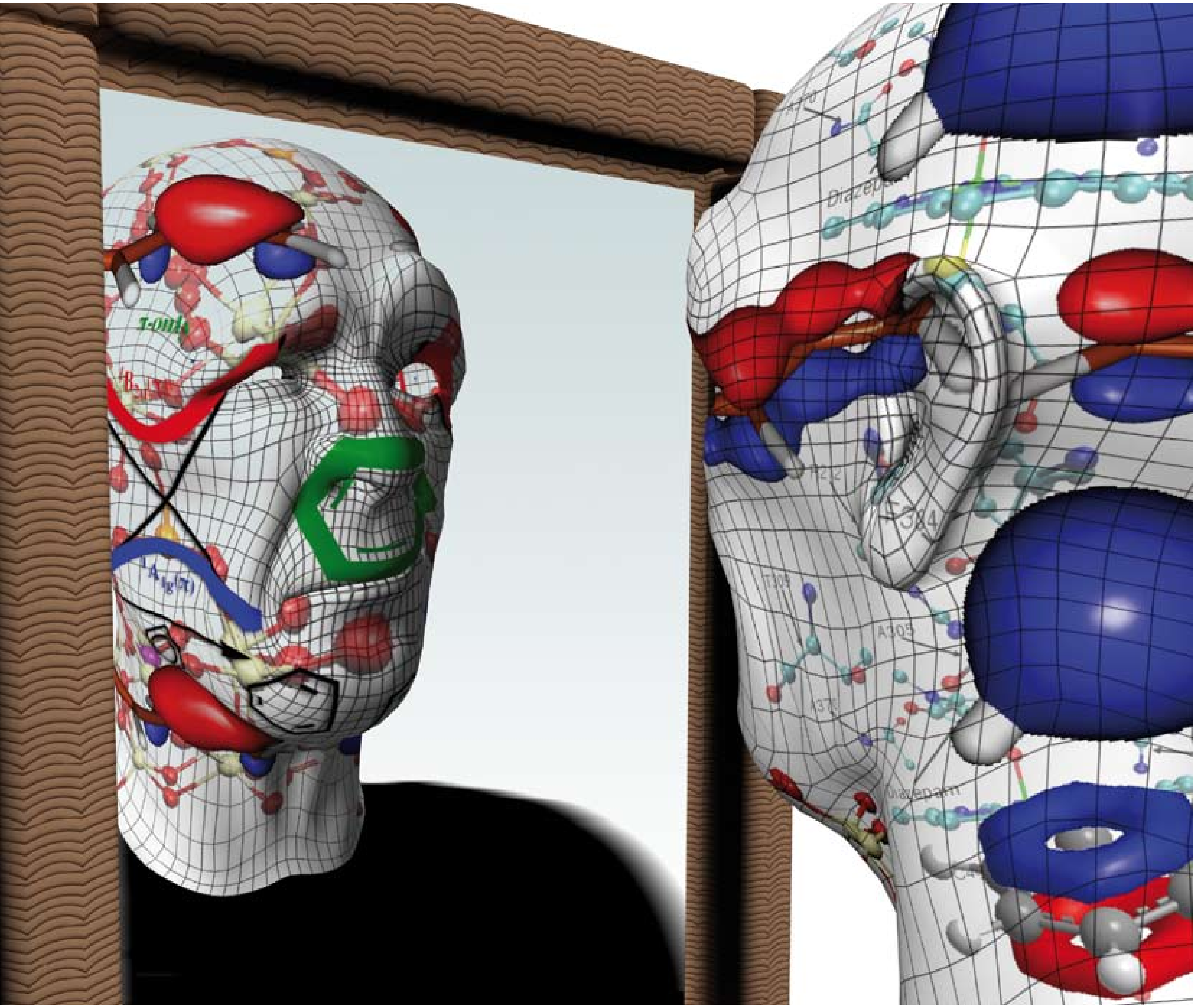
View Article Online / Journal Homepage / Table of Contents for this issue

NJC

New Journal of Chemistry
An international journal of the chemical sciences
www.rsc.org/njc
Volume 31 Number 12 | December 2007 | Pages 1981–2128



ISSN 1144-0546

RSC Publishing

CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

30TH ANNIVERSARY ARTICLE
Sason Shaik
Is my chemical universe localized or delocalized? is there a future for chemical concepts?

1144-0546(2007)31:12;1-6

Is my chemical universe localized or delocalized? is there a future for chemical concepts?†

Sason Shaik

Received (in Montpellier, France) 30th July 2007, Accepted 24th September 2007
First published as an Advance Article on the web 5th October 2007
DOI: 10.1039/b711641c

The essay discusses the interplay between the two major concepts of molecular description: the localized and delocalized representations. It is shown by means of examples that *crossing through the looking glass between the two conceptual worlds intensifies the insight*. The role of concepts as generators of our worlds is stressed and it is argued that concepts are needed more than ever in to-day's computational quantum chemistry.

Downloaded by University of Belgrade on 01 January 2013
Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C

1 Preamble

The *New Journal of Chemistry* was established 30 years ago as an initiative by Lionel Salem to create a new forum for fresh unorthodox ideas in chemistry. The journal was called then *Nouveau Journal de Chimie* (*NJC*), and under the guidance of Lionel Salem, *NJC* kept its policy of open spirit and became a haven of unorthodox concepts. In 1980, when I was a young lecturer at Ben-Gurion University, I began developing ideas that dealt with a valence bond (VB) representations of reactivity and of the behavior of the π-electrons of benzene. VB theory was considered at that time passé if not outright wrong and I had difficult time to publish my papers; I was desperate! With advice from Roald Hoffmann, "*send your paper to NJC, they are more open minded*", I turned to *NJC* and managed to publish there three key papers that dealt with these concepts.[1] In many ways these three papers were door openers for others that have followed since and been published in a variety of journals. This essay is my modicum dedication to the New Journal of Chemistry in its celebration of its 30th anniversary. Let me comment briefly about the contents of this essay:

During my PhD days, with Nicholaos Epiotis, and later during the postdoc year I spent with Roald Hoffmann, I was exposed to the wonderful and enigmatic world of chemical concepts. There was a dominant family of concepts that derived from the delocalized molecular orbital (MO) representation of molecules, while in the background there were concepts nascent from Lewis and valence bond (VB) theory where molecules were presented as localized objects, and these seemed like faint murmurs echoing from an "older world". Fiddling with MO → VB projection and watching the localized ↔ delocalized orbital acrobatics of Roald Hoffmann in deriving the "isolobal analogy", I have slowly learnt to cross the mirror between these conceptual worlds of chemistry, and it was a lot of fun and very enriching! In the meantime I also became a computational chemist, and have been witnessing how theoretical quantum chemists have been gradually laying aside the conceptual aspects of theory in favor of emphasis on the details of computational technology. Following Coulson's "two-cultures nightmare" speech in Boulder in 1960,[2] and in the spirits of the title of Hoffmann's Nobel Lecture, "Building Bridges...",[3] and Coulson's admonition: "*give me insight and numbers*", I wish to dedicate this viewpoint to concepts and to the enriching experience of walking between conceptual worlds.

Sason Shaik was born in 1948 in Iraq. The family immigrated to Israel in the Exodus of the Iraqi Jewry. He has received his BSc and MSc in chemistry from Bar-Ilan University, and his PhD from the University of Washington with Nicolaos D. Epiotis. In 1978–1979 he spent a Post Doctoral year with Roald Hoffmann at Cornell University. In 1980 he started his first academic position as a Lecturer at Ben-Gurion University where he became Professor in 1988. He subsequently moved, in 1992, to the Hebrew University, where he is currently the director of The Lise Meitner-Minerva Center for Computational Quantum Chemistry. His research interests are in the use of quantum chemistry to develop paradigms, which can pattern data and lead to the generation and solution of new problems. During 1981–1992 the main focus of his research was on valence bond theory and its relationship to MO theory, and during this time he has developed a general model of reactivity based on a blend of VB and MO elements. During these years he and his co-workers have demonstrated the applicability of this model in particular and of VB theory in general to a variety problems in chemical bonding and reactivity. Starting 1994, he has entered the field of oxidation and bond activation by metal oxo catalysts and enzymes, an area where he has contributed a few seminal ideas (e.g., two-state reactivity), which lead to resolution of major controversies and make new predictions.

The Institute of Chemistry and the Lise Meitner Minerva Center for Computational Quantum Chemistry, The Hebrew University, 91904 Jerusalem, Israel

† The HTML version of this article has been enhanced with a colour image.

Downloaded by University of Belgrade on 01 January 2013
Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C

Fig. 1 A mud castle in the Moroccan desert.

2 A few words about concepts

Concepts are generators of our worlds and the creative means whereby these worlds evolve and change.[4] This idea pervades everything that surround us; our entire physical world is just a manifestation of our concepts. Look at this mud castle, in Fig. 1, it is a manifested concept of the human mind (a dream haven, a shelter?), made from countless unrelated sand particles, its virtual existence adorns the desert…

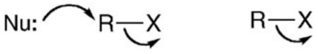
Chemists differ in their attitude towards concepts. Some of us fight about concepts, like those endless fights about localized–delocalized nature of molecules which were discussed in a recent conversation.[5] Others use concepts permissively as heuristic aids.[6–9] These two approaches to concepts are rooted back in the 18th Century in the different attitudes of two of Chemistry's forefathers, Lavoisier (concepts must be tight and economical) and Priestley (concepts can be creatively fuzzy, measurements must be accurate).[10] In the present days of computing capabilities, one hears the argument that all the simple concepts of chemistry in fact dissolve in the computer,[11,12] or in 'thin air',[13] and some go as far as suggesting *that theory is the calculation itself*. In this respect, the opening paragraph of this section is my simplest answer to the second title question—there is no science without concepts. I will however, argue in more details in this essay in favor of concepts especially in these days of computing-dominated theory.[14]

Regarding the first question in the title: chemists have traditionally exhibited a split consciousness when it comes to the question of localized *vs.* delocalized representations of chemical matter. At present, most chemists actually think with a localized representation, and at the same time they carry out computations with delocalized-dominated software packages, and many hold the belief that the delocalized description is the only correct representation of molecules, while the localized picture is somehow archaic and/or wrong.[15,16] Not all chemists, but many… To further understand this split consciousness, I am going to try and discuss this title question in the broader context of the naissance of the localized–delocalized dichotomy in chemistry, primarily because this aspect is associated also with the genesis of chemistry as a modern science and with the creation of a universal language for the representation of the molecular universe. Historical facts will be mentioned but with no intention to write an essay about history of chemical concepts. Readers interested in historical details related to this essay may find them in a recent publication,[17] as well as in other professional historical accounts mentioned throughout the essay.

Fig. 2 Lewis with the colon symbol for a covalent bond (with courtesy of W. B. Jensen).

