.007(2)	-0.008(2)
N(1)	0.035(2)	0.064(2)	0.059(2)	-0.003(2)	0.013(1)	-0.001(1)
N(2)	0.061(2)	0.038(2)	0.064(2)	-0.013(1)	0.019(2)	-0.003(2)
O(1)	0.048(1)	0.074(2)	0.090(2)	-0.019(2)	0.026(1)	0.011(1)
O(2)	0.035(1)	0.088(2)	0.109(2)	-0.030(2)	0.010(1)	-0.017(1)
O(3)	0.080(2)	0.048(2)	0.111(2)	-0.036(1)	0.028(2)	-0.019(1)
O(4)	0.057(2)	0.064(2)	0.124(3)	-0.036(2)	0.021(2)	0.011(1)
O(5)	0.059(2)	0.041(1)	0.087(2)	-0.022(1)	0.008(1)	-0.007(1)
O(6)	0.045(2)	0.077(2)	0.137(2)	-0.059(2)	0.015(2)	-0.013(1)
Molecule B						
C(1)	0.041(2)	0.047(2)	0.040(2)	-0.002(2)	0.010(2)	-0.009(1)
C(2)	0.054(2)	0.037(2)	0.050(2)	-0.011(2)	0.011(2)	-0.003(2)
C(3)	0.038(2)	0.045(2)	0.064(2)	-0.011(2)	0.013(2)	0.003(1)
C(4)	0.039(2)	0.040(2)	0.048(2)	-0.008(2)	0.010(1)	-0.004(1)
C(5)	0.039(2)	0.041(2)	0.053(2)	-0.010(2)	0.013(2)	-0.000(1)
C(6)	0.039(2)	0.047(2)	0.051(2)	-0.006(2)	0.013(2)	-0.001(1)
C(7)	0.053(2)	0.053(2)	0.045(2)	-0.008(2)	0.010(2)	-0.010(2)
C(8)	0.053(2)	0.057(2)	0.057(2)	-0.006(2)	0.010(2)	-0.007(2)
C(9)	0.056(2)	0.050(2)	0.058(2)	-0.008(2)	0.005(2)	-0.011(2)
C(10)	0.039(2)	0.062(2)	0.106(3)	-0.017(2)	0.020(2)	-0.006(2)
C(11)	0.055(2)	0.056(2)	0.114(4)	-0.034(2)	0.028(2)	-0.018(2)
N(1)	0.036(2)	0.051(2)	0.096(2)	-0.028(2)	0.017(2)	-0.008(1)
O(1)	0.063(2)	0.068(2)	0.129(3)	-0.036(2)	0.007(2)	-0.021(1)
O(2)	0.060(2)	0.067(2)	0.078(2)	-0.018(1)	0.015(1)	-0.018(1)

Table 2.13

Final anisotropic thermal vibrational parameters (Å^2) for non-H atoms in complex **6** (e.s.d's are in parentheses).

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_1
Molecule A						
C(1)*	0.049(6)					
C(2)*	0.039(5)					
C(3)*	0.052(6)					
C(4)*	0.034(5)					
C(5)*	0.049(6)					
C(6)*	0.056(6)					
C(7)*	0.089(8)					
C(8)*	0.097(8)					
C(9)*	0.066(8)					
N(1)	0.046(12)	0.081(15)	0.058(14)	0.001(12)	0.007(11)	0.023(
N(2)	0.037(10)	0.011(14)	0.059(13)	-0.042(12)	-0.010(10)	0.019(
O(1)	0.105(11)	0.044(8)	0.082(11)	-0.006(8)	0.003(10)	-0.01
O(2)	0.047(9)	0.010(12)	0.054(10)	-0.027(9)	-0.023(8)	0.024
O(3)	0.050(10)	0.098(13)	0.082(13)	-0.019(11)	-0.018(10)	0.017(
O(4)	0.046(9)	0.065(10)	0.089(14)	0.012(10)	0.011(9)	0.020
O(5)	0.043(8)	0.093(11)	0.069(11)	-0.004(9)	-0.003(9)	0.031
O(6)	0.084(12)	0.063(10)	0.260(24)	-0.038(14)	-0.036(14)	-0.039
Molecule B						
C(1)*	0.041(5)					
C(2)*	0.037(5)					
C(3)*	0.059(6)					
C(4)*	0.057(6)					
C(5)*	0.060(6)					
C(6)*	0.080(7)					
C(7)*	0.051(6)					
C(8)*	0.051(6)					
C(9)*	0.030(5)					
C(10)	0.031(13)	0.164(26)	0.113(22)	-0.008(21)	0.018(16)	-0.002
C(11)	0.113(25)	0.211(34)	0.128(27)	-0.059(24)	-0.052(23)	0.096(
O(1)	0.036(7)	0.047(8)	0.065(10)	-0.002(8)	-0.007(8)	0.016
O(2)	0.030(7)	0.043(8)	0.096(12)	0.015(8)	0.005(8)	-0.00
O(3)	0.047(9)	0.095(11)	0.082(12)	0.022(10)	0.002(9)	0.025
O(4)	0.113(12)	0.067(10)	0.113(14)	-0.002(10)	0.022(12)	0.012(

* fixed geometrically and refine isotropically.

Table 2.14

Final anisotropic thermal vibrational parameters (Å^2) for non-H atoms in complex **4** (e.s.d's are in parentheses).

