

CHAPTER- 3

COMPUTATIONAL TECHNIQUES

3.1 COMPUTATIONAL CHEMISTRY

Computational chemistry or molecular modelling is the science and art of studying molecular structure and function through model building and computation. It is fairly cheap, fast, and environmentally safe compared to experiment. It does not replace experiment, which remains the final arbiter of truth about nature. However, theoretical studies can be extremely helpful, essentially at different levels: (i) supporting and complementing the experimental results to determine electronic structure of molecule; (ii) dissecting and quantifying the role of different effects in determining the spectroscopic properties of a given molecular system; and (iii) predicting electronic, molecular and spectroscopic properties for novel or modified systems. For this reason, computational chemistry is rapidly evolving from a highly specialized research field into a versatile and fundamental tool for the study of physical and chemical aspects of molecular systems. Various methods have been used to explain molecular properties in computational chemistry. The methods encompass *ab initio*, semi-empirical, density functional theory, molecular dynamics and molecular mechanics methods.

3.1.1 *Ab initio* method

The term *ab initio* is Latin for “from the beginning” or “from first principles”. *Ab initio* calculations are based on the Schrödinger equation. These calculations give very good qualitative results and can yield increasingly accurate quantitative results as the molecules in question become smaller (Hehre, 1976). The advantage of *ab initio* methods is that they eventually coverage to exact solution once all the approximations are made sufficiently small in magnitude. There are four sources of error in *ab initio* calculations: the Born-Oppenheimer approximation, the use of an incomplete basis set, incomplete correlation and the omission of relativistic effects. The disadvantage of *ab initio* methods is that they are expensive. These methods often take enormous amounts of computer central processing unit time, memory and disk space. These methods are relatively slow.

3.1.2 Semi empirical method

Semi empirical calculations are like *ab initio*, based on the Schrödinger equation. These methods can provide results accurate enough to be useful, particularly for organic molecules with computation requirements low enough to make them convenient on personal computer. Semi empirical methods are generally good for predicting molecular geometry and energies. These methods can be used for predicting vibrational modes and the transitions structures but do so less reliably than *ab initio* methods. Semi empirical

calculations generally give poor results for van der Waals and dispersion intermolecular forces, due to the lack of diffuse basis functions (Young, 2004).

3.1.3 Density Functional Theory method (DFT)

Recently, DFT is method of choice for many problems in physics and chemistry. Density functional calculations are, like *ab initio* and Semi empirical calculations, based on Schrödinger equation. However, unlike the other two methods, DFT does not calculate wave function, but rather derives the electron distribution (electron density function) directly. A functional is a mathematical entity related to a function. Density functional calculations are usually faster than *ab initio*, but slower than Semi empirical (Lewars, 2016). DFT is relatively new method and its limitations are still nuclear.

3.1.4 Molecular dynamics method

Molecular dynamics is a simulation of the time-dependent behavior of a molecular system such as, vibrational motion or Brownian motion. Running Molecular dynamics is often more difficult than running single-molecule calculations. The input must specify not only the molecular structure, but also the temperature, pressure, density, boundary condition, time steps, annealing schedule and more (Young, 2004). The actual calculations can be easily as computationally intensive as *ab initio* calculations due to the large amount of information being simulated and the large number of iterations needed to obtain a good statistical description of the system.

3.1.5 Molecular mechanics method

The term molecular mechanics was coined in the 1970s to describe the application of classical mechanics to determine physico-chemical properties of molecules. The advantages of molecular mechanics methods are that it allows the modeling of enormous molecules, such as proteins, steroids, segments of deoxyribonucleic acid etc. This is why it is the primary tool of computational biochemists. It also models intermolecular forces well. The disadvantage of molecular mechanics is that there are many chemical properties that are not even defined within the method, such as electronic excited states. Since chemical bonding terms are explicitly included in the force field, it is not possible without some sort of mathematical manipulation to examine reactions in which bonds are formed or broken. In order to work with extremely large and complicated systems, molecular mechanics software packages often have powerful and easy-to-use graphic interfaces. (Hinchliffe, 2005).