3 Some conceptual roots in chemistry

Chemistry has evolved as an independent scientific and philosophical discipline owing to a few concepts that are still with us. The first one is the concept of "elements" pragmatically defined by Lavoisier, and later transformed by Dalton into physical bodies called "atoms". Atoms were not new terms in natural philosophy, but it was Dalton who effectively implemented the atom concept in chemistry by its definition as *a quantum of weight of matter*.[18–20] He ushered thereby the "constitutional revolution", which culminated in the notions of valence, molecule, and structure.[18] The second concept is the "bond", which emanated from the older notions of "elective affinity" and then "valence", and which culminated in the "electronic structure revolution" of Lewis.[19] Thus in a single paper and a single symbol (the colon in Fig. 2),[21] Lewis defined the *quantal building block* from which we are able to construct an entire chemical universe.[19] The Lewis concept and the many ideas in his paper have subsequently inspired the English school of reaction mechanisms to articulate electronic reorganization in molecules in terms of the curly arrow in Scheme 1, the notions of electrophile, nucleophile, mesomeric and inductive effects, and the classification of reaction mechanisms.[21–24] The bond concept has also been instrumental in the enhanced development of synthetic organic chemistry as an intellectual science with architectural elements of construction and retro-synthetic principles.



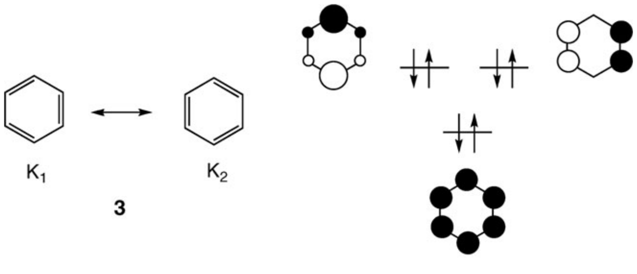
1 **2**

Scheme 1 Curly arrows describe electron reorganization in S_N2 and S_N1.

Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C
Downloaded by University of Belgrade on 01 January 2013

Starting in the 1930s, the new quantum theory has entered chemistry. Here I have to digress for a moment and remark about the current tendency to classify chemistry as a service science and a sub-branch of physics,[25] presumably so, because it falls under the sovereignty of quantum mechanics. I dislike this description of the situation in terms of a father science and a submissive science, and have doubts it can be seriously considered by scientists who are familiar with chemistry and its creative elements,[7,10,26] or even by physicists who wrote against reductionism in science.[27] I would rather think in terms of cross fertilization between two independent sciences, which I feel is a more balanced picture. Thus despite the origins of quantum mechanics in physics, one must remember that chemists have been the first to employ quantum-notions in their science, starting with the quantized weight of matter, going to the quantal building-blocks of structure, and the quantal magic numbers, such as octet and duet rules that control the number of bonds a molecule will possess. One wonders how much did these ideas affect physics? I do not know that anyone has ever studied this question seriously. More so, the very first paper of the new quantum chemistry that dealt with the nature of the chemical bond, the paper by Heitler and London,[28] was actually a dressing of the Lewis bond by the language of quantum mechanics. Pauling recognized this link and Lewis' priority in a paper[29] and in the enthusiastic letter he wrote to Lewis to let the latter know that his idea of a bond rests on a firm theoretical ground.[30] Chemistry was not really a submissive passive science in the story of the chemical bond; it was a partner science with a full share if not the pioneering science!

During the early 1930s, Pauling has imported this emerging theory to chemistry and was referring to it as valence bond (VB) theory and thereby paying homage to the originators of the concept of valency and to his chemical heritage. In his hands, VB theory was a superposition theory of Lewis structures, which was later to be called resonance theory. The most famous cartoon of resonance theory is concerned with benzene **3**, Scheme 2. Pauling's book "*The Nature of the Chemical Bond*",[31] was dedicated to Lewis. Indeed, Pauling's work was a theoretical construct that cleverly and faithfully dressed the Lewis notion of a bond with a theoretical guise that could be presented in the new language of the Schrödinger equation in terms of a wave function and a Hamiltonian that extracts the energy of the molecule from this wave function.[17] The Pauling–Lewis theory constituted the localized representation of the chemical world, where the great majority of molecules would be described by a single Lewis structure having a set of localized bonds and lone pairs, whereas the minority of molecules required a few Lewis structures to be represented properly (*e.g.*, **3**). The obvious affinity of resonance theory to the Lewis concept and to the ideas of the Ingold school of physical organic chemistry[32] further entrenched the localized representation of the molecular universe in terms of local bonds and lone-pairs. Most chemists still use this representation!



3

4

Scheme 2 Benzene in localized and delocalized representations.

Quite at the same time, another theory,[17] nascent from the spectroscopic studies of Hund[33] and Mulliken,[34] called molecular orbital (MO) theory was ushered into mainstream chemistry, initially by Mulliken and subsequently by Hückel[35] who devised a simple topological theory that allowed him to treat large molecules. Following Lennard-Jones' treatment of the dioxygen molecule,[36] Hückel applied a clever idea of σ–π separation[35] and focused on the π-electronic structure of conjugated molecules. One of his earliest treatments was benzene **4** in Scheme 2 and its description in terms of delocalized MOs was the archetypal example of the delocalized paradigm.[37] Here, the π-system of benzene was one, the electrons were distributed all over the molecule in all the MOs and there was no need to move electrons to and fro as in the localized picture (**3**). As discussed by Berson,[26] the Hückel MO (HMO) theory was received with suspicion by chemists, who where subscribers of the Lewis–Pauling localized representation of molecular species, and who were not accustomed to the new language of secular determinants and secular equations, nor to the MOs that were spread all over the molecule. Where are my bonds? Was the silent outcry of the suspicious *chymist*.

While HMO was held back and awaiting its chance (that came in the 1950s), Mulliken and Pauling who have been contemporaries and influential figures were competing on charting the mental map of chemistry.[32,38,39] Initially the Pauling school had the upper hand and the localized representation dominated chemical thinking. Mulliken ascribed this dominance to the communication skills of Pauling, and so did Hager, Pauling's biographer.[32,40] Certainly Pauling was a great communicator, but science is not only about communication. It must be recalled that, in those days, computationally both MO and VB theories were not very practical tools for investigating molecules, and with the qualitative advantages of Lewis bonding and resonance theory the localized representation seemed a superior concept. Thus, the Lewis–Pauling theory dominated chemical thought mainly because its localized representation was so much reminiscent of the primal structural concepts of chemistry dating from the days of Kekulé (1829–1896), Couper (1831–1892), Frankland (1825–1899), and others through the electron-pair notion and electron-dot structures of Lewis. Pauling himself emphasized that his VB theory is a natural evolution of chemical experience, and that it emerges directly from the chemical conception of the chemical bond. This has made VB-resonance theory appear intuitive and chemically meaningful in terms of structure and valence. By contrast, MO theory seemed alien to everything chemists had thought about the nature of the chemical bond. Even Mulliken admitted that MO theory departs from the "chemical ideology".[32] And to top it all,

Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C
Downloaded by University of Belgrade on 01 January 2013

back at that period, MO theory offered no visual representation that could compete[32,39] with the resonance hybrid representation of VB-resonance theory, and its direct lineage to the structure of molecules, the heartland of chemistry. At the end of World War II, VB-resonance theory dominated the epistemology of chemists. However, the tide has changed in the 1950s up to the mid 1960s, when several chemical communities took on to the new theory.[32,39] The conceptual advantage of HMO theory was brought to light by the synthesis of new "aromatic" species, which obeyed the Hückel magic number $4n + 2$, while other species with the magic number $4n$ were either unknown or known to be very reactive compared with their $4n + 2$ congeners.[26] Books on HMO theory and its application were written and demonstrated the insight of the theory to practising chemists.[41,42] The synthesis of molecules like ferrocene,[43] for which the MO picture due to Orgel and Dunitz,[43b] was so much more elegant than the resonating theoretical description of Pauling reinforced the notion that the delocalized representation was superior.

At the same time, semiempirical MO methods started to appear which allowed to treat large molecules and to consider σ-electrons as well.[32,39] Great communicators[44–46] of MO theory like Coulson[45] and Dewar[46] started to offer visual representations of the delocalized picture and re-chart thereby the mental map of chemistry. The Woodward–Hoffmann Rules,[47] and in retrospect also the Frontier MO (FMO) theory of Fukui,[48] which patterned a great deal of data on pericyclic reactions and made many predictions that were successfully tested by chemists, highlighted the role of orbital symmetry and hence underscored the eminence of the delocalized representation. Hoffmann and his school have continued and demonstrated the unifying power of the delocalized representation in almost every area of chemistry. The connection of the delocalized MOs (canonical MOs) to observables in spectroscopy (*e.g.*, ionization energies and the work of the late Edgar Heiblronner and Hans Bock and others)[17,38,44] has further established a credibility nexus between MO theory and experiment.

This dominance of the delocalized representation has further intensified with the development of *ab initio* computation methods, which started somewhere in the 1960s but was ripened in the early 1970s when Pople and his collaborators introduced GAUSSIAN 70, which was based on MO theory and which enabled the calculation of molecular species and reactions, without any *à priori* assumption (other than the used basis set). The delocalized picture became the consensus and resonance and VB theories were slanted and considered to be archaic, if not simply wrong theories.[17,38]

Despite this seemingly decisive crush, still chemists have been teaching the localized picture in terms of Lewis structures, VSPER[49] (used for the 3-D representation of molecules) and resonance theory and using it to design syntheses and/or think about reaction mechanisms. Thus, many parts of the chemical community have been functioning with split consciousness between the localized and delocalized worlds. And although this "doubled consciousness" is arguably advantageous (see later), the "conceptual war" has never really subsided. One of the later reverberations of the struggle between localized and delocalized approaches is the classical–nonclassical controversy regarding the structure of the 2-norbornyl cation.[50] Much as this controversy has never been completely settled (the cation is still arguably different in magic acid and under solvolytic conditions), the preoccupation of chemists with localized–delocalized picture is still continuing.[51,52]

While computational methods implemented with delocalized orbitals have dominated the way chemists are computing their molecules or reactions, there has been an ever-growing counter-tide of applications of the localized approach to a variety of problems in chemistry. This counter-tide is perhaps a clear message that the localized representation is more easily implemented in human thought process, even if the delocalized representation is more easily implemented by computing machines. Thus, VB theory, although muted in main stream chemistry, has continued to live very well in several communities; those of chemical dynamics,[53] photochemistry,[54–56] electron transfer chemistry,[57] and in solid state chemistry (*e.g.*, conductivity, *etc.*), where the localized representation seemed indispensable. Starting the late 1970s, there has been an intense surge of concepts that rely on localized representation, and some examples follow: The recent interest in multiple bonding between transition metals[58–60] emphasized the great insight brought about using the hybridization concepts[60] to understand unusual structural features of molecules, and the development of natural resonance theory (NRT), which allows to discuss molecular structure and bonding in terms of resonance theory.[61,62] The powerful "isolobal analogy"[3] uses a localized representation of bonding and moves to and fro between the representations. The reactive-bond orbital (RBO) approach, which finds the "identity" of the orbitals that are responsible for a given interaction between molecules, and yields nice localized orbitals rather than the usual HOMO and LUMO delocalized orbitals.[63] There is a VB approach that treats chemical reactivity and reaction mechanisms with a localized and semi-localized representations, going back and forth between the representations.[64] VB methods and models allow to derive new ideas on chemical bonding.[65] VB ideas are prominently useful in analyzing enzymatic reactivity.[66] There are thriving theories of photochemical reactions based on conical intersections in the localized representation.[53–56] And of course, theories of conductivity use localized representations, and so on and so forth. So, the pendulum continues to swing between the alternatives: delocalized or localized, which one is better or truer? How can we continue with the split reality in which we compute with one approach and think with the other?