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
Molecule A						
C(1)	0.062(3)	0.049(3)	0.059(3)	0.025(2)	0.019(2)	0.022(2)
C(2)	0.060(3)	0.045(2)	0.050(3)	0.016(2)	0.014(2)	0.020(2)
C(3)	0.071(3)	0.053(3)	0.050(3)	0.007(2)	0.014(2)	0.019(3)
C(4)	0.069(3)	0.068(3)	0.040(2)	0.016(2)	0.013(2)	0.018(3)
C(5)	0.092(4)	0.083(4)	0.065(3)	0.040(3)	0.030(3)	0.035(3)
C(6)	0.093(4)	0.079(3)	0.076(4)	0.040(3)	0.033(3)	0.055(3)
C(7)	0.084(4)	0.077(3)	0.068(3)	0.038(3)	0.034(3)	0.047(3)
C(8)	0.073(3)	0.062(3)	0.060(3)	0.022(3)	0.024(3)	0.034(3)
C(9)	0.075(3)	0.080(3)	0.064(3)	0.027(3)	0.028(3)	0.046(3)
N(1)	0.126(4)	0.067(3)	0.074(3)	0.034(2)	0.045(3)	0.058(3)
N(2)	0.094(4)	0.092(4)	0.055(3)	0.018(3)	0.017(2)	0.018(3)
O(11)	0.127(5)	0.112(5)	0.051(4)	0.039(3)	0.030(3)	0.077(4)
O(12)	0.166(12	0.074(8)	0.103(9)	0.047(7)	0.074(10	0.043(8)
O(2)	0.188(4)	0.099(3)	0.124(3)	0.045(2)	0.053(3)	0.101(3)
O(3)	0.175(4)	0.141(3)	0.087(3)	0.073(3)	0.056(3)	0.061(3)
O(4)	0.164(4)	0.116(3)	0.067(2)	0.014(2)	0.046(2)	0.045(3)
O(5)	0.096(3)	0.074(2)	0.064(2)	0.027(2)	0.034(2)	0.050(2)
O(6)	0.192(4)	0.148(3)	0.103(3)	0.088(3)	0.094(3)	0.137(3)
Molecule B						
C(1)	0.059(3)	0.050(3)	0.042(2)	0.015(2)	0.015(2)	0.020(2)
C(2)	0.059(3)	0.047(3)	0.054(3)	0.014(2)	0.016(2)	0.021(2)
C(3)	0.072(3)	0.056(3)	0.050(3)	0.025(2)	0.018(2)	0.024(3)
C(4)	0.073(3)	0.058(3)	0.047(3)	0.016(2)	0.020(3)	0.023(3)
C(5)	0.071(3)	0.050(3)	0.050(3)	0.010(2)	0.019(2)	0.025(2)
C(6)	0.071(3)	0.046(3)	0.051(3)	0.023(2)	0.020(2)	0.025(2)
C(7)	0.068(3)	0.047(3)	0.055(3)	0.020(2)	0.017(2)	0.021(3)
C(8)	0.084(4)	0.063(3)	0.061(3)	0.025(3)	0.028(3)	0.037(3)
C(9)	0.077(4)	0.062(3)	0.053(3)	0.018(2)	0.023(3)	0.031(3)
C(10)	0.119(6)	0.056(3)	0.081(4)	0.031(3)	0.033(4)	0.047(4)
C(11)	0.116(6)	0.074(4)	0.087(5)	0.024(4)	0.034(5)	0.061(4)
O(1)	0.132(3)	0.108(3)	0.083(3)	0.042(2)	0.058(2)	0.081(3)
O(2)	0.103(3)	0.073(2)	0.065(2)	0.030(2)	0.036(2)	0.046(2)
O(3)	0.106(3)	0.061(2)	0.074(2)	0.035(2)	0.039(2)	0.047(2)
O(4)	0.109(3)	0.064(2)	0.062(2)	0.023(2)	0.035(2)	0.049(2)

Table 2.15

Final anisotropic thermal vibrational parameters (Å^2) for non-H atoms in complex **9** (e.s.d's are in parentheses).