3.2 DENSITY FUNCTIONAL THEORY METHOD

In 1964, Pierre Hohenberg and Walter Kohn (Hohenberg & Kohn, 1964) proved that the ground state molecular energy, wave function and all other molecular electronic properties of molecules with a non-degenerate ground state can be uniquely determined by the ground state electron probability density $\rho_0(X, Y, Z)$, a function of only three variables. The ground state electronic energy 'E' is a function of ρ_0 ie, $E_0 = E_0(\rho_0)$ where the

variables in the brackets denote a functional relation. Density functional theory attempts to calculate 'E₀' and other ground state molecular properties from the ground state electron density 'ρ₀'.

DFT analysis was originally formulated for a non-degenerate system in the ground state, where there exists a one to one mapping between the external potentials and the electron densities. Once the electron density is known, the external potential and consequently the Hamiltonian, the wave function calculated may be used to determine the desired molecular properties. DFT calculations require about the same amount of computation resources as Hartee-Fock theory. DFT methods are attractive because they include in their model the effect of electron correlation and hence receive ever-increasing popularity in the chemical community due to its capability to treat electron correlation with low computational cost.

Basic theory

The basic notion in DFT, that the energy of an electronic system can be expressed in terms of its density instead of wave functions. That is, the chief element of DFT is the electron density. Owing to the enormous rise in popularity in chemistry and physics DFT was rewarded with the Nobel Prize for chemistry in 1998 to Walter Kohn (for developing DFT) and to John Pople (for his developments of computational methods in quantum chemistry in general). Viewed from this perspective, the success of DFT is truly remarkable

and must be considered as very fortunate for the development of theory in chemistry. The entire theory of DFT rests on two fundamental mathematical theorems proved by Walter Kohn and Pierre Hohenberg and the derivation of a set of equations by Kohn and Sham in the mid- 1960s. The practical application of this theory was developed by Kohn and Sham who formulated a method similar in structure to the Hartree-Fock (HF) method as well as the common current realization of DFT is through the Kohn-Sham (KS) approach (Kohn & Sham, 1965).

In KS theory, we assume that the time-dependent density $\rho(r, t)$ is represented in terms of a time-dependent reference Slater determinant $|t\rangle$. The KS energy is then written as a functional of this density in the following manner:

$$E[\rho, t] = T_s[\rho] + V_{ext}[\rho, t] + J[\rho] + E_{xc}[\rho] + V_{NN} \quad (3.1)$$

The first term is the kinetic energy evaluated as an expectation value.

$$T_s = -\frac{1}{2} \sum_i \langle t | \nabla_i^2 | t \rangle \quad (3.2)$$

Whereas the second and third terms represent, respectively, the classical Coulomb interactions of the electron density with the external potential and with itself,

$$V_{ext}[\rho, t] = V_N[\rho] + V[\rho, t]$$

$$= \int \rho(r, t) \left(\sum_I \frac{Z_I}{|r-R_I|} + v(r, t) \right) d\tau$$

$$J[\rho] = \frac{1}{2} \iint \frac{\rho(r_1, t)\rho(r_2, t)}{r_{12}} d\tau_1 d\tau_2 \quad (3.3)$$

In Eqn.3.3, we have split the external potential into a static nuclear potential and as explicitly time-dependent perturbation. The exchange correlation functional $E_{xc}(\rho)$ in Eqn. 3.1 contains all two-electron interactions except the Hartree term $J[\rho]$, that is, it includes the effects of exchange and correlation. In addition, it corrects for the error made in the evaluation of the kinetic energy according to Eqn. 3.2. The last term in Eqn. 3.1 represents the classical nuclear-nuclear repulsion energy.

In the widely used adiabatic approximation, which we have adopted here, the time-dependence of the exchange-correlation energy is contained in the density, that is, the exchange-correlation functional is approximated using the same functional form in the time-dependent and time-independent cases. It is not obvious that this approximation holds for other than slowly varying external fields, but it has been verified that the adiabatic approximation is adequate for calculating excitation energies (Bauernschmitt & Ahlrichs 1996).