Before we can grapple with these questions, we must mention the serious cloud that looms over the orbital-related concepts as a whole by the advent of density functional theory (DFT) in chemistry and the electron density based approaches. On the one hand, DFT relies on the density (ρ), which is a delocalized molecular property and therefore the theory brings a measure of support to the conception of a delocalized chemical universe. On the other hand, in the eyes of many in our community, with DFT the entire simple orbital picture collapses altogether because, as the argument goes: ρ and the energy (E) are "the only real quantities that count". It is true that the Kohn–Sham (KS) orbitals look like MOs;[67] they are

This journal is © the Royal Society of Chemistry and the Centre National de la Recherche Scientifique 2007

Downloaded by University of Belgrade on 01 January 2013
Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C

delocalized and follow the symmetry of the molecule. However, since one can in principle solve the DFT problem without invoking any orbitals at all, this leads to arguing that the density is self-sufficient with no need anymore for orbitals.[68] But since the bond concept is immensely useful, most density-only proponents devise density probes for locating bonds such as in AIM and in ELF. [69] In AIM theory,[69a] bonds are recognized by bond paths, while in ELF theory,[69b,c] bonds are defined by molecular basins and their population. However, both these probes need to be computed and cannot be foretold without performing the calculations. In some cases the emerging bond paths defy chemical understanding. What aggravates the situation is that there is a growing school for which the computations itself is the theory with no need for further conceptualization. If one accepts this verdict then indeed, all our concepts seem to dissolve in the computer. I shall try to counter this verdict. For the time being, let me recall a second admonition attributed to Wigner who wrote: "*It is nice to know that the computer understands the problem. But I would like to understand it too*". Understanding relies on concepts, which brings us back to the question of localized *vs.* delocalized concepts in chemistry.

4 Sampling complementary parts of chemical reality: bridges between representations

Moving between worlds if fun, and like "*Alice Through the Looking Glass*" it is also a way of sampling additional bits of reality. Those things that are seen through the glass seem merely reversed and the unification of the pictures is naturally a stage in higher understanding. In this Section I will discuss a few examples where traversing the borders between localized and delocalized representations has been enriching.

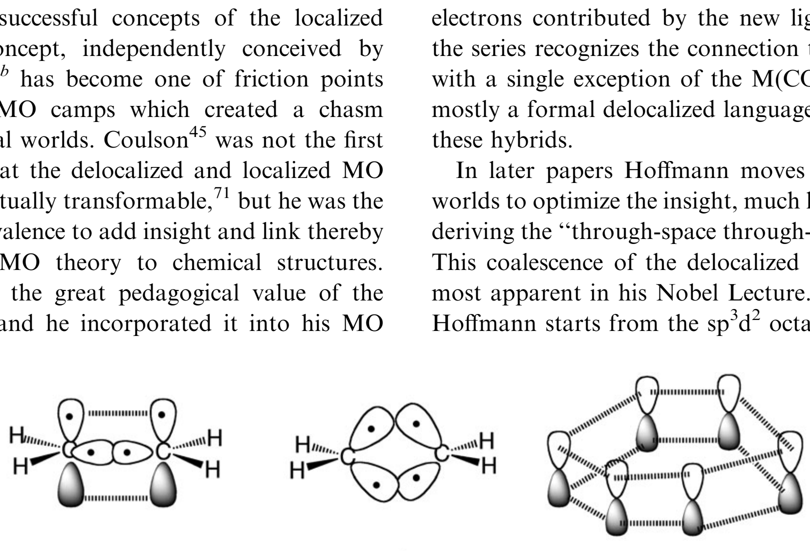
4.A Incorporation of localized elements in the delocalized representation

4.A.1 Coulson and the hybridization concept. Hybridization and its connection to molecular geometry was one of the earliest and most successful concepts of the localized representation. This concept, independently conceived by Pauling[70a] and Slater,[70b] has become one of friction points between the VB and MO camps which created a chasm between these conceptual worlds. Coulson[45] was not the first to recognize the fact that the delocalized and localized MO representations were mutually transformable,[71] but he was the first to employ this equivalence to add insight and link thereby the "strange-looking" MO theory to chemical structures. Thus, Coulson realized the great pedagogical value of the hybridization concept, and he incorporated it into his MO description of molecules. As argued by Park,[72] the most commonly used picture of ethylene with sp^2 hybridized carbons, which form the σ-skeleton and a π-orbital (as in the Hückel picture), **5** in Scheme 3, is due to Coulson, while Pauling insisted for a long time after on using the sp^3 hybridized carbons with the banana bonds, **6**. Subsequently, in his description of benzene, Coulson used a σ-skeleton of sp^2 hybridized carbons bonded to H's, and a π-system of six overlapping p_π AOs, **7**; later to be known as the "doughnut" model, for which he also defined the "delocalization energy" (not "resonance energy").[73] Thus, while Coulson was not among the originators of MO theory*, he was the one who made it a chemical language by wedding VB-type elements into the theory*. His walking between the localized and delocalized worlds enriched his conceptual input into chemistry and the so resulting vivid imagery caught on and in the end ushered in MO theory into mainstream chemistry.

To day most chemists know, or at least ought to now, that the delocalized MO based wave function and representations based on localized MOs (LMOs) are entirely identical[71,74,75] and provide complementary insight into chemistry. The LMO wave function is not strictly a VB wave function, but it is a nice starting point for jumping all the way to the VB picture,[17] *e.g.*, through the perfectly paired generalized VB wave function (PP-GVB).[76] Pictorially the LMO and GVB-PP wave functions look alike, though the bonds in the GVB-PP wave function involve correlated electrons.[77]

4.A.2 The isolobal analogy. Some years later, Roald Hoffmann, another teacher of MO-theory, went through the looking glass and generated the isolobal analogy between the bonding capabilities of ML_n fragments with $n < 6$ and CH_n ($n < 4$) fragments in organic chemistry. In the first paper in the series, Elian and Hoffmann[78] started out from an octahedral $M(CO)_6$ complex and successively cut CO ligands. The calculations revealed that a hybrid orbital grew on the metal in the missing ligand site, *e.g.*, **8** in Scheme 4. These hybrids can participate in bonding with other ligands depending on the number of d-electrons on the metal and the number of electrons contributed by the new ligand. This first paper in the series recognizes the connection to the VB language, but, with a single exception of the $M(CO)_4$ fragment, it still uses mostly a formal delocalized language of MO theory to derive these hybrids.

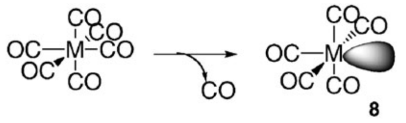
In later papers Hoffmann moves to and fro between the worlds to optimize the insight, much like he did years before in deriving the "through-space through-bond coupling" concept. This coalescence of the delocalized and localized pictures is most apparent in his Nobel Lecture.[3] As shown in Fig. 3(a), Hoffmann starts from the sp^3d^2 octahedral-hybridized metal,



5 **6** **7**

Scheme 3 Electronic structures cartoons used by Coulson[73] for ethylene (**5**) and the π-system of benzene (**7**). Pauling used cartoon **6**.[72]

Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C
Downloaded by University of Belgrade on 01 January 2013



Scheme 4 A hybrid grows at the site of the missing ligand (**8**) of $M(CO)_5$.

and mixes these hybrids with the ligand orbitals to form the octahedral complex, with all hybrids becoming M–L σ-bonds, leaving behind a set of t_{2g} d-orbitals as nonbonding orbitals on the transition metal. Bringing a gradually decreasing number of ligands leaves on the metal an increasing number of hybrids pointing in the direction of the missing ligands, as exemplified for ML_5 in Fig. 3(b), and generalized for ML_n (n = 5–3) in Fig. 3(c).

Then Hoffmann goes back to the delocalized picture by mixing the so remaining hybrids and creating symmetry-adapted orbitals, as shown in Fig. 4, for ML_4 and ML_3 fragments. Now, he has all the tools he needs to buildup new complexes and to expound thereby the isolobal analogy.

An example of this added insight is the bonding of ethylene by the $Fe(CO)_4$ fragment in Fig. 5. Using the symmetry adapted orbitals of $Fe(CO)_4$ one can take advantage of symmetry consideration and use an orbital mixing diagram showing that the symmetric and antisymmetric hybrids find a perfect symmetry match to mix with the π and π* orbitals of C_2H_4, respectively, when the ethylene plane is in the equatorial positions of the octahedron, and are hence responsible for the sizable rotational barrier in the molecule. Furthermore, using the localized representation (at the bottom), one can see that the $Fe(CO)_4(C_2H_4)$ molecule is also a metallacyclopropane, and hence once can understand the non-planar geometry of the ethylene moiety and draw a wide-ranging analogy to other molecules, which bear isolobal relationship. The complementary pictures intensify the insight. Duly, the isolobal analogy continues to have a productive impact on the chemical community.

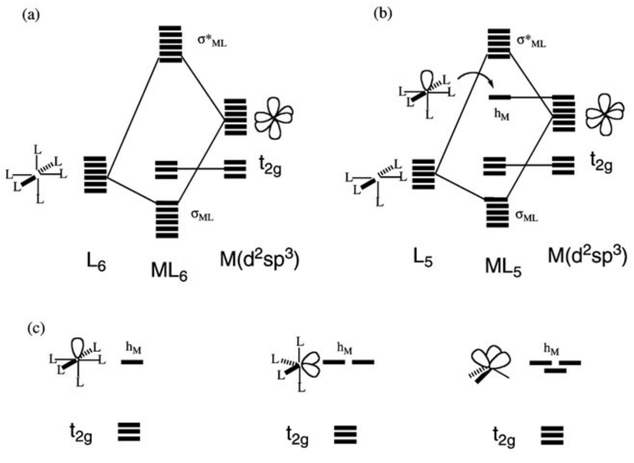


Fig. 3 LMOs of ML_n from d^2sp^3 hybridized M and n ligand orbitals.