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
Molecule A						
C(1)	0.038(2)	0.036(2)	0.050(2)	0.003(1)	0.011(1)	-0.002(1)
C(2)	0.045(2)	0.049(2)	0.047(2)	-0.000(2)	0.009(1)	-0.003(1)
C(3)	0.034(2)	0.061(2)	0.051(2)	0.005(2)	0.008(1)	0.003(1)
C(4)	0.044(2)	0.050(2)	0.055(2)	0.003(2)	0.019(1)	0.006(1)
C(5)	0.050(2)	0.038(2)	0.046(2)	-0.001(1)	0.014(1)	-0.001(1)
C(6)	0.042(2)	0.037(2)	0.051(2)	0.004(1)	0.004(1)	-0.001(1)
C(7)	0.041(2)	0.035(2)	0.053(2)	0.003(1)	0.010(1)	-0.003(1)
N(1)	0.044(2)	0.132(3)	0.064(2)	-0.003(2)	0.010(1)	0.013(2)
N(2)	0.071(2)	0.057(2)	0.051(2)	-0.002(1)	0.017(1)	0.001(1)
O(1)	0.064(2)	0.323(6)	0.058(2)	-0.027(2)	-0.005(1)	0.042(2)
O(2)	0.046(1)	0.239(4)	0.089(2)	0.000(2)	0.012(1)	0.036(2)
O(3)	0.085(2)	0.116(2)	0.056(1)	-0.019(1)	-0.005(1)	0.010(2)
O(4)	0.084(2)	0.103(2)	0.066(1)	-0.012(1)	0.038(1)	0.013(2)
O(5)	0.051(1)	0.071(2)	0.057(1)	-0.010(1)	0.018(1)	-0.000(1)
O(6)	0.038(1)	0.075(2)	0.069(1)	-0.009(1)	0.008(1)	0.003(1)
Molecule B						
C(1)	0.039(2)	0.037(2)	0.055(2)	0.001(1)	0.006(1)	0.000(1)
C(2)	0.043(2)	0.041(2)	0.045(2)	0.003(2)	0.006(1)	-0.003(1)
C(3)	0.033(2)	0.046(2)	0.048(2)	0.003(1)	0.000(1)	-0.000(1)
C(4)	0.045(2)	0.043(2)	0.044(2)	0.004(1)	0.006(1)	-0.001(1)
C(5)	0.051(2)	0.063(2)	0.048(2)	-0.001(2)	-0.003(2)	0.004(2)
C(6)	0.035(2)	0.066(2)	0.066(2)	0.001(2)	-0.003(2)	0.006(2)
C(7)	0.042(2)	0.040(2)	0.068(2)	0.007(2)	0.010(2)	-0.000(1)
C(8)	0.086(3)	0.118(4)	0.051(2)	-0.001(3)	0.014(2)	0.016(3)
C(9)	0.052(2)	0.092(4)	0.071(3)	-0.007(3)	0.018(2)	0.003(2)
N(1)	0.049(2)	0.071(2)	0.043(1)	-0.003(1)	0.007(1)	0.004(1)
O(1)	0.039(1)	0.094(2)	0.085(2)	-0.018(1)	0.009(1)	0.002(1)
O(2)	0.046(1)	0.079(2)	0.062(1)	-0.004(1)	0.010(1)	0.010(1)

Table 3.1

Crystallographic Details for acids **2b, 2c** and ester **21**			
	2b	**2c**	**21**
Formula	$C_9H_6N_2O_6$	$C_9H_6N_2O_6$	$C_{10}H_8N_2O_6$
Mol wt	238.16	238.16	252.18
Crystal system	Monoclinic	Monoclinic	Monoclinic
Space group	$P2_1/c$	$P2_1/n$	$P2_1/n$
a/Å	15.767(15)	8.760(9)	4.842(2)
b/Å	7.796(3)	7.869(5)	16.848(4)
c/Å	16.155(5)	14.040(10)	13.489(3)
$\alpha/^o$	90	90	90
$\beta/^o$	95.61(6)	93.12(7)	90.56(2)
$\gamma/^o$	90	90	90
Cell vol $Å^3$	1976.3	966.4	1100.4
Z	8	4	4
F(000)	976	488	520
D_{calcd}, $g.cm^{-3}$	1.601	1.637	1.522
λ , Å	0.7107	0.7107	0.7107
μ , cm^{-1}	0.14	0.14	0.13
Crystal size, mm	.30 × .20 × .16	.25 × .22 × .14	.25 × .10 × .20
Diffractometer	Nicolet R3m	Nicolet	R3m P3
Radiation	MoKα	Mokα	MoKα
2θ range/^{o}	2-50	2-50	2-50
h	-19 to 19	-10 to 10	0 to 5
k	0 to 9	0 to 9	0 to 20
l	0 to 19	0 to 16	-15 to 16
Total reflctn	866	1785	1932
Non-zero reflctn	545	1137	1136
σ-level	2.0	3.0	2.0
R	0.038	0.034	0.048
R_w	0.090	0.085	0.118
Min e $Å^{-3}$	-0.19	-0.24	-0.18
Max e $Å^{-3}$	0.15	0.17	0.25

Table 3.2

Fractional coordinates and equivalent thermal parameters for acid **2b** (e.s.d.'s are given in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
C(1)	0.7560(3)	0.0148(13)	0.0222(3)	0.025(5)
C(2)	0.7336(3)	0.0927(11)	0.0963(3)	0.018(6)
C(3)	0.7944(3)	0.0919(12)	0.1646(3)	0.019(6)
C(4)	0.8747(3)	0.0310(12)	0.1644(3)	0.030(6)
C(5)	0.8952(3)	-0.0454(12)	0.0908(3)	0.018(5)
C(6)	0.8370(3)	-0.0497(11)	0.0199(3)	0.020(5)
C(7)	0.6965(3)	0.0130(12)	-0.0542(3)	0.028(6)
C(8)	0.6130(3)	0.0354(11)	-0.0594(3)	0.021(6)
C(9)	0.5627(3)	0.0423(13)	-0.1425(3)	0.030(6)
N(1)	0.7708(3)	0.1788(12)	0.2418(2)	0.036(6)
N(2)	0.9808(3)	-0.1187(10)	0.0865(3)	0.033(5)
O(1)	0.4802(2)	0.0362(9)	-0.1388(2)	0.032(4)
O(2)	0.5969(2)	0.0460(9)	-0.2074(2)	0.038(4)
O(3)	0.8212(2)	0.1668(9)	0.3045(2)	0.040(4)
O(4)	0.7028(3)	0.2534(10)	0.2382(2)	0.045(5)
O(5)	1.0324(2)	-0.1024(9)	0.1478(2)	0.054(5)
O(6)	0.9963(2)	-0.1893(8)	0.0219(2)	0.031(4)
H(2)*	0.6786(3)	0.1440(10)	0.0992(3)	0.02
H(4)*	0.9156(3)	0.0399(12)	0.2123(3)	0.03
H(6)*	0.8536(3)	-0.0980(12)	-0.0307(3)	0.02
H(7)*	0.7210(3)	-0.0062(13)	-0.1056(3)	0.02
H(8)*	0.5848(3)	0.0471(11)	-0.0096(3)	0.02
H(O1)	0.4570(4)	0.0543(12)	-0.1796(4)	0.06

* fixed geometrically.

