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# Molecular Graphics: Bridging Structural Biologists and Computer Scientists

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## Abstract

Visualization of molecular structures is one of the most common tasks carried out by structural biologists, yet the technical details and advances required to efficiently display molecular structures are often hidden from the end user. During decades molecular viewer software such as Chimera, COOT, PyMOL, or VMD provided the most common solutions to quickly visualize structures. Nowadays, new and efficient ways to depict molecular objects are changing how structural biologists interact with their data. Such novelties are often driven by advances made by computer scientists, but an important gap remains between this community and the final users such as structural and computational biologists. In this perspective article, we clarify how developments from computer graphics and data visualization have led to novel ways of understanding protein structure. We present future developments from computer science that will be beneficial for structural biology. By pointing to canonical papers and explaining technical progress underlying new graphical developments in simple terms, we hope to promote communication between the different communities to shape future developments in molecular graphics.

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## 11 **1. Introduction and Motivation**

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14 Molecular graphics tools and methods has been actively developed for over  
15 50 years, always tightly linked to advances in computer hardware [1]. Early on,  
16 key developments in molecular graphics attracted interest from a broad range  
17 of scientists — hence, some were published in journals such as Science [2]. To-  
18 5 day, however, the field has fragmented into two main communities: advances  
19 in computer graphics are almost always reported in publications aimed at com-  
20 puter scientists, while applications of these methods that uncover new biological  
21 insights are reported in journals aimed at structural biologists. One key issue  
22 caused by this fragmentation is that publications are often difficult to access  
23 for scientists outside of the respective sub-field — fortunately, this situation  
24 is slowly improving due to the increase in open-access publication. A related  
25 issue is that interaction between the two communities is low as they rarely at-  
26 tend common meetings. As a result of these issues, many structural biologists  
27 10 are unaware of interesting advances in molecular graphics methods; conversely,  
28 computer scientists working in molecular graphics are not always aware of or  
29 focused on the most interesting visualization challenges raised by cutting edge  
30 experimental methods.  
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41 This perspective article aims to help address some of these issues result-  
42 20 ing from the fragmentation of these communities. We begin by briefly review-  
43 ing highlights in the history of molecular graphics. We then outline some of  
44 core computational visualization methods currently used in molecular graph-  
45 ics tools, and explain how they help advance our understanding of biomolecu-  
46 lar structures. We also discuss methods currently being developed to address  
47 emerging challenges, such as structures derived from cryo-electron microscopy  
48 (cryo-EM) [3, 4].  
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## 2. A Brief History of Molecular Graphics

Some key moments in molecular graphics are summarized in figure 1, which also lists several recent review articles.

As described in the review from Jane and David Richardson [13], the earliest molecular graphics were drawings and physical models created by hand. As these began to be replaced by computer graphics, a key initial focus was on inventing novel visual representations that help push forward the understanding of biomolecular function by emphasising important structures features. Two striking examples were: (1) the ribbon representation developed by Jane Richardson, published in *Nature* in 1977 [5] and (2) the molecular surface representation developed by Michael Connolly, published in *Science* in 1983 [14]. Such developments profoundly transformed the practise of structural biology, leading to the launch of the *Journal of Molecular Graphics* in 1983, first giving the field its own dedicated journal.

Since then, a large number of molecular graphics tools have been developed. The reviews from Goddard *et al.* [15], O'Donoghue *et al.* [16], and Johnson and Hertig [17] each give a guide to the available tools and help identify the best visualization methods for addressing specific biological questions. Johnson and Hertig [17] further present visual tools and methods for 3D animations and describe how these can be effectively combined with visual metaphors to create visual narratives that explain complex, biomolecular mechanisms, either to other scientists or to the general public.

In recent years, as described in the review from Im *et al.* [18], structural biology has become increasingly interconnected with many other kinds of data, and the visualization challenges have moved from the static views of single molecules toward dynamics views of much larger scales, such as whole viruses, subcellular organelles, or even entire cells.

These challenges have inspired intense research within the computer graphics community, aimed at creating solutions that take advantage of advances in GPU capabilities (described by Chavent *et al.* [19]), as well as new analysis and im-

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mersive approaches (described by Hirst *et al.* [20]). These recent developments are summarized in three recent *state of the art* reviews of molecular graphics, each describing technical developments that can help structural biologists choose the best algorithms for a dedicated purpose. The review from Kozlikova *et al.* [21] details algorithms that can be used to render small molecules up to large macromolecular assemblies, such as microtubules. The reviews from Krone *et al.* [22] and Simoes *et al.* [23] focus on detection of cavities on protein surfaces and their rendering.