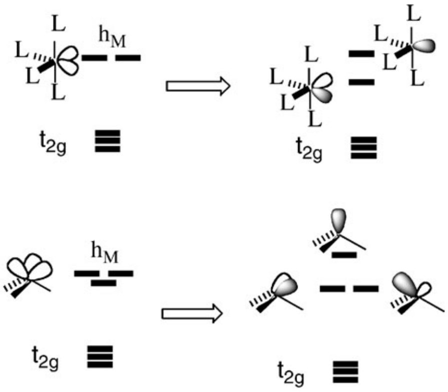


Fig. 4 Generating symmetry adopted MOs from the hybrids of ML_4 and ML_3.

4.A.3 Other examples. In fact all the models that consider molecules in terms of fragment–orbital interactions incorporate localized elements into the delocalized representation. Hoffmann and his school have applied this approach throughout chemistry and showed its powerful insight.[79] Mulliken himself used this approach by formulating his hyperconjugation concept,[80] which was later used in many varieties of orbital-mixing interaction *e.g.*, to describe the "anomeric effect". The now very popular NBO analysis enables one to carry out these orbital interactions on a routine basis after an MO-based or DFT calculations.[62] These ideas are used to understand chemical phenomena, ranging from structure all the way to properties such as anisotropic diamagnetic and paramagnetic properties in NMR. Although it focuses on the energetic aspects, the energy decomposition analyses (EDA) in both MO[81] and DFT[82,83] are other variants of the fragment in molecules approach. The recent block-localized wave function (BLW) approach is also related and allows quantifying the energy consequences of these interactions.[84] A beautiful and constructive essay on the hierarchy and relationships of wave functions from delocalized to localized is given in the work of Malrieu and co-workers.[52]

This infiltration of localized elements into the delocalized representation is a testimony that the human thought process functions like a game of "LEGO" in which understanding of

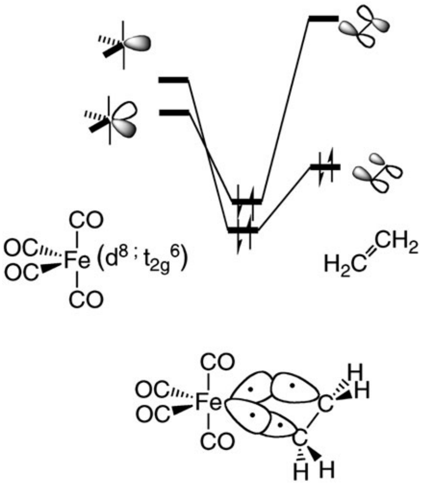


Fig. 5 An MO mixing diagram describing the bonding of $Fe(CO)_4$ with ethylene alongside the metallacycle Lewis-type description.

This journal is © the Royal Society of Chemistry and the Centre National de la Recherche Scientifique 2007

Downloaded by University of Belgrade on 01 January 2013
Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C

the whole rests on the process of its assembly from building blocks.

4.B Extracting localized representations from delocalized pictures

While it is possible to day to calculate molecules with pure VB formalism,[85] the paradigm of this essay concerns the bridges between the worlds. The simplest way of finding these bridges is by starting with the delocalized representation and then applying gradual localization of the wave function. Localization can be achieved by various orbital transformation techniques or by expansions of the MO determinant into its constituent VB determinants, which involve either fragment orbitals (FOs) or atomic orbitals (AOs). In the case we start from a single MO-based determinant, the orbital transformation will generate the LMO wave function, which was discussed above in the works of Coulson and Hoffmann that involved MO–LMO transformations.[74,75] The expansion (or projection) of MO determinants in terms of determinants containing FOs or AOs produces, on the other hand, VB wave functions, which we refer to as FO–VB and AO–VB.[17,38,77] Arguably, the natural resonance theory (NRT) of Weinhold[61] combines the two approaches. I shall discuss now examples of the latter approach.

4.B.1 MO–VB projections. Every delocalized wave function can be expressed in terms of VB structures by a projection procedure. The procedure involves writing down the MO-based wave function, replacing the MOs by their LCAO expressions and then "multiplying" out the diagonal term of the determinant to produce a collection of determinants that are themselves VB structures or can be grouped into such structures.[17,77] This expansion is shown in Fig. 6 for the simplest and well-known case of the H_2 molecule, where the MO wave function is expanded to produce covalent and ionic determinants in equal weights (recall, CI will reduce the weights of the ionics[38]).

For larger molecules, with extended basis sets, the procedure becomes technically more complicated, and requires also regrouping of the VB determinants into VB structures.[77] Nevertheless, such an expansion is helpful for understanding large molecules. This is especially true for the MO–CI wave functions, which are complex and inscrutable even for rather small molecules. For example, the spin polarization in *e.g.*, allyl radical,[86] which is revealed *via* MO–CI wave functions,[87] is due to the dominance of the wave function by the spin-alternant determinant, **9** in Scheme 5. In fact, as has been shown[88,89] one can start from the constituent VB determinants and demonstrate that the resonating allyl radical has a wave function that is dominated by the spin alternant determinant. This is general for the entire polyenyl radicals, in each case; the wave function is dominated by the spin-alternant determinant that has the lowest energy amongst the covalent determinants. The spin-alternant determinant of the higher analog, pentadienyl radical **10**, shows that the spin polarization in the series will fluctuate, with negative density exchanging positions from the center to the sides and back. This insight of the localized representation is instant and portable.

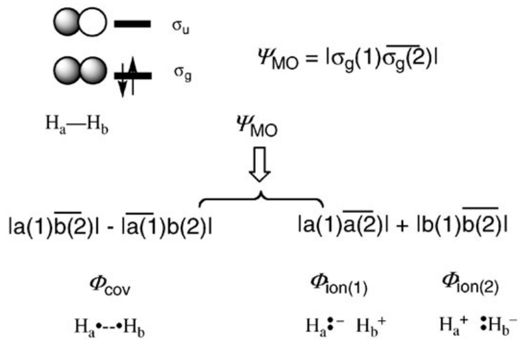
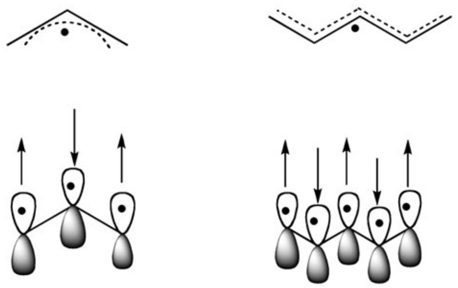


Fig. 6 The VB wave functions contained in the MO wave function of H_2.



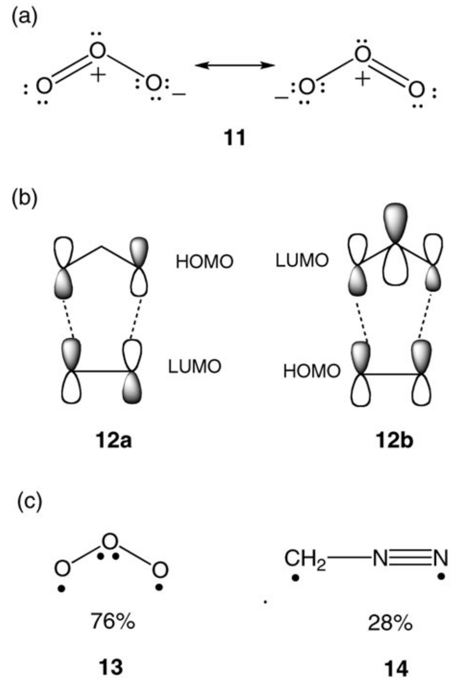
9 **10**

Scheme 5 The VB determinants of allyl (**9**) and pentadienyl (**10**) radicals, which cause the observed, spin polarization. These determinants are contained within the MO–CI description of the radicals.

The first systematic method for MO–VB projection was proposed by Hiberty and Leforestier,[90] who expanded MO and MO–CI wave functions into a set of Rumer structures, which are linearly independent set of chemical structures. As explained by Hiberty in his reviews,[91] the motivation for doing this expansion was to gain insight into chemical puzzles. One of these puzzles was concerned with a special class of molecules, so called 1,3-dipoles (a better name is dipolarophiles), and of which ozone **11** (Scheme 6(a)) is a prototype. These species generated a controversy that was laden with concepts, all of which were reasonable, but at the same time they were separated by the conceptual chasm between MO and VB theories.

Dipolarophiles have great synthetic utility in heterocyclic chemistry and, as shown by Huisgen, participate in polar cycloaddition reactions.[92] Huisgen relied on various experimental data and on the isoelectronic analogy to allyl anion to represented dipolarophiles in terms of two resonance structures, *e.g.* **11** in Scheme 6(a), and argued in favor of a concerted cycloaddition mechanism. Huisgen's conclusions were further supported by a perturbation MO treatment by Eisenstein and Nguyen Trong Anh[93] and Sustmann[94] who showed that the HOMO and LUMO interactions of dipolarophiles and olefins are symmetry matched in a concerted cycloaddition, as depicted in **12a** and **12b** in Scheme 6(b), and accounted also for the observed regioselectivity. By contrast, Firestone used Linnett's VB theory to argue that the dipolarophiles are in fact 1,3-diradicals and therefore their

Downloaded by University of Belgrade on 01 January 2013
Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C



Scheme 6 (a) Ozone (**11**) and its resonance theoretic description as a representative of 1,3-dipoles (dipolarophiles). (b) The HOMO–LUMO interactions for a cycloaddition of a dipolarophile and an olefin. (c) The content of 1,3-diradical structure obtained by MO–VB projection.[91]

cycloaddition reactions were arguably stepwise with due supportive experimental evidence.[95] In such a case where each theory has some support, one naturally wonders: is VB wrong and MO right or *vice versa*? No, of course not. Hiberty's projection of the MO and MO–CI wave functions of the 1,3-dipole reagents revealed very clearly that all these species have a prominent 1,3-diradical character, as shown for two cases, **13** and **14** in Scheme 6(c), where in the case of ozone this is also the dominant VB structure in the MO wave function, Scheme 6(c).[91] This character is implicit, but concealed in the delocalized wave function while being explicit in the VB wave function.

In fact, one can start from a complete set of VB structures and reconstruct the dipolarophiles and all their isoelectronic species with four electrons on three centers, like allyl anion, S_N2 transition states, F_3^-, I_3^-, and so on and so forth; all these species have a 1,3-diradical characters of different weights that can be easily reasoned from VB theory.[1b] This does not mean however, that the reactions of these species will be stepwise or concerted. Thus, the MO–VB projection of Hiberty showed that there was no contradiction between the pictures; these are complementary descriptions of the dipolarophile molecule: VB theory could reveal that the species was a 1,3-diradicaloid, which is not apparent in the MO picture, while MO theory was better at revealing the propensity for concerted cycloaddition reactivity due to orbital symmetry. As summarized in Fig. 7 in all respects, the three-center bonding of MO theory is equivalent to a resonance of three VB structures, two of these are the Lewis structures describing the left- and right-hand bonds, and the third one is the 1,3-diradicaloid known also as the long bond structure.[1b,91]

The MO–VB projection is general and can be applied to a variety of problems. Projection techniques of various kind were used by Cooper *et al.*,[96] Hirao *et al.*,[97] and Malrieu *et al.*[52] NRT is another type of MO–VB projection, which uses density matrices and natural orbitals to obtain weights of resonance structures from a given wave function.[62]

4.B.2 MO–VB projections and chemical reactivity. I allow myself to make a few comments about my own work on generating VB diagrams for chemical reactivity.[98] I am confident that the reader will recognize that this is done for the sake of strengthening the underlying message in this essay.