Table 3.3

Fractional coordinates and equivalent thermal parameters for acid **2c** (e.s.d.'s are given in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
C(1)	0.1141(2)	1.0241(3)	0.1280(2)	0.016(1)
C(2)	0.0290(3)	1.0394(3)	0.2097(2)	0.015(1)
C(3)	-0.0436(3)	1.1874(3)	0.2345(2)	0.017(1)
C(4)	-0.0271(2)	1.3276(3)	0.1766(2)	0.017(1)
C(5)	0.0545(3)	1.3221(3)	0.0946(2)	0.019(1)
C(6)	0.1224(3)	1.1700(2)	0.0705(2)	0.017(1)
C(7)	0.1919(3)	0.8679(3)	0.0997(2)	0.017(1)
C(8)	0.3305(3)	0.8672(3)	0.0650(2)	0.019(1)
C(9)	0.4022(3)	0.7053(3)	0.0388(2)	0.017(1)
N(1)	0.0187(2)	0.8956(3)	0.2765(1)	0.017(1)
N(2)	-0.0958(2)	1.4895(3)	0.2046(1)	0.019(1)
O(1)	0.5474(2)	0.7226(2)	0.0194(1)	0.022(1)
O(2)	0.3339(2)	0.5690(2)	0.0369(1)	0.022(1)
O(3)	0.1209(2)	0.7877(2)	0.2785(1)	0.023(1)
O(4)	-0.0896(2)	0.8932(2)	0.3286(1)	0.023(1)
O(5)	-0.1368(2)	1.5020(2)	0.2869(1)	0.026(1)
O(6)	-0.1083(2)	1.6040(2)	0.1447(1)	0.025(1)
H(3)*	-0.1032(3)	1.1928(3)	0.2898(2)	0.02
H(5)*	0.0636(3)	1.4212(3)	0.0555(2)	0.02
H(6)*	0.1767(3)	1.1640(3)	0.0130(2)	0.02
H(7)*	0.1404(3)	0.7613(3)	0.1065(2)	0.02
H(8)*	0.3839(3)	0.9724(3)	0.0570(2)	0.02
H(OA)	0.4193(30)	0.3754(37)	-0.0002(19)	0.04

* fixed geometrically

Table 3.4

Fractional coordinates and equivalent thermal parameters for ester **21** (e.s.d.'s are given in parentheses).

Atom	x/a	y/b	z/c	U_{eq}
C(1)	0.4867(5)	0.0007(1)	0.1782(2)	0.0519(6)
C(2)	0.2879(5)	-0.0321(2)	0.2409(2)	0.0557(6)
C(3)	0.1450(4)	0.0163(1)	0.3045(2)	0.0542(6)
C(4)	0.1867(5)	0.0964(2)	0.3094(2)	0.0582(7)
C(5)	0.3844(5)	0.1277(1)	0.2486(2)	0.0576(6)
C(6)	0.5339(5)	0.0819(2)	0.1836(2)	0.0568(6)
C(7)	0.6499(5)	-0.0470(2)	0.1086(2)	0.0563(6)
C(8)	0.6507(6)	-0.1237(2)	0.0999(2)	0.0664(8)
C(9)	0.8277(5)	-0.1658(2)	0.0291(2)	0.0624(7)
C(10)	0.9649(10)	-0.2915(3)	-0.0301(3)	0.0898(11)
N(1)	0.0642(4)	-0.0193(2)	0.3690(2)	0.0684(6)
N(2)	0.4429(5)	0.2135(1)	0.2529(2)	0.0740(7)
O(1)	-0.0855(5)	-0.0905(1)	0.3697(2)	0.1015(8)
O(2)	-0.2077(4)	0.0253(1)	0.4179(2)	0.0849(6)
O(3)	-0.6481(6)	0.2377(1)	0.2135(2)	0.1272(11)
O(4)	0.2862(5)	0.2553(1)	0.2984(2)	0.0991(8)
O(5)	0.7900(4)	-0.2436(1)	0.0321(1)	0.0806(6)
O(6)	0.9876(4)	-0.1340(1)	-0.0254(2)	0.0859(7)
H(2)	0.249(5)	-0.083(1)	0.238(2)	0.05(1)
H(4)	0.093(5)	0.126(2)	0.349(2)	0.06(1)
H(6)	0.657(5)	0.103(1)	0.144(2)	0.06(1)
H(7)	0.768(5)	0.017(2)	0.068(2)	0.07(1)
H(8)	0.549(6)	0.156(2)	0.137(2)	0.09(1)
H(101)	0.926(7)	0.341(3)	-0.019(3)	0.12(1)
H(102)	0.924(7)	0.280(2)	-0.098(3)	0.12(1)
H(103)	1.151(8)	-0.282(2)	-0.010(3)	0.13(2)

Table 3.5

Final anisotropic thermal vibrational parameters (Å^2)) for non-H atoms in acid 2b (e.s.d's are given in parentheses).