In KS theory, the time evolution of the spin orbitals is governed by the differentiation equation

$$[f(r_1, t) + v(r_1, t)]\phi_j(r_1, t) = i \frac{d\phi_j(r_1, t)}{dt} \quad (3.4)$$

Where we have introduced the KS operator,

$$f(r_1, t) = h(r_1) + j(r_1, t) + v_{xc}(r_1, t) \quad (3.5)$$

The first term in Eqn. (3.5) contains the one-electron combined kinetic and nuclear-attraction operators.

$$h(r_1) = -\frac{1}{2}\nabla_1^2 + \sum_i \frac{Z_i}{|r_1 - R_i|}$$

Whereas the last two terms are the Coulomb and exchange-correlation potentials, respectively,

$$j(r_1, t) = \int \frac{\rho(r_2, t)}{|r_1 - r_2|} d\tau_2 \quad (3.6)$$

$$v_{xc}(r_1, t) = \left. \frac{\delta E_{xc}}{\delta \rho(r_1)} \right|_{\rho(r_1)=\rho(r_1, t)} \quad (3.7)$$

These terms are themselves functional of the density.

3.3 GAUSSIAN PROGRAM PACKAGE

Gaussian '09 is powerful software that can perform density functional theory calculations. Gaussian is capable of predicting many properties of molecules and reactions including,

- Molecular energies and structures
- Energy and structure of transition states
- Vibrational frequencies

- IR and Raman spectra
- Molecular orbitals
- Bond and reaction energies
- Reaction pathways
- Atomic charges, etc.

3.3.1 Basis Sets

Practically, the effective on-electron KS equations are nonlinear partial differential equations that are iteratively solved by representing the electronic wave functions by a linear combination of a set of basic functions or basis sets, which yield molecular orbitals. DFT methods use a wide range of basis sets to perform theoretical calculations. The molecular orbital is expressed as linear combination of a predefined set of one-electron functions known as basis function as

$$\text{Optimal wave function, } \phi_j = \sum_{i=1}^N a_{ij} \psi_i$$

Where, a_{ij} are molecular orbital expansion coefficients.

In one-electron system, the lowest energy molecular orbital would thus define the ‘ground state’ of the system, and the higher energy orbitals would be ‘excited states’. Obviously, as these are different molecular orbitals, they have different basis function coefficients. An approximate wave function can be made up from molecular orbitals which are themselves approximated by

linear combinations of atomic orbitals. The atomic orbitals are themselves constructed from combinations of basic functions. The list of all basis functions used is called the basis set.

Basis set (Basis functions) → Atomic Orbitals → Molecular Orbitals → Wave function

The Gaussian program package offers a wide range of predefined basis set, which may be classified by the number and type of basic functions that they contain;

Minimal Basis Sets: (STO-3G)– It is simplest possible atomic orbital representation. They use fixed-size atomic type orbitals. Each of the basic functions in the STO-3G representation is, three Gaussian functions have been contracted to expand a Slater Type Orbitals.

Split Valence Basis Sets: (3-21G, 6-31G, 6-311G)– Split valence basis set have two sizes of basis function for each valence orbital and allow orbitals to change size, but not to change shape. Each core atomic orbital in the 6-31G basis set is expanded in terms of six Gaussians, while basis functions representing inner and outer components of valence atomic orbitals are expanded in terms of three and one Gaussians.

Polarized Basis Sets: (6-31G*, 6-31G**, 6-311G*, 6-311G**)– Polarized basis sets, by adding orbitals with angular momentum beyond what is required for the description of each atom in the ground state, allow orbitals to change

the shape. The 6-31G(d,p) basis set also represent as 6-31G** which contains d and p functions. This may be addressed by providing d-type functions on main-group elements (valence orbitals are of s and p-type) and p-type functions on hydrogen (valence orbital is of s-type).

Diffuse Functions– Basis sets with diffuse functions are important for system where electrons are relatively far from the nucleus, situation like anionic cationic systems. They need to be supplemented by diffuse s and p-type functions on heavy atoms. It is also possible to add diffuse functions to hydrogens. Diffuse functions are designated by ‘++’ as in 6-311++G** (Hehre 1976).