The motivation for the work[98] was a conceptual puzzle, which preoccupied me as an MO-fan. MO theory could not reveal explicitly the origins of the barrier except for the case of forbidden reactions, where the orbital crossing gave a pictorial origin for the barrier. During my PhD I already had some ideas about the origins of the barrier; however, this became a real preoccupation only during my postdoctoral year in 1979 at Cornell. During that year, I have been exposed to orbital mixing ideas using fragment orbitals (FOs), and could see that there is a straightforward transformation from the fully delocalized MO, to the MO expressed in terms of the FO basis, and further to the LCAO expression. I therefore decided, that the best chances of understanding the origins of the barrier was by computing simple reactions with MO and/or MO–CI based theory and then projecting the wave functions unto more localized ones based on FOs, and subsequently all the way to classical VB wave function based on atomic orbitals or hybrids. As the FOs I chose the orbitals of the reactant state. For example, when projecting the MO wave function for $H:^- + H_2$ as a model of S_N2 reaction, the chosen FOs were those of the fragments $H:^-$ (1s) and H_2 (σ and σ^*),

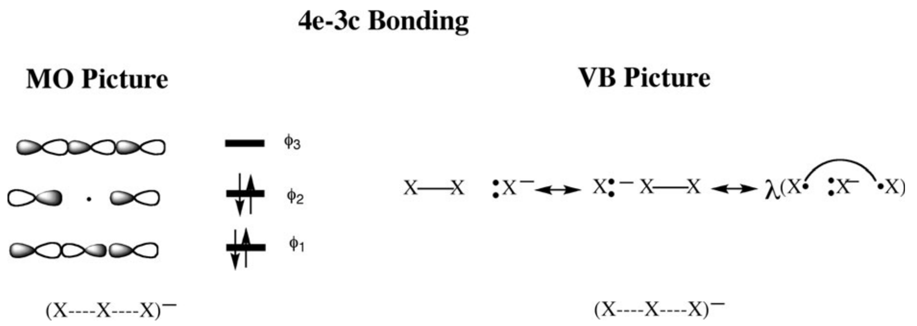


Fig. 7 MO and VB description of three-center–four-electron bonding.

Downloaded by University of Belgrade on 01 January 2013
Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C

and this assignment was kept unchanged throughout the pathway. In so doing, in any reaction tried I observed that the initial reactant wave function was gradually diminishing along the reaction coordinate and being replaced by a collection of FO-based configurations; in the transition state (TS) one of these was dominant, for example in for the $H:^- + H_2$ reaction the dominant FO-configuration was the charge transfer one, involving the following electronic structure, $1s^1\sigma^2\sigma^{*1}$.[98]

Augmentation of the MO wave function by CI enhanced the weight of the leading configuration and further clarified the picture. Use of Hückel orbitals led to the same results, thus demonstrating that the phenomenon was topologically independent of the quality of the orbitals or the wave function. Shifting to "larger" systems, *e.g.*, nucleophilic attack on a double bond of ethylene or formaldehyde, I again retrieved the same description, and the very same picture reappeared in a model electrophilic attack.[98] The inevitable conclusion was that in all electrophile–nucleophile combinations, the barrier arises due to the avoided crossing of the charge transfer and the reactant FO–VB configurations, as shown schematically in Fig. 8(a).

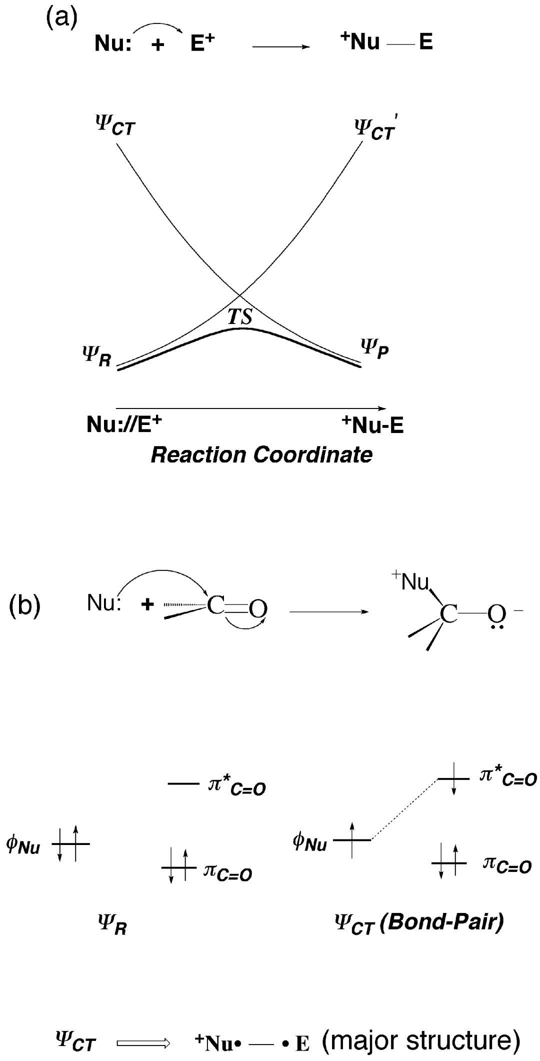


Fig. 8 (a) A valence bond state correlation diagram for reactions between electrophiles and nucleophiles. (b) The reactant and charge transfer FO–VB configurations projected from the MO and MO–CI wave functions for the nucleophilic cleavage of a C=O bond. Ψ_{CT} contains a bond-pair between the reactants which by projection is seen to involve the major AO–VB structure describing the product.[98]

The reason for this uniform avoided crossing picture became clear when the FO–VB charge transfer configuration was projected unto the AO–VB structures, revealing that the charge transfer configuration contained the covalent AO–VB structure of the products, as exemplified for nucleophilic attack on a C=O bond in Fig. 8(b). Thus, the charge transfer FO–VB configuration contained a *bond-pair* between the reactants in the ϕ_{Nu} and $\pi^*_{C=O}$ orbitals that were rehybridized,[98] compared with the original reactant orbitals, to maximize the bond-pair interaction.

Later on, I tried radical attacks, *e.g.*, $H^\bullet + H_2$, and found a similar picture, but now the excited FO–VB configuration involved a triplet excited H_2, coupled to a total of doublet spin with the attacking $H^\bullet$ radical. The Diels–Alder and ethylene dimerization reactions required an FO–VB configuration where both reactants were excited to their triplet states and were coupled to a singlet state across the intermolecular linkages. The reason for this crossing/avoided crossing became apparent upon further projection of these key excited configurations into the VB–AO wave functions. The leading excited FO–VB configuration invariably contained the covalent structure of the product. *The FO–VB configuration itself contained the same number of bond-pairs as the number of bonds in the product state.*

This recognition led in turn to a general mechanism for barrier formation, shown in Fig. 9: the reactants have a specific bond pairing, and the only way to change it is to replace the reactants state by another one in which the reactants are "prepared for bonding" by having spin-paired odd electrons on the reaction centers. Since at the geometry of the reactants, the "prepared state" (***R****) is an excited state of the reactants, this "preparation for bonding" takes expression as crossing/avoided crossing of the two configurations. At the

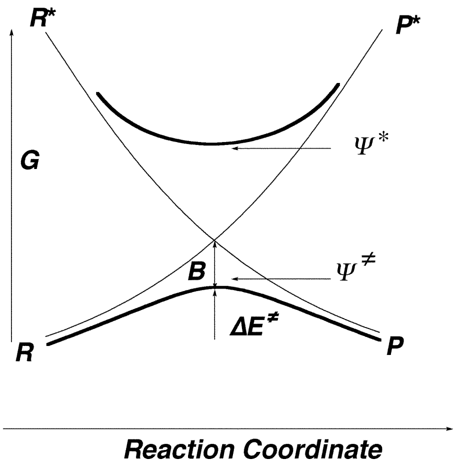


Fig. 9 A generalized VB state correlation diagram for a single step reaction. ***R**** and ***P**** are "the prepared excited states", which hence correlate to products (***P***) and reactants (***R***), respectively. Ψ^* is the twin-excited state of the transition state.

Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C
Downloaded by University of Belgrade on 01 January 2013

crossing point (the lowest one) the two configurations were mixed, avoided the crossing, and generated a transition state for the chemical reaction; the mixing energy was the resonance energy or the delocalization energy of the transition state, *B*.

The advantage of using a localized picture was subsequently revealed, when the VB diagram enabled to rationalize/predict reactivity trends using the promotion energy gap in the diagram (*G*),[1,64,99] and led to understanding how for example, X_3 species varied from being transition states for strong binders (X = H) to stable delocalized intermediates for cases with weaker binders like Li_3.[1b] In balance, the advantage of using the partially delocalized FO–VB picture was *the importing into the VB description a missing element*, orbital symmetry that controlled the value of the resonance energy of the TS. This is precisely the element that was missing in the original VB picture of Evans,[100] who thought simply that the resonance energy of the TS was a quantity that increased with the number of electrons that participated in the reaction. This lack of the orbital symmetry role, was the great divider between the "old" VB theory and the successful MO-based Woodward–Hoffmann Rules.[47] Due to the projection to FO–VB configurations it was possible to augment the new VB approach with the orbital symmetry facility and derive orbital selection rules for chemical reactions.[64] In this manner, the new VB approach to reactivity[64] has become a complete system of thought with quantum mechanical basis, while the older VB approach[100] remained an *ad-hoc* tool used to generate potential energy surfaces.

In the course of time, shifting between the pictures became a habit that was exercised in many different ways, *e.g.*, by defining the FOs in ways congruent with the symmetry of the reactants and products. This enabled a direct analysis of the TS and the formulation of *its twin-excited state* (Ψ^* in Fig. 9),[64,101] with the obvious extension of the model to photoreactivity.[17,38,102] There are many VB representations as there are fragmentation modes one chooses to consider for the VB configurations. One can even describe a molecule like ferrocene with a single VB structure by using symmetry adapted FOs, which include electrons that are coupled into spin-pairs in the VB-mode.[77] Fig. 10 shows for example, the bonding between $Fe(CO)_4$ and ethylene, using the bond diagram in the FO–VB formulation alongside the MO mixing diagram. This compact cartoon describes an FO–VB wave function that contains four determinants, which together describe two bond-pairs, where each electron-pair is allowed to have the permutation of the spin function, $\alpha(1)\beta(2) - \beta(1)\alpha(2)$, as in covalent bonding between two atomic centers (see Fig. 6). The difference compared with a bond like in H_2 is that the orbitals are not anymore hybrids on atomic centers but rather fragment orbitals on more than one center. This wave function is implicitly present in the MO wave function $\psi_1{}^2\psi_2{}^2$ in Fig. 10.