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
O(1)	0.018(2)	0.062(9)	0.018(2)	0.005(3)	-0.002(1)	0.001(4)
O(2)	0.021(2)	0.076(8)	0.017(2)	0.001(3)	-0.002(1)	-0.003(3)
O(3)	0.047(2)	0.060(8)	0.012(2)	-0.001(3)	-0.002(2)	-0.003(4)
O(4)	0.040(3)	0.061(10)	0.034(2)	-0.019(3)	0.004(2)	0.014(4)
O(5)	0.0 31(2)	0.085(10)	0.047(2)	-0.019(3)	-0.021(2)	0.027(4)
O(6)	0.029(2)	0.024(7)	0.040(2)	-0.007(3)	0.002(2)	0.003(4)
N(1)	0.032(3)	0.056(14)	0.019(2)	-0.002(3)	0.005(2)	0.005(4)
N(2)	0.020(2)	0.040(1)	0.039(3)	-0.007(4)	-0.005(2)	0.006(4)
C(1)	0.017(2)	0.040(11)	0.017(2)	0.006(4)	0.001(2)	-0.001(1)
C(2)	0.020(2)	0.015(1)	0.020(2)	0.006(4)	0.003(2)	-0.001(4)
C(3)	0.028(3)	0.016(1)	0.013(2)	-0.001(3)	0.002(2)	0.001(5)
C(4)	0.027(3)	0.046(1)	0.018(2)	-0.002(4)	-0.004(2)	0.003(5)
C(5)	0.017(2)	0.011(1)	0.025(3)	0.007(4)	0.011(2)	-0.000(5)
C(6)	0.023(3)	0.020(1)	0.017(2)	-0.001(4)	-0.000(2)	0.004(5)
C(7)	0.026(3)	0.043(1)	0.015(2)	-0.001(4)	-0.001(2)	-0.005(5)
C(8)	0.025(3)	0.024(1)	0.014(2)	0.002(4)	0.000(2)	-0.006(5)
C(9)	0.020(3)	0.050(1)	0.021(2)	-0.004(4)	0.000(2)	-0.003(5)

Table 3.6

Final anisotropic thermal vibrational parameters (Å^2) for non-H atoms in acid **2c** (e.s.d's are given in parentheses).

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
O(1)	0.018(1)	0.018(1)	0.029(1)	-0.004(1)	0.008(1)	0.000(1)
O(2)	0.021(1)	0.016(1)	0.028(1)	-0.000(1)	0.010(1)	-0.002(1)
O(3)	0.022(1)	0.022(1)	0.025(1)	0.004(1)	0.000(1)	0.008(1)
O(4)	0.024(1)	0.024(1)	0.022(1)	0.003(1)	0.008(1)	0.002(1)
O(5)	0.028(1)	0.023(1)	0.027(1)	-0.004(1)	0.005(1)	0.004(1)
O(6)	0.024(1)	0.017(1)	0.034(1)	0.005(1)	0.000(1)	0.001(1)
C(1)	0.010(1)	0.019(1)	0.019(1)	-0.003(1)	0.003(1)	-0.002(1)
C(2)	0.013(1)	0.015(1)	0.017(1)	0.001(1)	0.000(1)	-0.000(1)
C(3)	0.013(1)	0.021(1)	0.018(1)	-0.002(1)	0.001(1)	-0.002(1)
C(4)	0.012(1)	0.016(1)	0.024(1)	-0.001(1)	0.003(1)	0.002(1)
C(5)	0.017(1)	0.017(1)	0.021(1)	0.003(1)	0.001(1)	-0.002(1)
C(6)	0.012(1)	0.023(1)	0.017(1)	-0.000(1)	0.000(1)	-0.001(1)
C(7)	0.020(1)	0.015(1)	0.015(1)	0.000(1)	0.000(1)	-0.000(1)
C(8)	0.020(1)	0.015(1)	0.020(1)	-0.000(1)	0.003(1)	0.000(1)
C(9)	0.017(1)	0.022(1)	0.013(1)	0.000(1)	0.005(1)	-0.001(1)
N(1)	0.017(1)	0.017(1)	0.017(1)	-0.000(1)	0.000(1)	0.000(1)
N(2)	0.014(1)	0.016(1)	0.028(1)	-0.000(1)	0.000(1)	0.000(1)

Table 3.7

Final anisotropic thermal vibrational parameters ($\mathring{A}^2$) for non-H atoms in ester **21** (e.s.d's are given in parentheses).