3.4 FREQUENCY CALCULATION

In reality, the nuclei in molecules are constantly in motion. In equilibrium states, these vibrations are regular and predictable, and the molecules can be identified by their characteristic spectra. Gaussian can compute the vibrational spectra of molecules in their ground and excited state. In addition to predicting the frequencies and intensities of spectral lines, the program can also describe the displacements a system undergoes in its normal modes. It can predict the direction and magnitude of the nuclear displacement that occurs when a system absorbs quantum of energy. Analytic second derivatives are available for the Hartree-Fock (HF) and density functional theory (DFT). Frequency calculations are valid only at stationary points on the

potential energy surface (PES), thus frequency calculations must be performed on optimized structures.

3.5 SCALING PROCEDURE

Scaling procedure is the determination of vibrational frequencies by *ab initio* computational methods is becoming increasingly important in many areas of chemistry. One such area is the identification of experimentally observed reactive intermediates for which the theoretically predicted frequencies can serve as fingerprint. The overestimation of *ab initio* harmonic vibrational frequencies is, however, found to be relatively uniform, and as a result generic frequency scaling factors are often applied. Good overall agreement between the scaled theoretical harmonic frequencies and the anharmonic experimental frequencies can then usually be obtained. The determination of appropriate scale factors for estimating experimental fundamental frequencies from theoretical harmonic frequencies has received considerable attention in the literature. Hartree-Fock can predict IR and Raman frequencies, with an overestimation of about 10-20% due to the neglect of electron correlation and anharmonicity. The advent of DFT has provided an alternative means of including electron correlation in the study of the vibrational frequencies of moderately large molecules. Thus, it has become essential to scale the vibrational frequencies to produce good agreement with the experimental values. To find the optimum values of scaling factor, least

square procedure is adopted (Scott and Radom, 1996). Scaling factor can be determined by minimizing the residual

$$\Delta = \sum_i^{all} (v_i^{theory} - \lambda v_i^{expt})^2 \quad (3.8)$$

Resulting in scaling factor,

$$\lambda = \frac{\sum_i v_i^{theory} v_i^{expt}}{\sum_i (v_i^{expt})^2} \quad (3.9)$$

3.6 FRONTIER MOLECULAR ORBITAL ANALYSIS

In principle, there are several ways to calculate the excitation energies. The first, and the simplest one, involves the difference between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of a neutral system. This form corresponds to the frozen orbital approximation, as the ground state properties are used to calculate excitation values. The conjugated molecules are characterized by a small highest occupied molecular orbital-lowest unoccupied molecular orbital (HOMO-LUMO) separation, which is the result of a significant degree of ICT from the end-capping electron-donor groups to the efficient electron-acceptor groups through π -conjugated path. The strong charge transfer interaction through π -conjugated bridge results in substantial ground state donor-acceptor mixing and the appearance of a charge transfer band in the electronic absorption spectrum. The HOMO and LUMO topologies show certain overlap of two orbitals in the middle region of the π -conjugated systems, which is a

prerequisite to allow an efficient charge transfer transition (Wemple, 1972, Del *et al.*, 1998; Bishop *et al.*, 1997). Molecular orbital and their properties such as energy are very useful for physicists and chemists. This is also used by the frontier electron density for predicting the most reactive position in π -electron systems and also explains several types of reaction in conjugated system (Fukui *et al.*, 1952). The Eigen values of LUMO and HOMO and their energy gap reflect the chemical activity of the molecule. Recently the energy gap between highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) has been used to prove the bioactivity from intramolecular charge transfer (ICT) (Padmaja *et al.*, 2009; Ravikumar *et al.*, 2008).

3.7 TIME-DEPENDENT DENSITY FUNCTIONAL THEORY

The time-dependent density functional theory (TD-DFT) (Runge & Gross, 1984) is usually found to be a robust and accurate method for describing low-lying excited states of conjugated molecules and has consequently been applied to solve countless chemical and physical problems. The TD-DFT method was used to calculate energies, oscillator strengths of electronic singlet-singlet transitions and the absorption wavelengths. Solvent effects were calculated using the polarizable continuum model (PCM) by (Miertus *et al.*, 1981; Miertus & Tomasi, 1982; Cossi *et al.*, 1996). The

absorption spectra of organic compounds stem from the ground-to-excited state vibrational transition of electrons.