Other approaches that lead to a similar picture of reactivity and structure can be based on NRT,[62] on the BLW technique,[103a] the concept of diabatic molecular orbitals,[103b] or on projection or localization of CASSCF wave function.[52,104]

Surely, with the present computational capabilities, one can use directly VB computations to do many of these tricks, even calculate the VB diagrams for chemical reactions.[85a] However, the "reading" of the MO wave function in terms of VB configurations was essential for the formulation of a credible VB theory of chemical reactivity. But more so, the experience of crossing through the looking glass was immensely rewarding: MO and VB theories were simply "the same" reality dressed in different guises.

5 Concepts in today's computational capability

I think most chemists will agree that there is a definite need for concepts in any living science. Nevertheless, one also hears another view, namely, that a quantum chemical calculation is a solution of the Schrödinger equation and is hence already a theory. Therefore, one does not really need to dig into the calculations for simple concepts, which might or might not be there anymore; all one needs to do is to carry out the calculations at a good and a reliable level.[12] I am not sure that this view appears explicitly in any paper, but the attitude is reflected necessarily in the general form of quantum chemical papers these days; there is an over emphasis on the technical issues of *e.g.*, basis set, level of correlation of the type of functional *etc.* Even though sometimes this is necessary, still I would like to take issue with the overemphasis on technical points at the expense of insight.

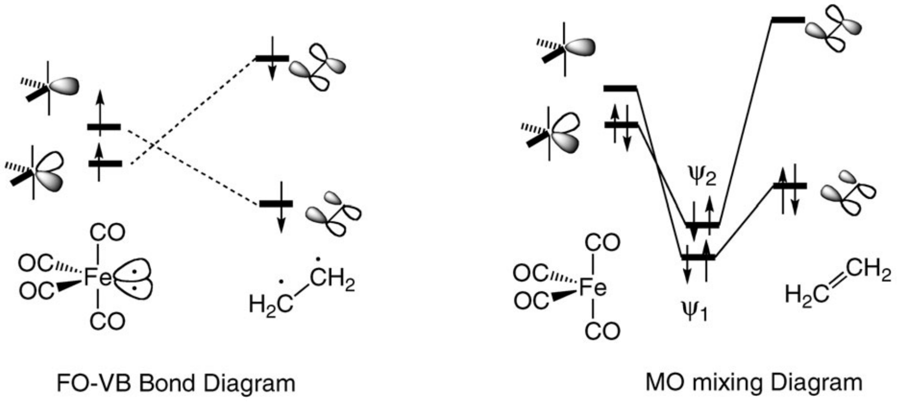


Fig. 10 FO–VB bond diagram and orbital mixing diagram representations of the bonding between $Fe(CO)_4$ and ethylene. The dashed lines in the FO–VB cartoon represent spin pairing of the orbitals connected by the line.

Downloaded by University of Belgrade on 01 January 2013
Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C

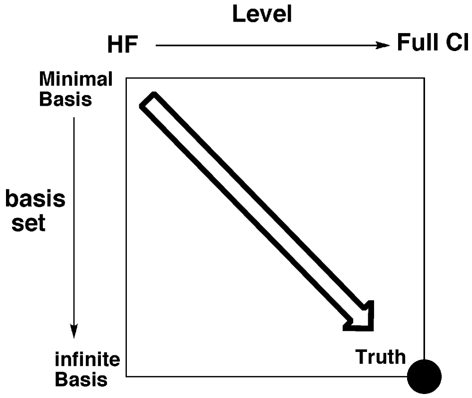


Fig. 11 A schematic representation of the Pople-square paradigm of doing quantum chemical calculations with the Schrödinger equation.

The current arsenal of computational quantum chemistry contains two main machineries: one is the *ab initio* solution of the Schrödinger equation that enables the calculations of relatively small molecules (less than 20 atoms) at the high levels with electron correlation and good basis sets. The second one is DFT that enables the calculations of large molecules with more than 100 atoms, including transition metals.

The *ab initio* solution of the Schrödinger equation follows the classical paradigm of the Pople square, Fig. 11, in which one dimension is the basis set and the other one is the level of correlation. According to this paradigm the way to the "truth" can be achieved by stepping further down the square and augmenting the basis set and level of correlation until the desired property converges. This is in the basis of the "black box" computational approach in quantum chemistry.

The recent paper on the "nonplanarity of benzene" shakes however this paradigm.[105] The paper shows that while in HF or DFT benzene is a nicely planar molecule, correlated levels with the commonly used basis sets give a nonplanar molecule. It was shown that the problem occurs due to imbalance of the basis set in terms of the angular and radial correlations, some sort of BSSE deficiency of the atom in the molecule. This BSSE and its adverse effects has been known for sometimes in other molecules as well.[106] And of course, with acquired expertise, one can take care of this technical problem by selecting balanced basis sets. Although it is a relief to know that this can be taken care of, one wonders how many such problems still lurk in the dark, just consider the problem of CCSD(T) to reproduce the dissociation energy curves of some simple molecules, like O_2, C_2, N_2, *etc*., and the renormalization needed to correct these problems.[107] These problems highlight the fact that the Pople square (Fig. 11) is in fact not a two-dimensional guide but infinitely dimensioned, and although in principle it is a correct paradigm, there are many ways to reach the truth and many ways to go astray. There are no black-box applications except for some well-behaved organic molecules.

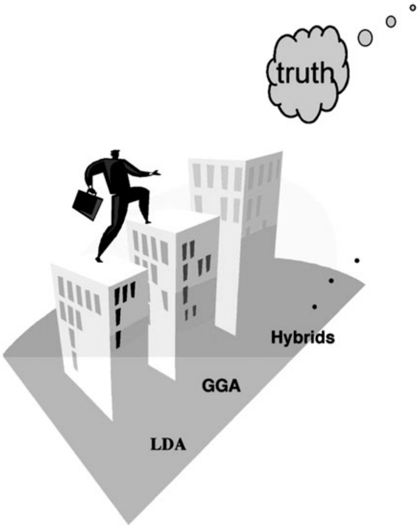


Fig. 12 Jacob's Ladder in DFT.

DFT appears to be a more robust black box. But, using DFT has its own problems. A major difficulty of the theory is the nonphysical self-repulsion of the electron, which cannot be corrected in an obvious and satisfactory manner, as long as the electron is described as a density cloud rather than as a particle as in the Schrödinger equation. Another thorny issue is the description of the density by a single-determinant; this problem too does not have a systematic solution.[108] Nevertheless, DFT is a remarkably efficient tool and the only one available for large molecules, especially ones containing transition metals; I use the tool myself in enzymatic mechanisms and structure. However, after a period of enchantment with this efficient method, chemists began to discover its deficiencies in organic molecules,[109] in transition metal chemistry,[110,111] in barrier heights,[112] and so on. Surely, many problems are handled very well with DFT,[112,113] and one can find a functional that will function better than others for a given problem. It is possible also to design semi-empirically new functionals to treat certain deficiencies by using training sets and reparametrization. While some of these new functionals work fabulously for their problem domains,[112] there is no universal functional that can treat chemical problems across the board with minimal amount of errors; B3LYP is probably overall still the best general purpose functional,[114] but far from being flawless. The major problem of DFT is that it has no paradigm of self-improvement like the Pople-square in Fig. 11. It has instead a Jacob's ladder that starts from LDA going through GGA and then to hybrid functionals, and ... finally to the true functional, Fig. 12. But the fact is that there is no real systematic way to climb this ladder and improve the error. DFT is essentially a semiempirical theory, a good one but still semiempirical.

This state of computational quantum chemistry highlights once again the critical role of understanding as beautifully put by Wigner, "*It is nice to know that the computer understands the problem. But I would like to understand it too*". In my view, concepts become all the more indispensable when our computational tools are fallible. Even in a later-day vision when the tools become perfect, the concept will remain the flashlight in the darkness.[115]

Conclusions and perspectives

There is no living science without concepts, this including computational quantum chemistry and its connection to

Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C
Downloaded by University of Belgrade on 01 January 2013

chemistry. Understanding nanosystems, active species of enzymes and their reactivity, protein-protein interactions, protein folding, noncovalent interactions, and so on are among the many problems that are awaiting quantum chemists. Given that computations will remain fallible and will continue to be done with the delocalized DFT representation, pedagogical concepts must be developed to meet the new demands. It appears that the human brain is more comfortable thinking with localized representations and with constructions of the whole in a LEGO-type process (which the scientific method in a nutshell). Therefore, a productive family of concepts will eventually emerge from the development of ways for reading the delocalized giant wave functions in terms of localized building blocks. This cannot be a simple VB-reading or use of LMOs as done for smaller molecules. Still a VB-type philosophy of large fragments in big systems is what is needed to extract insight and develop bridges between the computations and the thought process that ultimately has to be anchored in chemical reality. An example, of such VB-type insight using large fragments, was recently proposed for the electronic structure of the active species of cytochrome P450 and its sensitivity to the medium.[116] Another problem where such insight was necessary is the electronic structure of oxyheme of myoglobin and its mechanism of formation from deoxyheme.[117]

In fact computational chemistry itself has already been blending delocalized and localized ideologies, for quite sometime. Thus CPU extensive calculations use nowadays methods like LMP2 and LCCSD(T), *etc*., which are based on LMOs alongside the standard methods of using delocalized MOs.[118] Linear scaling methods for large molecules also use LMOs in some regions and usual MOs in others.[119,120] All these developments mean that methodological computational quantum chemistry too has to live with the localized/delocalized dilemma. The strategies employed in these methods may become conducive for the development of new insights and new ways of VB-type deciphering of the wave function.

Noncovalent interactions are extremely important in chemistry and biology.[116,121,122] While there is a tendency to consider these weak interactions as "complexities" unrelated to the electronic structure, this is true in quite a few cases, but untrue in others. For example, in the active species[116] of cytochrome P450 and the resting state of the enzyme,[122] the interactions of the protein residues with the ligands of the heme affect the electronic structure of these species and change their bonding and structural features. There are many examples of these kinds and not only in biological systems *e.g*., the change in mechanism and oxidation state of an iridium complex due to counter ion effect,[121] the role of additives in palladium complexes, *etc*. Thus one can develop concepts that incorporate the complexity into the electronic structure. VB reading of the wave function can be especially effective in this respect, since the noncovalent interactions affect the relative energies of VB structures and hence gauge their resonance mixing.[116] But in some cases,[122] inspection of the noncovalent interaction effects on single MOs of the molecule may lead to the requisite insight.