Atom	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
C(1)	0.048(1)	0.056(2)	0.052(1)	-0.001(1)	0.005(1)	0.006(1)
C(2)	0.055(2)	0.049(2)	0.063(2)	0.002(1)	0.009(1)	-0.001(1)
C(3)	0.048(1)	0.060(2)	0.055(1)	0.003(1)	0.008(1)	0.003(1)
C(4)	0.053(2)	0.064(2)	0.058(2)	-0.003(1)	0.009(1)	0.013(1)
C(5)	0.061(2)	0.049(1)	0.063(2)	0.003(1)	0.006(1)	0.008(1)
C(6)	0.057(2)	0.054(2)	0.059(2)	0.004(1)	0.011(1)	0.003(1)
C(7)	0.058(2)	0.057(2)	0.054(2)	0.002(1)	0.012(1)	-0.003(1)
C(8)	0.066(2)	0.057(2)	0.077(2)	-0.002(1)	0.026(2)	-0.006(1)
C(9)	0.060(2)	0.063(2)	0.064(2)	-0.001(1)	0.014(1)	0.001(1)
C(10)	0.110(3)	0.070(2)	0.090(3)	-0.022(2)	0.036(2)	0.008(2)
N(1)	0.062(1)	0.078(2)	0.066(2)	0.001(1)	0.018(1)	0.002(1)
N(2)	0.086(2)	0.054(1)	0.082(2)	-0.000(1)	0.022(1)	0.007(1)
O(1)	0.115(2)	0.071(2)	0.119(2)	-0.000(1)	0.059(1)	-0.017(1)
O(2)	0.074(1)	0.100(2)	0.081(1)	0.001(1)	0.033(1)	0.010(1)
O(3)	0.163(3)	0.061(1)	0.159(2)	-0.009(1)	0.093(2)	-0.018(1)
O(4)	0.104(2)	0.062(1)	0.131(2)	-0.010(1)	0.035(2)	0.023(1)
O(5)	0.089(1)	0.059(1)	0.094(2)	-0.016(1)	0.039(1)	-0.007(1)
O(6)	0.101(1)	0.068(1)	0.089(1)	0.003(1)	0.049(1)	0.003(1)

Table 4.1

Crystallographic Details for diacid **24**	
Formula	$C_{20}H_{18}N_2O_{10} : (C_7H_8)_{0.5} : (H_2O)_{0.5}$
Mol wt	509.5
Crystal system	Triclinic
Space group	$P\bar{1}$
a/Å	8.150(1)
b/Å	8.927(2)
c/Å	17.894(4)
$\alpha/^o$	98.91(1)
$\beta/^o$	97.60(2)
$\gamma.^o$	110.62(2)
Cell vol, $\mathring{A}^3$	1178.95
Z	2
F(000)	564
$D_{calcd}, g.cm^{-3}$	1.435
$\lambda, \mathring{A}$	0.7107
μ,cm^{-1}	0.71
Crystal size, mm	.10x.10x.30
Diffractometer	Enraf Nonius Fast area detector
Radiation	MoKα
2 θ range/^{o}	2-70
h	-10 to 10
k	-11 to 11
l	0 to 23
Total reflctn	5475
Non-zero reflctn	2910
σ-level	3.0
R	0.063
R_w	0.072
Min e $\mathring{A}^{-3}$	-0.25
Max e $\mathring{A}^{-3}$	0.52

Table 4.2

Fractional co-ordinates and equivalent thermal parameters for diacid **1b** (e.s.d's are in parentheses).

Atom	x/a	y/b	z/c	U_eq
C(1)	-0.0403(4)	0.0222(4)	-0.2151(2)	0.029(2)
C(2)	-0.1751(4)	0.0555(4)	-0.1856(2)	0.037(2)
C(3)	-0.2630(4)	0.1398(4)	-0.2219(2)	0.038(2)
C(4)	-0.2238(5)	0.1930(4)	-0.2879(2)	0.040(2)
C(5)	-0.0904(4)	0.1565(4)	-0.3166(2)	0.036(2)
C(6)	-0.0007(4)	0.0723(4)	-0.2823(2)	0.033(2)
C(7)	-0.2253(5)	-0.3449(4)	-0.2504(2)	0.035(2)
C(8)	-0.2138(6)	-0.3684(5)	-0.3279(2)	0.049(2)
C(9)	-0.3698(8)	-0.4530(6)	-0.3839(2)	0.075(2)
C(10)	-0.5326(7)	-0.5117(7)	-0.3636(3)	0.083(2)
C(11)	-0.5467(6)	-0.4872(5)	-0.2877(3)	0.059(3)
C(12)	-0.3916(5)	-0.4052(4)	-0.2311(2)	0.043(2)
C(13)	0.0559(4)	-0.0748(4)	-0.1801(2)	0.032(2)
C(14)	-0.0566(4)	-0.2621(4)	-0.1903(2)	0.032(2)
C(15)	-0.0656(4)	-0.2313(4)	-0.1046(2)	0.029(2)
C(16)	0.0787(4)	-0.0550(4)	-0.0906(2)	0.030(2)
C(17)	-0.0326(9)	-0.3114(6)	-0.4217(3)	0.095(4)
C(18)	-0.7351(7)	-0.5173(6)	-0.1967(4)	0.100(4)
C(19)	0.2613(4)	-0.0336(4)	-0.0501(2)	0.031(2)
C(20)	-0.0344(4)	-0.3492(4)	-0.0590(2)	0.033(2)
N(1)	-0.4096(4)	0.1675(4)	-0.1907(2)	0.060(2)
N(2)	-0.0421(4)	0.2096(4)	-0.3872(2)	0.050(2)
O(1)	-0.4178(4)	0.1584(4)	-0.1244(2)	0.095(2)
O(2)	-0.5147(5)	0.2028(5)	-0.2311(2)	0.115(3)
O(3)	-0.0973(5)	0.3080(4)	-0.4089(2)	0.087(2)
O(4)	0.0515(4)	0.1534(4)	-0.4199(2)	0.073(2)
O(5)	0.3266(3)	-0.1357(3)	-0.0769(1)	0.045(1)
O(6)	0.3405(3)	0.0812(3)	0.0073(1)	0.041(1)
O(7)	0.0209(4)	-0.2930(3)	0.0134(1)	0.048(2)
O(8)	-0.0678(4)	-0.4927(3)	-0.0919(1)	0.051(2)
O(9)	-0.0463(4)	-0.3041(3)	-0.3417(1)	0.064(2)
O(10)	-0.7148(4)	-0.5489(5)	-0.2723(2)	0.081(3)

Table 4.2 contd...