3.8 NATURAL BOND ORBITAL ANALYSIS

Natural bond orbital (NBO) analysis is an effective technique for studying hybridization and covalency effects in polyatomic wave functions, based on local block eigenvectors of the one-particle density matrix. NBOs are conceived as a "chemist's basis set" that corresponds closely to the picture of localized bonds and lone pairs as basic units of molecular structure. In the NBO analysis, the electronic wave function is interpreted as a set of occupied Lewis-type orbitals, paired with a set of formally unoccupied non-Lewis-type orbitals. The electronic interactions within these orbitals, the deviations from the Lewis electronic structure, and the delocalization effects can be interpreted as charge transfer between the filled Lewis orbitals (donors) and the theoretically empty non-Lewis orbitals (acceptors). The magnitude of these delocalization effects can be determined from an analysis of the off-diagonal elements in the Fock matrix in the NBO basis by taking into account of all possible donor-acceptor interactions and then by calculating the strength of them all by second-order perturbation theory.

The NBO for a localized σ bond σ_{AB} between atoms A and B is formed from directed orthonormal hybrids h_A , h_B [natural hybrid orbitals (NHOs)]

$$\sigma_{AB} = c_A h_A + c_B h_B \quad (3.10)$$

The natural hybrids in turn are composed of a set of effective valence-shell atomic orbitals [natural atomic orbitals (NAOs)], optimized for the chosen wave function. The important feature of the filled NBOs σ_{AB} of the "natural Lewis structure" is both orthonormality and maximum occupancy, leading to describe the covalence effects in molecules. Similarly the NBOs σ_{AB}^* that are unoccupied in the formal Lewis structure is used to describe the non-covalence effects.

$$\sigma_{AB}^* = c_A h_A - c_B h_B \quad (3.11)$$

This antibond σ_{AB}^* arises from the same set of atomic valence-shell hybrids that make σ_{AB} , which represent the unused atomic valence space formally unsaturated by covalent bond formation. Small occupancies of these antibonds correspond to deviations from the idealized Lewis picture and thus to small non-covalent corrections to the picture of localized covalent bonds. The symbols σ and σ^* are formally used to refer to filled and unfilled orbitals of the formal Lewis structure, though the former may represent core orbitals (c), lone pairs (n), and σ or π bonds etc., and the latter may be σ^* or π^* antibonds, extra-valence-shell Rydberg (r) orbitals, etc., according to the specific case. The interaction between filled orbitals of one subsystem and vacant orbitals of another subsystem can be used as a measure of the delocalization or hyperconjugation. The hyperconjugative interaction energy can be deduced from the second order perturbation approach

$$E^{(2)} = -n_{\sigma} \frac{\langle \sigma | F | \sigma \rangle^2}{\epsilon_{\sigma^*} - \epsilon_{\sigma}} = -n_{\sigma} \frac{F_{ij}^2}{\Delta E} \quad (3.12)$$

where $\langle \sigma | F | \sigma \rangle^2$, or F_{ij}^2 is the Fock matrix element between the i and j NBO orbitals, ϵ_{σ} and ϵ_{σ^*} are the energies of σ and σ^* NBO's, and n_{σ} is the population of the donor σ orbital. The transfer of electron density between subsystems may be small but these values are chemically significant since 0.001 e of charge transfer is almost equivalent to 1 kcal mol⁻¹ of the stabilization energy.

3.9 HIRSHFELD SURFACE ANALYSIS

A new technique of exploring crystal packing modes and intermolecular interactions in molecular crystals is described by using Hirshfeld surfaces to partition crystal space. These molecular Hirshfeld surfaces were named in honour of Fred Hirshfeld's stockholder partitioning, divide the crystal into regions where the electron distribution of a sum of spherical atoms for the molecule (the promolecule) dominates the corresponding sum over the crystal (the procrystal). These surfaces reflect intermolecular interactions in a novel visual manner, offering a previously unseen picture of molecular shape in a crystalline environment. Surface features characteristic of different types of intermolecular interactions can be identified and such features can be revealed by color coding distances from the surface to the nearest atom exterior or interior to the surface, or by functions of

the principal surface curvatures. These simple devices provide a striking and immediate picture of the types of interactions present, and even reflect their relative strengths from molecule to molecule. A complementary two-dimensional mapping is also presented, which summarizes quantitatively the types of intermolecular contacts experienced by molecules in the bulk and presents this information in a convenient color plot (McKinnon *et al.*, 2004, Spackman and Jayatilaka, 2009).