Still, there are noncovalent interaction effects that are associated with molecular dynamics (MD) of the reactions. A pretty example that comes to mind is the recent study of the enzyme horseradish peroxidase, where only through an MD simulation were it possible to find that a molecule of water appears from the deep of the enzyme to the active site and helps the deprotonation of hydrogen peroxide, and subsequently the water molecule returns to its original location to enable the heterolytic O–O bond breaking that leads to the formation of the active species.[123] *"Purpose" in biological system is dictated by free energy and dynamics*... Still, I would argue that without understanding of the electronic structure of the species of horseradish peroxidase, we would have missed the need for the water molecule and we would have never thought to merge the MD with the QM/MM calculations, which we were doing to study the formation of the active species. There is a vast field and many interesting problems, waiting for new concepts that will come from deeper understanding of molecular dynamics and molecular motions, and will enable chemists to think about these problems and design new experiments. The Car–Parrinello method may be a good tool for developing such insights and related concepts.[124]

Structure is still the heartland of chemistry. A potential drastic change in the core chemical concepts may come from chemistry at very low (sub-milli Kelvin) temperatures, where matter becomes waves and even a molecule like C_{70} exhibits self-interference.[125] In such temperatures, the De Broglie wavelength of the chemical matter is so large ($\lambda \sim h/T^{1/2}$), much larger than the chemical structure, and hence the concept of a localized structure in spaces dissolves; *matter becomes delocalized*. Doing chemistry at these temperatures may lead to new molecules that will localize from the wavy soup as temperature warms up. But then too, one will have to deal with the transition from delocalized to localized matter.

Going through the looking glass will continue to be a most fascinating experience in computational quantum chemistry. Monolithic ideologies are boring.

Acknowledgements

The author is thankful for helpful comments from S. Alvarez, O. Eisenstein, P. C. Hiberty, R. Hoffmann, M. Karni, W. Thiel, and D. G. Truhlar.

References

1 (*a*) S. S. Shaik, *Nouv. J. Chim.*, 1982, **6**, 159; (*b*) S. S. Shaik and R. Bar, *Nouv. J. Chim.*, 1984, **8**, 411; (*c*) S. S. Shaik, P. C. Hiberty, G. Ohanessian and J.-M. Lefour, *Nouv. J. Chim.*, 1985, **9**, 385.
2 C. A. Coulson, *Rev. Mod. Phys.*, 1960, **32**, 170.
3 R. Hoffmann, *Angew. Chem., Int. Ed. Engl.*, 1982, **21**, 711.
4 R. Schecter, *Cosmology and Language*, the Publishing Department of the Israeli Ministry of Defense, Israel, 1999 (in Hebrew). In her book the author discusses the role of a "word" as a creative element of worlds.
5 R. Hoffmann, S. Shaik and P. C. Hiberty, *Acc. Chem. Res.*, 2003, **36**, 750.
6 (*a*) R. Hoffmann, *Synthése*, 2007, **156**, 321; (*b*) R. Hoffmann, *Am. Sci.*, 1988, **76**, 182.
7 E. R. Grosholz and R. Hoffmann, in How Symbolic and Iconic Languages Bridge the To Worlds of the Chemist, in *Of Minds and Molecules*, ed. N. Bhushan and S. Rosenfeld, Oxford University Press, NY, 2000, pp. 230–247.
8 G. Frenking and A. Krapp, *J. Comput. Chem.*, 2007, **28**, 15.

This journal is © the Royal Society of Chemistry and the Centre National de la Recherche Scientifique 2007

Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C
Downloaded by University of Belgrade on 01 January 2013

9 J. A. Berson, *Chemical Discovery and the Logicians' Program—A Problematic Pairing*, Wiley-VCH, Weinheim, Germany, 2003.
10 (*a*) W. H. Brock, *The Norton History of Chemistry*, W. W. Norton & Co., NY, 1993; (*b*) See also, M. Chayut, *History of Chemistry*, The Publishing Department of the Israeli Ministry of Defense, Israel, 2003, in Hebrew.
11 B. T. Sutcliffe, *Int. J. Quantum Chem.*, 1996, **58**, 645.
12 See for example the discussion on pp. 1674–1675 in vol. 90 of *J. Chem. Soc., Faraday Trans.*, 1994.
13 R. S. Muliken, *J. Chem. Phys.*, 1965, **43**, S2.
14 R. Hoffmann, *J. Mol. Struct. (THEOCHEM)*, 1998, **424**, 1.
15 (*a*) P. Atkins and L. Jones, *Chemical Principles, The Quest for Insight*, W. H. Freeman and Co., New York, 1999, p. xxiii and 121–122; (*b*) L. Jones and P. Atkins, *Chemistry Molecules Matter and Change*, W. H. Freeman and Co., New York, 2000, pp. 400–1.
16 S. Wolfe and Z. Shi, *Isr. J. Chem.*, 2000, **40**, 343.
17 S. Shaik and P. C. Hiberty, *A Chemist's Guide to Valence Bond Theory*, Wiley, New York, 2008, ch. 1.
18 R. Siegfried, *From Elements to Atoms: A History of Chemical Composition*, American Philosophical Society, Philadelphia, 2002.
19 S. Shaik, *J. Comput. Chem.*, 2007, **28**, 51.
20 G. Frenking and S. Shaik, *J. Comput. Chem.*, 2007, **28**, 1.
21 G. N. Lewis, *J. Am. Chem. Soc.*, 1916, **38**, 762.
22 W. B. Jensen, *J. Chem. Educ.*, 1984, **61**, 191.
23 A. Simoes, *J. Comput. Chem.*, 2007, **28**, 63.
24 M. J. Nye, *From Chemical Philosophy to Theoretical Chemistry*, University of California Press, Los Angeles, CA, 1993.
25 D. Knight, *Ideas in Chemistry: A History of Science*, Rutgers University Press, New Braunscwick, NJ, 1992.
26 J. A. Berson, *Chemical Creativity*, Wiley-VCH, Weinheim, 1999.
27 P. W. Anderson, *Science*, 1972, **177**, 393.
28 (*a*) W. Heitler and F. London, *Z. Phys.*, 1927, **44**, 455; (*b*) H. Hettema, *Quantum Chemistry Classic Scientific Paper*, World Scientific, Singapore, 2000, p. 140 (English Translation).
29 L. Pauling, *Proc. Natl. Acad. Sci. U. S. A.*, 1928, **14**, 359.
30 M. D. Saltzman, *Bull. Hist. Chem.*, 1996, **19**, 25.
31 L. Pauling, *The Nature of the Chemical Bond*, Cornell University Press, Ithaca, New York, 1939.
32 S. G. Brush, *Stud. Hist. Phil. Sci.*, 1999, **30**, 21.
33 F. Hund, *Z. Phys.*, 1931, **73**, 1.
34 R. S. Mulliken, *Chem. Rev.*, 1931, **9**, 347.
35 E. Hückel, *Z. Phys.*, 1930, **60**, 423.
36 J. E. Lennard-Jones, *Trans. Faraday Soc.*, 1929, **25**, 668.
37 E. Hückel, *Z. Phys.*, 1931, **70**, 204.
38 S. Shaik and P. C. Hiberty, *Rev. Comput. Chem.*, 2004, **20**, 1.
39 S. G. Brush, *Stud. Hist. Phil. Sci.*, 1999, **30**, 263.
40 T. Hager, *Force of Nature: The Life of Linus Pauling*, Simon and Schuster, New York, 1995, p. 63.
41 (*a*) J. D. Roberts, *Acc. Chem. Res.*, 2004, **37**, 417; (*b*) A. Streitwieser, *Acc. Chem. Res.*, 2004, **37**, 419.
42 Another book, which appeared earlier in the French language, was written by the Pullmans (B. Pullman and A. Pullman), but had relatively little impact compared with those in ref. 41.
43 (*a*) P. Laszlo and R. Hoffmann, *Angew. Chem., Int. Ed.*, 2000, **39**, 123; (*b*) L. E. Orgel and J. D. Dunitz, *Nature*, 1953, **171**, 121.
44 E. Heilbronner and H. Bock, *The HMO Model and its Applications*, Wiley, New York, 1976.
45 C. A. Coulson, *Valence*, Oxford University Press, London, 1952.
46 M. J. S. Dewar, *Electronic Theory of Organic Chemistry*, Clarendon Press, Oxford, 1949.
47 R. B. Woodward and R. Hoffmann, *The Conservation of Orbital Symmetry*, Verlag Chemie, Weinheim, 1971.
48 K. Fukui, *Theory of Orientation and Stereoselection*, Springer-Verlag, Heidelberg, 1972.
49 R. J. Gillespie and P. L. A. Popelier, *Chemical Bonding and Molecular Geometry*, Oxford University Press, London, 2001.
50 J. F. Bunnett, *The Great Carbocation Problem*, a foreword to a series of papers on the controversy, *Acc. Chem. Res.*, 1983, **16**, 425.
51 E. Heilbronner, *J. Chem. Educ.*, 1989, **66**, 471.
52 J. P. Malrieu, N. Guihéry, C. J. Calzado and C. Angeli, *J. Comput. Chem.*, 2007, **28**, 35.
53 D. G. Truhlar, *J. Comput. Chem.*, 2007, **28**, 73.
54 (*a*) A. Th. Van der Lugt and L. J. Oosterhoff, *J. Am. Chem. Soc.*, 1969, **91**, 6042; (*b*) J. Michl, *Top. Curr. Chem.*, 1974, **46**, 1.
55 (*a*) R. Cimiraglia, J. P. Malrieu, M. Persco and F. Spiegelman, *J. Phys. B*, 1985, **18**, 3073; (*b*) G. J. Atchity and K. Ruedenberg, *Theor. Chem. Acc.*, 1997, **97**, 47; (*c*) H. Nakamura and D. G. Truhlar, *J. Chem. Phys.*, 2001, **115**, 1010353.
56 M. A. Robb, M. Garavelli, M. Olivucci and F. Bernardi, *Rev. Comput. Chem.*, 2000, **15**, 87.
57 R. A. Marcus, *Angew. Chem., Int. Ed. Engl.*, 1993, **32**, 1111.
58 (*a*) B. O. Roos, A. C. Borin and L. Gagliardi, *Angew. Chem., Int. Ed.*, 2007, **46**, 1469; (*b*) M. Brynda, L. Gagliardi, P.-O. Widmark, P. P. Power and B. O. Roos, *Angew. Chem., Int. Ed.*, 2006, **45**, 3804.
59 G. Frenking and R. Toner, *Nature*, 2007, **446**, 276.
60 F. Weinhold and C. Landis, *Science*, 2007, **316**, 61.
61 E. D. Glendening and F. Weinhold, *J. Comput. Chem.*, 1998, **19**, 593–610.
62 F. Weinhold and C. Landis, *Valency and Bonding: A Natural Bond Orbital Donor–Acceptor Perspective*, Cambridge University Press, Cambridge, 2005.
63 H. Hirao, *Chem. Phys. Lett.*, 2007, **443**, 141.
64 S. Shaik and A. Shurki, *Angew. Chem., Int. Ed.*, 1999, **38**, 586.
65 S. Shaik, D. Danovich, B. Silvi, D. Lauvergnat and P. C. Hiberty, *Chem.–Eur. J.*, 2005, **11**, 6358.
66 S. Braun-Sand, M. H. M. Olsson and A. Warshel, *Adv. Phys. Org. Chem.*, 2005, **40**, 201.
67 R. Stowaser and R. Hoffmann, *J. Am. Chem. Soc.*, 1999, **121**, 3414.
68 See, however, the need for orbitals *(There is an increasing awareness that many body descriptions must also include real-space, orbitally resolved, descriptions of the solid, close to the quantum chemistry of the material under consideration.)* in: F. Lechermann, A. Georges, S. Biermann, M. Posternak, A. Yamasaki and O. K. Andersen, *Phys. Rev. B*, 2006, **74**, 125120.
69 (*a*) R. F. W. Bader and T. T. Nguyen-Dang, *Adv. Quantum Chem.*, 1981, **14**, 63; (*b*) B. Silvi and A. Savin, *Nature*, 1994, **371**, 683; (*c*) B. Silvi, *J. Phys. Chem. A*, 2003, **107**, 3081.
70 (*a*) L. Pauling, *J. Am. Chem. Soc.*, 1931, **53**, 1367; (*b*) J. C. Slater, *Phys. Rev.*, 1931, **37**, 481.
71 (*a*) J. H. van Vleck and A. Sherman, *Rev. Mod. Phys.*, 1935, **7**, 167; (*b*) J. C. Slater, *Phys. Rev.*, 1931, **41**, 255.
72 B. S. Park, In the Context of Pedagogy: Teaching Strategy and Theory Change in Quantum Chemistry, in *Pedagogy and the Practice of Science*, ed. D. Kaiser. MIT Press, Boston, MA, 2005, pp. 287–319.
73 See pp. 214, 215 and 237–242 in ref. 45.
74 C. Edmiston and K. Ruendenberg, *Rev. Mol. Phys.*, 1963, **35**, 457.
75 S. F. Boys, in *Quantum Theory of Atoms, Molecules, and the Solid State*, ed. P. O. Löwdin, Academic Press, New York, 1968, p. 253.
76 W. A. Goddard III and L. B. Harding, *Annu. Rev. Phys. Chem.*, 1978, **29**, 363.
77 See ch. 3 in ref. 17.
78 M. Elian and R. Hoffmann, *Inorg. Chem.*, 1975, **14**, 1058.
79 (*a*) See, for example: T. A. Albright, J. K. Burdett and M. H. Whangbo, *Orbital Interactions in Chemistry*, Wiley, NY, 1985; (*b*) Y. Jean and F. Volatron, *Les Orbitales Moleculaires En Chimie*, McGraw Hill, Paris, 1991.
80 R. S. Mulliken, *J. Chem. Phys.*, 1939, **7**, 339.
81 K. Kitaura and K. Morokuma, *Int. J. Quantum Chem.*, 1976, **10**, 325.
82 T. Ziegler and A. Rauk, *Theor. Chim. Acta*, 1977, **46**, 1.
83 (*a*) F. M. Bickelhaupt and E. J. Baerends, *Rev. Comput. Chem.*, 2000, **15**, 1; (*b*) A. Kovacs, C. Esterhuysen and G. Frenking, *Chem.–Eur. J.*, 2005, **11**, 1813.
84 Y. Mo, L. Song, W. Wu and Q. Zhang, *J. Am. Chem. Soc.*, 2004, **126**, 3974.
85 For example,(*a*) L. Song, Y. Mo, Q. Zhang and W. Wu, *J. Comput. Chem.*, 2005, **26**, 514; (*b*) J. Li and R. McWeeny, *VB2000: An Ab initio Valence Bond Program Based on Product Function Method and the Algebrant Algorithm*, 2000; (*c*) J. H. van Lenthe, F. Dijkstra and W. A. Havenith, in TURTLE — A Gradient VBSCF Program Theory and Studies of Aromaticity, in *Valence Bond Theory*, ed. D. L. Cooper, Elsevier, Amsterdam, 2002, pp. 79–116.