Atom	x/a	y/b	z/c	$U_{e}q$
H(2)	-0.206(4)	0.027(4)	-0.137(2)	0.03(1)
H(4)	-0.288(4)	0.252(4)	-0.308(2)	0.03(1)
H(6)	0.089(4)	0.049(4)	-0.303(2)	0.03(1)
H(9)	-0.351(6)	-0.472(5)	-0.435(2)	0.08(1)
H(10)	-0.636(6)	-0.565(5)	-0.404(4)	0.09(2)
H(12)	-0.408(4)	-0.384(4)	-0.175(2)	0.04(1)
H(13)	0.164(4)	-0.061(3)	-0.196(2)	0.02(1)
H(14)	0.017(3)	-0.320(3)	-0.198(1)	0.01(1)
H(15)	-0.181(3)	-0.229(3)	-0.094(1)	0.01(1)
H(16)	0.045(3)	0.030(3)	-0.064(2)	0.01(1)
H(171)	0.109(7)	-0.264(7)	-0.415(3)	0.11(2)
H(172)	-0.101(9)	-0.245(8)	-0.445(4)	0.17(3)
H(173)	-0.077(9)	-0.431(8)	-0.453(4)	0.16(2)
H(181)	-0.869(6)	-0.573(6)	-0.201(2)	0.09(2)
H(182)	-0.697(8)	-0.401(7)	-0.184(3)	0.13(2)
H(183)	-0.655(9)	-0.580(8)	-0.157(4)	0.16(3)
H(50)	0.451(6)	-0.120(5)	-0.053(2)	0.08(1)
H(70)	0.043(7)	-0.349(6)	0.037(3)	0.10(2)
Toluene				
C(1a)	-0.4031(10)	0.0399(9)	-0.5501(6)	0.127(7)
C(2a)	-0.4300(11)	0.1149(9)	-0.4886(7)	0.188(7)
C(3a)	-0.5303(10)	0.0775(9)	-0.4379(5)	0.115(6)
C(4a)*	-0.5689(22)	0.1611(16)	-0.3645(10)	0.147(9)
H(1a)	-0.312	0.070	-0.587	0.139
H(2a)	-0.363	0.189	-0.491	0.139
H(4a1)*	-0.512	0.251	-0.360	0.158
H(4a2)*	-0.716	0.221	-0.368	0.158
H(4a3)*	-0.519	0.068	-0.309	0.158
Water				
O(w)*	0.5000	0.5000	0.0000	0.340(17)
H(1Ow)*	0.555	0.454	0.011	0.409
H(2Ow)*	0.421	0.502	0.050	0.409

* 0.5 occupancy

Table 4.3

Final anisotropic thermal vibrational parameters for non-hydrogen atoms in diacid 1b (e.s.d's are in parentheses).

