Understanding chemical bonding through immersive virtual reality: development of an integrated environment for visualization and analysis of electron charge rearrangement

1. Introduction

Modern molecular sciences make extensive use of computational methods to predict the properties of a great variety of chemical systems over a wide range of space and time scales. Coupled to the growing computational power available, the results of such theoretical calculations produce data sets of increasing size and complexity. While this situation leads to the development of automatic data analysis procedures, it does not diminish the need for the insight and reasoning capabilities of the human mind. Chemical processes such as bond formation or electron excitation are often interpreted in terms of the changes that the molecular electron density undergoes in going from a reference (unbound or ground) state to the final (bound or excited) one. Understanding these processes requires therefore a careful analysis of the topology and features of the electron charge rearrangement occurring throughout the molecular volume in three-dimensional space. Fortunately, since the two-dimensional projections (contour maps) adopted in the pioneering works of Bader on chemical bonding fifty years ago, much progress has been done in visualizing scientific data of similar complexity. Scientific Visualization (SV) tries to exploit the capabilities of the human visual system to quickly identify structures, patterns, and anomalies in images. The rapid evolution of computer graphics and Immersive Virtual Reality (IVR) has made feasible their employment in SV; IVR also makes it possible to perceive the nearby physical environment based on proprioception and thus “rescale” visualized object to “human-readable” dimensions and proportions. Scientists have tried to exploit IVR technologies in molecular sciences since the late 60’s, though previous generations of hardware and software were too limited for actual usage. The recent introduction of a new generation of consumer-grade immersive helmets (Oculus Rift, HTC Vive) will change the scenario, leading to a wide adoption of IVR technologies. The only obstacle, at this point, is the availability of proper software capable to fully exploit the potential of these technologies.

2. State-of-the-art and motivation

Among the most popular molecular graphics systems, VMD has a relatively good support for IVR systems. Stone et al. explains in Ref. 6 that it was originally designed primary for IVR systems like the CAVE. However, VMD supports those visual rendering systems by means of legacy software. Recent versions use a GPU-accelerated ray-tracing engine integrated into the program, allow to create high quality 360° (not interactive) videos that can be viewed with Head-Mounted Displays (HMDs). Stone et al. proposed a method to generate near real-time high quality omnidirectional stereoscopic images by means of the integrated GPU-accelerated ray-tracing engine, and to allow their fruition via HMD (and potentially also in CAVE-like systems). However, the generation of such images is so computationally expensive that a cluster of GPUs was required, making this proposal unsuitable for common
users. As for other well-known molecular graphics systems, a commercial VR plugin for PyMOL\textsuperscript{10} is developed and distributed by Virtalis\textsuperscript{11}, although experimental solutions exist to run PyMOL in CAVE-like system by means of the Chromium library\textsuperscript{12} or to support the Oculus Rift.\textsuperscript{13} YASARA\textsuperscript{14} has some support for VR devices in its commercial versions. Support for modern HMDs is one of the main features of UCSF ChimeraX\textsuperscript{15} (successor of UCSF Chimera, currently under development), while their experimental support in UnityMol\textsuperscript{16} was recently announced.

From the previous discussion, it follows that IVR support in well-known molecular graphics systems is either bound to legacy technologies and/or provided as commercial product or introduced as an experimental feature. Fully functional analysis tools beyond molecular representations are very limited or non existent. Given the outlined scenario, molecular sciences can definitely benefit from a new molecular graphics system capable of fully exploit modern VR technologies for both research and dissemination purposes. This is the aim of the “Caffeine” project, a new molecular viewer for Immersive Virtual Reality (IVR) systems developed at the SMART Laboratory of Scuola Normale Superiore.\textsuperscript{17,18} It allows to visualize both static and dynamic structures standard representations (all-atoms and ribbons), isosurfaces extracted interactively by volume data sets, and line charts displaying additional scalar data resulting from further data analysis in a augmented reality fashion. Support for latest generation of HMDs is currently being developed and will be introduced soon. The program and its main features have been presented in a recent work published on the International Journal of Quantum Chemistry.\textsuperscript{17}