Downloaded by University of Belgrade on 01 January 2013
Published on 05 October 2007 on http://pubs.rsc.org | doi:10.1039/B711641C

86 R. W. Fessenden and R. H. Schuler, *J. Chem. Phys.*, 1963, **39**, 2147.
87 W. T. Borden, in *Encyclopedia of Computational Chemistry*, ed. P. V. R. Schleyer, N. L. Allinger, T. Clark, J. Gasteiger, P. A. Kollman, H. F. Schaefer III and P. R. Schreiner, Wiley, Chichester, 1998, vol. 1, p. 708.
88 D. Maynau, M. Said and J. P. Malrieu, *J. Am. Chem. Soc.*, 1983, **105**, 5244.
89 Y. Luo, L. Song, W. Wu, D. Danovich and S. Shaik, *ChemPhysChem*, 2004, **5**, 515.
90 P. C. Hiberty and C. Leforestier, *J. Am. Chem. Soc.*, 1978, **100**, 2012.
91 P. C. Hiberty, *Isr. J. Chem.*, 1983, **23**, 10.
92 R. Huisgen, *J. Org. Chem.*, 1976, **41**, 403.
93 O. Eisenstein and N. T. Anh, *Tetrahedron Lett.*, 1971, 1191.
94 R. Sustmann, *Tetrahedron Lett.*, 1971, 2721.
95 R. A. Firestone, *J. Org. Chem.*, 1968, **33**, 2285.
96 D. L. Cooper, P. B. Karadakov and T. Thorsteinsson, in *Valence Bond Theory*, ed. D. L. Cooper, Elsevier, Amsterdam, 2002, pp. 41–53.
97 K. Hirao, H. Nakano and K. Nakayama, *Int. J. Quantum Chem.*, 1998, **66**, 157.
98 S. S. Shaik, *J. Am. Chem. Soc.*, 1981, **103**, 3692.
99 S. S. Shaik and A. Pross, *J. Am. Chem. Soc.*, 1982, **104**, 2708.
100 M. G. Evans, *Trans. Faraday Soc.*, 1939, **35**, 824, See also p. 54 in ref. 26.
101 S. S. Shaik, in *A Qualitative Valence Bond Model for Organic Reactions in New Theoretical Concepts for Understanding Organic Reactions*, ed. J. Bertran and I. G. Csizmadia, NATO ASI Series, C267, Kluwer Academic Publ., 1989, pp. 165–217.
102 (*a*) S. Shaik and A. C. Reddy, *J. Chem. Soc., Faraday Trans.*, 1994, **90**, 1631; (*b*) ch. 7 in ref. 17.
103 (*a*) Y. Mo and J. Gao, *J. Phys. Chem. A*, 2000, **104**, 3012; (*b*) H. Nakamura and D. G. Truhlar, *J. Chem. Phys.*, 2002, **117**, 5576.
104 M. W. Schmidt and M. S. Gordon, *Annu. Rev. Phys. Chem.*, 1998, **49**, 233.
105 D. Moran, A. C. Simmonett, F. E. Leach III, W. D. Allen, P. v. R. Schleyer and H. F. Schafer III, *J. Am. Chem. Soc.*, 2006, **128**, 9342.
106 J. M. L. Martin, P. R. Taylor and T. L. Lee, *Chem. Phys. Lett.*, 1997, **275**, 414.
107 (*a*) P. Piecuch, S. A. Kucharski and K. Kowalski, *Chem. Phys. Lett.*, 2001, **344**, 176; (*b*) C. D. Sherrill and P. Piecuch, *J. Chem. Phys.*, 2005, **122**, 124104.
108 P. R. T. Schipper, O. V. Gritsenko and E. J. Baerends, *Theor. Chem. Acc.*, 1998, **99**, 329.
109 For example: (*a*) S. Grimme, M. Steinetz and M. Korth, *J. Chem. Theor. Comput.*, 2007, **3**, 42; (*b*) P. R. Schreiner, A. A. Fokin, R. A. Pascal, Jr and A. de Meijere, *Org. Lett.*, 2006, **8**, 3635.
110 J. N. Harvey, *Struct. Bonding*, 2004, **112**, 151.
111 F. Neese, *JBIC, J. Biol. Inorg. Chem.*, 2006, **11**, 702.
112 (*a*) Y. Zhao and D. G. Truhlar, *J. Phys. Chem. A*, 2005, **109**, 5656; (*b*) J. Zheng, Y. Zhao and D. G. Truhlar, *J. Phys. Chem. A*, 2007, **111**, 4632.
113 See, for example, good performance on spin states in heme systems(*a*) J. C. Schöneboom, F. Neese and W. Thiel, *J. Am. Chem. Soc.*, 2005, **127**, 5840; (*b*) M.-S. Liao, J. D. Watts and M.-J. Huang, *J. Comput. Chem.*, 2006, **27**, 1577.
114 P. E. M. Siegbahn, *JBIC, J. Biol. Inorg. Chem.*, 2006, **11**, 695.
115 R. Hoffmann, *Am. Sci.*, 2003, **91**, 9.
116 F. Ogliaro, S. Cohen, S. P de Visser and S. Shaik, *J. Am. Chem. Soc.*, 2000, **128**, 12892.
117 J. Ribas-Arino and J. J. Novoa, *Chem. Commun.*, 2007, 3160.
118 M. Schütz and H.-J. Werner, *Chem. Phys. Lett.*, 2000, **318**, 370.
119 Fodorov, D. G. K. Kitaura, H. Li, J. H. Jensen and M. S. Gordon, *J. Comput. Chem.*, 2006, **27**, 976.
120 K. Kitaura, E. Ikeo, T. Asada, T. Nakano and M. Uebayasi, *Chem. Phys. Lett.*, 1999, **313**, 701.
121 L. N. Appelhans, D. Zuccaccia, A. Kovacecevic, A. R. Chianese, J. R. Miecznikowski, A. Macchioni, E. Clot, O. Eisenstein and R. H. Crabtree, *J. Am. Chem. Soc.*, 2005, **127**, 16299.
122 J. C. Schöneboom and W. Thiel, *J. Phys. Chem. B*, 2004, **108**, 7468.
123 E. Derat, S. Shaik, C. Rovira, P. Vidossic and M. A. Priesto, *J. Am. Chem. Soc.*, 2007, **129**, 6346.
124 R. Car and M. Parrinello, *M. Phys. Rev. Lett.*, 1985, **55**, 2471.
125 See comment on the Zellinger experiment: C. Seife, *Science*, 2001, **292**, 1471.

This journal is © the Royal Society of Chemistry and the Centre National de la Recherche Scientifique 2007