3.9.1 Crystal explorer

Crystal Explorer is a standard tool for investigating intermolecular interactions and packing in crystalline materials by using Hirshfeld surface analysis which is also includes powerful tools to generate surfaces based on *ab initio* quantum mechanical property densities. By mapping these properties and other distance and curvature-related metrics on Hirshfeld surfaces, Crystal Explorer gives unique insights into the in-crystal environment.

3.9.2 Hirshfeld surface

The Hirshfeld surface (McKinnon *et al.*, 2004, Spackman and Byrom, 1997) of a molecule in a crystal is constructed by partitioning space in the crystal into regions where the electron distribution of a sum of spherical atoms for the molecule (the promolecule) dominates the corresponding sum over the crystal (the procrystal). Following Hirshfeld (Hirshfeld, 1977) a molecular

weight function $w(r)$ can be defined as: $\rho_A(r)$ is a spherically-averaged atomic electron density centred on nucleus A, and the promolecule and procrystal are sums over the atoms belonging to the molecule and to the crystal, respectively. The Hirshfeld surface is then defined in a crystal as that region around a molecule where $w(r) \geq 0.5$. That is, the region where the promolecule contribution to the procrystal electron density exceeds that from all other molecules in the crystal. The Hirshfeld surface represents a measure of the space occupied by a molecule in a crystal and as such summarizes information on all intermolecular interactions and contacts concurrently, decoding this information both qualitatively and quantitatively. They are used in visualizing molecular crystals, their size, global attributes of their shape and local descriptors of shape using curvature. Hirshfeld surfaces were introduced quite recently in the context of partitioning molecular crystals into molecular regions for the purposes of electron density integration (Spackman and Byrom, 1997). Since then, we have obtainable grey scale three-dimensional isosurfaces for a variety of molecular crystals (McKinnon *et al.* 1998a) and demonstrated their relationship with fused vdW sphere and electron density isosurface representations of molecules in crystals of naphthalene and terephthalic acid (McKinnon *et al.*, 1998b). The two-dimensional fingerprint plots, providing numerous examples of their application to molecular crystals (Spackman and McKinnon, 2002).

3.9.3 Property mapped on the surface using color graphics

To explore the use of five different functions mapped in color on the Hirshfeld surfaces are d_e , mean curvature, Gaussian curvature, curvedness, shape index. The simplest and most immediate useful property to map onto the surface is d_e . It means that the distance from the surface to the closest nucleus external to the surface. This property provides an abrupt picture of the nature of intermolecular contacts in the crystal. Similarly the distance from the surface to the closest nucleus internal to the surface is called as d_i (Mckinnon *et al.*, 2004). The range of d_e and d_i across the Hirshfeld surface varies considerably depending on size and interaction of the atoms in the crystal molecule. (Mckinnon *et al.*, 2004).

3.9.4 d_{norm}

d_{norm} is a normalized contact distance. Normalized contact distance is defined as the sum of d_i and d_e quantities (Mckinnon *et al.* 2007).

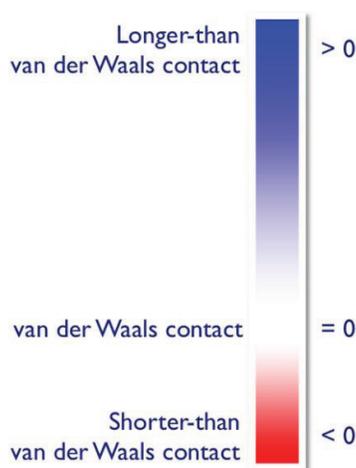


Fig. 3.1: d_{norm}

On the d_{norm} surface, the red, blue and white color regions are corresponding to the intermolecular interactions closer to the total of their van der Waals radii, greater than (vdW) radii and approximately equal to (vdW) radii, respectively.