3. Bond-analysis techniques: theoretical framework

An in-depth analysis of chemical bonding requires careful inspection of the change rearrangement occurring, upon bond formation, throughout the molecular region. Given an adduct $AB$ resulting from chemical bonding between fragments $A$ and $B$, such rearrangement can be conveniently formulated as the difference $\Delta p$ between the molecular electron density of the adduct and those of its constituting unbound (non-interacting) fragments $A$ and $B$ taken at their in-adduct geometries.\textsuperscript{1} The resulting volume data are then commonly visualized through volume rendering techniques highlighting charge depletion (negative values of $\Delta p$) and charge accumulation (positive values of $\Delta p$) regions (see Figure 1). Despite a visual analysis of $\Delta p$ provides itself considerable insight into the nature of the chemical bond at hand, a quantitative estimate of the charge flow along a suitably chosen direction is often desirable. This can be easily achieved via the so-called charge-displacement (CD) function,\textsuperscript{19,20} $\Delta q(z)$, defined as a progressive partial integration along a suitable axis $z$ of the electron density difference $\Delta p(x,y,z')$

$$\Delta q(z) = \int_{-\infty}^{z} \Delta p(x,y,z') \, dx \, dy$$

The $z$ axis is usually chosen to be the bond axis between the fragments. Accordingly, the CD function at a given point $z$ quantifies the exact amount of electron charge that, upon bond formation, is transferred from right to left (the direction of decreasing $z$) across a plane perpendicular to the bond axis through $z$. 


Figure 1. Charge rearrangement (red: depletion, blue: accumulation) upon bond formation between Ni(CO)\textsubscript{2} (left-hand-side fragment) and a bidentate phosphine (right-hand-side fragment).

Molecular electron densities are the outcome of electronic-structure calculations routinely carried out with quantum chemistry packages such as Gaussian, Dalton, ADF and Molpro. Whereas these quantities are formally represented as vectors or matrices reflecting their expansion in a basis set of known functions, for visualization purposes they are commonly discretized onto a finite-volume regular grid in physical space and saved in so-called ‘cube’ files (.cub or .cube extensions), the advantage of discrete representations being of course their independence form the basis definition. Unfortunately, most molecular graphics programs provide poor or no support for operating on cube files, and the required numerical data analysis is usually demanded to external utilities such as Gaussian’s CUBEMAN (allowing for basic operations like add or subtract) or the CUBES suite,\textsuperscript{21} fully capable of carrying out CD analysis.

4. Aims and workplan

Goal of the present project is to develop an integrated environment for immersive analysis of chemical bonding in Caffeine, to demonstrate the real untapped potential that IVR has for computational chemistry. We will integrate Caffeine with a set of analysis tools, deriving from the CD-analysis formalism, for a qualitative and quantitative study of electron charge rearrangement upon formation of a chemical bond. Accordingly, the research activity will be articulated as follows:

A. **Upgrade Caffeine’s data structures.** Caffeine’s data structures will be refactored to support density-difference data.

B. **Integrate Caffeine with a set of analysis tools.** This second stage will involve writing computational procedures for carrying out operations on grid-discretized
three-dimensional functions. The required operations for bond analysis range from basic ones (linear combinations) to more complex such as partial integrations.

C. **Develop a user interface for real-time immersive analysis.** This third stage will be concerned with the design and implementation of a user-friendly interface allowing chemists to perform real-time analysis of chemical bonding in IVR environments. The user must be able to perform basic operations on molecular densities during an IVR session, and also to carry out CD analysis choosing interactively the desired directional axis $z$.

D. **Demonstrate the potential of the developed environment through a real study case.** A deep comprehension of the electronic rearrangement plays a fundamental role in the rationalization of physical observables and in the development of new materials with predetermined characteristics. A valuable example in this respect is the design of new transition-metal homogeneous catalysts, where a careful choice of the ligands and their substituents is able to strongly influence the electron richness at the metal and, in turn, the reactivity of the complex. We will thus focus our attention on transition-metal complexes with bidentate phosphines, that are a successful and widely used class of ligands which have proved their worth over many decades. These systems are also challenging because they feature a three-centre bond and the choice of a directional axis for CD analysis is no more trivial. Therefore evaluating different orientations of the axis could be the only way to catch the different aspects of the electronic reorganization upon coordination of the ligand to the metal centre. The results of our project will be reported in a research paper to be submitted to a scientific journal addressing the broad audience of the chemistry community.

References


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