Atom	U_{11}	U_{22}	U_{23}	U_{23}	U_{13}	U_{12}
C(1)	0.032(2)	0.025(2)	0.031(2)	0.009(1)	0.001(1)	0.006(1)
C(2)	0.036(2)	0.033(2)	0.032(2)	0.014(1)	0.005(2)	0.011(2)
C(3)	0.036(2)	0.035(2)	0.042(2)	0.011(2)	0.007(2)	0.013(2)
C(4)	0.041(2)	0.037(2)	0.043(2)	0.019(2)	0.001(1)	0.015(2)
C(5)	0.041(2)	0.035(2)	0.032(2)	0.015(1)	0.004(1)	0.009(2)
C(6)	0.037(2)	0.028(2)	0.033(2)	0.009(1)	0.005(1)	0.009(1)
C(7)	0.053(2)	0.024(2)	0.029(2)	0.006(1)	-0.002(1)	0.010(2)
C(8)	0.072(3)	0.043(3)	0.032(2)	0.011(2)	0.002(2)	0.008(2)
C(9)	0.112(4)	0.083(4)	0.030(2)	0.003(2)	-0.009(2)	-0.005(3)
C(10)	0.079(4)	0.112(5)	0.057(3)	0.010(3)	-0.023(3)	-0.014(3)
C(11)	0.058(3)	0.055(3)	0.063(3)	0.005(2)	-0.009(2)	-0.003(2)
C(12)	0.048(2)	0.038(2)	0.043(2)	0.003(2)	-0.004(2)	0.008(2)
C(13)	0.032(2)	0.034(2)	0.030(2)	0.012(2)	0.006(1)	0.015(1)
C(14)	0.038(2)	0.030(2)	0.027(1)	0.009(1)	0.006(1)	0.015(1)
C(15)	0.031(2)	0.029(2)	0.027(1)	0.009(1)	0.003(1)	0.011(1)
C(16)	0.034(2)	0.027(2)	0.030(1)	0.009(1)	0.004(1)	0.013(1)
C(17)	0.151(5)	0.087(4)	0.048(3)	0.016(3)	0.048(3)	0.026(4)
C(18)	0.050(3)	0.089(4)	0.161(6)	0.056(4)	0.036(4)	-0.002(3)
C(19)	0.032(2)	0.031(2)	0.031(2)	0.011(1)	0.002(1)	0.012(2)
C(20)	0.035(2)	0.034(2)	0.031(2)	0.013(1)	0.004(1)	0.011(2)
N(1)	0.053(2)	0.058(2)	0.068(2)	0.031(2)	0.022(2)	0.032(2)
N(2)	0.061(2)	0.052(2)	0.038(2)	0.022(1)	0.006(2)	0.017(2)
O(1)	0.089(2)	0.116(3)	0.081(2)	0.053(2)	0.049(2)	0.066(2)
O(2)	0.089(3)	0.148(3)	0.110(3)	0.070(2)	0.039(2)	0.091(3)
O(3)	0.106(3)	0.085(2)	0.069(2)	0.054(2)	0.027(2)	0.051(2)
O(4)	0.088(2)	0.086(3)	0.046(2)	0.032(2)	0.029(2)	0.043(2)
O(5)	0.039(1)	0.043(1)	0.053(1)	0.002(1)	-0.005(1)	0.021(1)
O(6)	0.039(1)	0.046(2)	0.039(1)	0.004(1)	-0.005(1)	0.015(1)
O(7)	0.078(2)	0.039(2)	0.028(1)	0.010(1)	-0.004(1)	0.020(1)
O(8)	0.085(2)	0.034(2)	0.033(1)	0.010(1)	0.005(1)	0.023(1)
O(9)	0.098(2)	0.058(2)	0.037(1)	0.010(1)	0.025(2)	0.016(2)
O(10)	0.046(2)	0.098(3)	0.100(3)	0.000(2)	-0.013(2)	-0.002(2)

Table 4.3 contd...

Toluene						
C(1a)	0.086(5)	0.102(6)	0.194(9)	-0.012(5)	-0.032(5)	0.046(4)
C(2a)	0.093(5)	0.084(6)	0.210(10)	-0.014(6)	-0.036(6)	0.050(5)
C(3a)	0.081(5)	0.083(5)	0.180(8)	-0.017(5)	-0.045(5)	0.019(4)
C(4a)	0.140(10)	0.071(9)	0.230(10)	0.030(10)	-0.070(10)	0.027(8)
Water						
O(w)	0.430(20)	0.170(10)	0.410(20)	0.000(10)	-0.190(20)	0.080(10)

List of Publications

1. G.R.Desiraju and *C.V.K.Sharma*, "C-H...O Hydrogen Bonding and Topochemistry in Crystalline 3,5-Dinitrocinnamic Acid and Its 1:1 Donor-Accepter Complex with 2,5-Dimethoxycinnamic Acid", *J. Chem. Soc., Chem. Commun.*, 1991, 1239.

2. *C.V.K.Sharma*, K.Panneerselvam, T.Pilati and G.R.Desiraju, "Molecular Recognition *via* C-H...O Hydrogen Bonding. Crystal Structure of the 1:1 Complex 4 Nitrobenzoic Acid-4(N,N-dimethylamino)benzoic Acid", *J.Chem. Soc., Chem. Commun.*, 1992, 832.

3. B.Kumar, *C.V.K.Sharma*, K. Panneerselvam, L. Shimoni, H.L. Carrel, D.E. Zacharias and G.R. Desiraju, "Solid State Supramolecular Assembly *via* C-H...O Hydrogen Bonds: Crystal Structures of the Complexes of 1,3,5-Trinitrobenzene with Dibenzylideneacetone and 2,5-Dibenzylidene cyclopentanone", *J. Chem. Soc., Chem. Commun.*, 1993, 1473.

4. *C.V.K.Sharma*, K.Panneerselvam, T.Pilati and G.R.Desiraju, "Molecular Recognition Involving an Interplay of O-H...O, C-H...O and π...π Interactions. The Anomalous Crystal Structure of the 1:1 Complex 3,5-Dinitrobenzoic Acid-4(N,N-Dimethylamino)benzoic Acid", *J. Chem. Soc., Perkin Trans., 2,* 1993, 2209.

5. *C.V.K.Sharma* , K. Panneerselvam, T. Pilati and G.R.Desiraju "Crystal and Molecular Structure of Methyl 3,5-Dinitrocinnamate". *Acta Crystallogr., Sect.* C, 1994, 000.

6. *C.V.K.Sharma* and G.R.Desiraju "C-H...O Hydrogen Bond Patterns in Crystalline Nitro Compounds: Studies in Solid State Molecular Recognition." *J. Chem. Soc., Perkin Trans., 2*, 1994, 000.

7. *C.V.K.Sharma*, K.Panneerselvam, L. Shimoni, H. Katz, H.L. Carrell and G.R.Desiraju, "3 -(3',5'-Dinitrophenyl) 4 -(2',5'-Dimethoxyophenyl) Cyclobutane, 1, 2-Dicarboxylic Acid: Engineered Topochemical Synthesis, Molecular and Supramolecular Properties", *Chem. Mater.* 1994, 000.