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Mostly, these developments in computer graphics have been first created as research prototypes, rather than as usable implementations, and have been reported in computer science publications. As a result, while some of these advances have been incorporated in widely-used molecular graphics tools (e.g., VMD [24, 25], Chimera [26]), unfortunately — as noted by Goddard *et al.* 10 years ago [15] — many developments in computer graphics are still not visible to, or accessible by, the structural biology community. This is evident from the very small fraction of computer graphics papers cited in recent reviews published for structural biologists (figure 1).

Thus, one of our goals for this work is to highlight recent computer graphics advances that have not yet been implemented in broadly accessible molecular viewers, but have potential to help address the emerging challenges in molecular graphics.

### 3. Advanced Lighting and Shading Effects

Many advances have been made in lighting and shading effects applied to molecular graphics that can, in turn, help users understand the overall spatial organization of complex biomolecules (figure 2).

**Blinn-Phong lighting and real-time shadows:** Currently, most molecular graphics tools use an approximation of physically based lighting called the Blinn-Phong model [27, 28], composed of three terms: (1) an ambient term that models incident light coming equally from all directions; (2) a diffuse term; and

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8 (3) a specular term that models surface reflections. Together, these three terms  
9 give a fairly realistic approximation of the local lighting and shading condi-  
10 tions at the surface of smooth 3D objects (figure 2). However, the Blinn-Phong  
11 model has key limitations; for example, it cannot convey shadows cast between  
12 objects. A range of computational strategies have been developed to overcomes  
13 these limitations; for example, Krone *et al.* [29] recently presented a strategy  
14 that can efficiently compute shadows for large scale molecular systems, such as  
15 virus capsids with up to 1 million atoms.  
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20 **Ambient occlusion:** Ambient occlusion (AO) is a shading and rendering  
21 technique that adds depth cues which, in turn, can greatly help in revealing  
22 detailed features for complex, 3D objects [30, 31] (see figure 2). For static 3D  
23 molecules, AO has been available for many years via the QuteMol viewer from  
24 Tarini *et al.* [8]. AO effects has also become available in more popular molecular  
25 graphics tools, such as VMD [32] and, more recently, ChimeraX [26].  
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29 Ambient occlusion darkens buried parts of a structure — mostly cavities  
30 and crevices — to approximate non-directional lighting effects. AO relies on a  
31 depth-map, computed for each point-of-view around the molecule; this is then  
32 used to determine and store the visibility of each atom in a texture map. If  
33 the atoms are hidden from the camera, the texel (one element of the texture  
34 map) of the corresponding part of this atom is darkened. These occlusion maps  
35 are computed once on the GPU; the effect is then very fast to render as long  
36 as the molecule is static. For dynamic molecular data, a fast approximation of  
37 AO was proposed by Grottel *et al.* [33] that allows for interactively rendering  
38 of dynamics systems composed of millions of atoms.  
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42 **Ray-tracing:** Ray tracing methods provide a much more realistic simula-  
43 tion of lighting by computing the paths and reflections that photons would travel  
44 from each light source to the view point. This produces photorealistic rendering  
45 that can be very helpful in conveying complex, 3D molecular structures (see  
46 figure 2). However, as these calculations require much computing power, many  
47 users only use ray tracing when finalizing high-quality, static images for pub-  
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7 BioBlender [35]; both these tools use the open-source 3D modelling software  
8 Blender on their backend for ray tracing.  
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10 The VMD tool [7] includes the **Tachyon** ray-tracer for computing static im-  
11 ages, and further offers real-time ray-tracing via highly efficient CPU (OSPRay)  
120 and GPU (OPTIX-CUDA) methods [32]. This approach was recently used to  
13 interactively display very large, dynamic molecular systems containing dozens  
14 of millions of atoms, such as chromatophores [25].  
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18 In summary, thanks to recent advances in both hardware and software,  
19 molecular graphics tools can now feasibly combine real-time global illumination  
125 with a range of non-photorealistic rendering methods; this provide high-quality  
20 depth cues that can greatly help users with the challenging task of understand-  
21 ing complex, 3D molecular structures [16].  
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#### 27 **4. Molecular Surface Rendering**

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30 130 Visualizing molecular surfaces has proven to be very useful representations  
31 for revealing functional aspects of biomolecules, such as proteins and nucleic  
32 acids. Thus, as described in the review from Kozlíková *et al.* [21], many different  
33 methods have been proposed to calculate molecular surfaces, each designed to  
34 highlight specific biomolecular properties. In this section, we briefly mention the  
35 methods that are most commonly used, as well as a few of the more promising  
36 methods that have recently been proposed.  
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41 One of the most commonly used molecular surface methods is to simply  
42 represent each atom as a sphere with corresponding **van der Waals (vdW)**  
43 radius (figure 2). In addition to being quick to compute, this method has the  
44 advantage that it automatically conveys a sense of spatial scale, since atoms  
45 140 are directly visualized; however, a limitation of the vdW surface is that it is  
46 often difficult to see where other molecules (e.g., **ligands**) are likely to interact  
47 favourably.  
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51 To address this limitation, the **Solvent Accessible Surface (SAS)** was  
52 proposed [36]. This is calculated using a spherical probe with a radius set to  
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150 SAS is significantly larger than the true molecular volume.