From the definition of d_{norm} above means that close contacts, which indicates on the Fig. 3.1 d_{norm} . Hirshfeld surface as red spots, must occur in pairs of identical size, either on another region of the same Hirshfeld surface, or on a neighbouring one. Curvedness and Shape Index The Hirshfeld surface defines the shape of the molecule in terms of its neighboring crystalline environment and it provides some chemical insight (Fig.3.2) shows a surface normal n , and u , v are the principal directions .

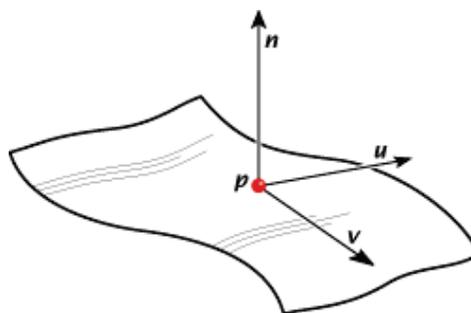


Fig. 3.2: Schematic diagram of a surface normal n and two principal directions u and v

At any point p on the surface, we can determine the outward normal, and there exist two principal directions u and v along which the principal curvatures κ_1 and κ_2 are calculated. The two conventional measures of curvature, the mean curvature, H , and the Gaussian curvature, K , do not provide much physical information. (Koenderink, 1990, Koenderink and Van

Doorn, 1992) has introduced two more useful measures of surface curvature, the curvedness, C , and the shape index, S . Curvedness is a function of the root-mean-square curvature of the surface, with flat areas of the surface having a low curvedness and areas of sharp curvature having a high curvedness. Areas on the Hirshfeld surface with high curvedness tend to divide the surface into contact patches with each nearest molecule, so that the curvedness of the Hirshfeld surface could be used to define a coordination number in the crystal. (Mckinnon *et al.*, 2004)

Shape index is a qualitative measure of shape and can be sensitive to very subtle changes in surface shape, particularly in regions where the total curvature (curvedness) is very low. One important attribute of the shape index is that two regions where the shape index differs only by a sign represent complementary "stamp" and "mould" pairs. This means that maps of shape index on the Hirshfeld surface can be used to identify complementary hollows (with shape index < 0) and bumps (with shape index > 0). Key references provide numerous examples of the application of shape index and curvature to a wide variety of molecular crystals (Mckinnon *et al.*, 2004, Spackman and Jayatilaka, 2009).

3.9.5 Fingerprint plots

The 2D-fingerprint of the Hirshfeld surface represents a novel method for summarising the complex information contained in a molecular crystal structure into a single, unique full color plot, which provides a 'fingerprint' of

the intermolecular interactions in the crystal. Derived from the Hirshfeld surface, these 2D-fingerprint plots provide a visual summary of the frequency of each combination of d_e and d_i across the surface of a molecule, so they not only indicate which intermolecular interactions are present, but also the relative area of the surface corresponding to each kind of interaction. For each point on the Hirshfeld surface (Fig.3.3) we determine both d_e and d_i . Each point on the 2D fingerprint plot corresponds to a unique (d_e, d_i) pair, and the color of each point corresponds to the relative area of the surface with that (d_e, d_i) pair.

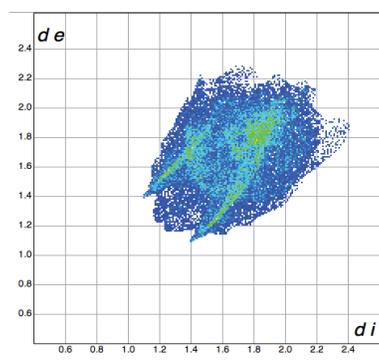


Fig. 3.3: Fingerprint plot

Points on the plot with no contribution on the surface are left uncolored, and points with a contribution to the surface are colored blue for a small contribution through green to red for points with the greatest contribution. All fingerprint plots are colored on the same relative scale, so some fingerprint plots do not have any red points. Because Hirshfeld surfaces nearly fill the available space, so void spaces are small, these 2D fingerprint plots are pseudo-mirrored along the $d_e=d_i$ diagonal. Features along the

diagonal occur due to like···like contacts (H···H contacts), while the 'wings' on the plot are due to the C-H··· π interaction (Spackman and Mckinnon, 2002).