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155 This limitation is mostly overcome by the **Solvent Excluded Surface** (SES), which is also known as the Smooth Molecular Surface, or the Connolly Surface [6, 14]. The SES is defined similarly to the SAS, but uses the probe contact surface instead of the probe center, thereby closing gaps that are inaccessible to the probe while also giving a better approximation to the true molecular volume. Over the past decade, many fast methods to compute and render the SES have been proposed: Krone *et al.* [37] used shader-based ray casting to render with high image quality. Lindow *et al.* [38] accelerated the computation on multi-core CPUs, while Krone *et al.* [39] presented a GPU-based algorithm  
160 to compute the surface interactively. Jurcik *et al.* [40] developed a method based on the work of Krone *et al.* [37, 39] to render the SES semi-transparently. Hermosilla *et al.* [41] computed the SES progressively on a 3D grid and rendered the results using volume rendering.

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170 In addition to the commonly used SES, a range of additional molecular surface definitions have been proposed: (1) The **Ligand Excluded Surface** by Lindow *et al.* [42] uses the actual ligand instead of a spherical probe to carve out the surface; (2) **Gaussian Surfaces** can be related to the electron density cloud of a molecule, modelled by radially symmetric Gaussian density kernels for each atom. Krone *et al.* [24] presented the fast**Quicksurf** algorithm to compute  
175 such surfaces on the GPU, available in VMD. (3) The smooth **Molecular Skin Surface** [43] can approximate the SES and may be rendered using shader-based ray casting (see work by Chavent *et al.* [11] and figure 1, 2008). Later, Lindow *et al.* [38] refined their approach and presented a fast, CPU-parallelized computation. (4) Cipriano and Gleicher [9] presented an SES-based **Molecular Surface Abstraction**, which smoothens areas of high frequency (see figure 1, 2007).



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8 In summary, molecular surface rendering methods, such as SES, remain very  
9 common in molecular graphics; however, these methods are not well suited for  
10 all kinds of structural data.  
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## 12 13 14 180 **5. Volume Rendering**

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16 Volume rendering methods are used to visualize density maps from X-ray  
17 crystallography or from cryo-EM (Figure 3). A commonly used method is **direct**  
18 **volume rendering** (DVR), in which the density map is shown as a fog of vary-  
19 ing opacity and color. DVR is often implemented via GPU-based ray marching.  
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21 Figure 3 (top left) shows a direct volume rendering of a cryo-EM map in combi-  
22 185 nation with a fitted protein structure. For some tasks, users might be interested  
23 in a certain interface of the volumetric data; in such cases, visualizing an iso-  
24 surface is a feasible approach (see Figure 3 top right).  
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28 Volume rendering methods are also used for a range of other kinds of molecu-  
29 lar data. For example, electrostatic fields are often visualized with either isosur-  
30 190 faces or field lines (Figure 3, bottom left and right, respectively). Additionally,  
31 volume rendering methods has been used to show uncertainty in biomolecular  
32 structures.  
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36 With modern GPUs, volume rendering can be done interactively [44]. Al-  
37 ternatively, interactivity can also be achieved with CPU-based methods. For  
38 195 example, Knoll *et al.* [45] recently presented a CPU-based volume rendering  
39 method for interactive ray tracing. They approximated the electron density  
40 field using radial basis functions for each atom to visualize molecular data,  
41 similar to the Gaussian surfaces mentioned in Section 4, which are isosurfaces  
42 extracted from the Gaussian volume.  
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## 47 48 **6. Dynamics and Flexibility**

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50 Biomolecules are often intrinsically very dynamic and flexible, leading to po-  
51 sitional uncertainty in experimentally derived models. Many of these dynamic  
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7 properties can be experimentally measured [46] and modeled in molecular sim-  
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9 205 ulations [47]. In any case, it is still challenging to clearly convey dynamic  
10 properties visually.

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12 One approach is to replace precisely defined atomic positions by probability  
13 distributions [48], another to accumulate sampled conformations on a grid and  
14 depict an isosurface or a volume rendering [49]. Alternatively, a given graphical  
15 representation can be made thicker or more fuzzy when positional uncertainty is  
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17 210 observed, versus making it thinner and well defined for precise conformations, as  
18 is commonly applied to tubular 'sausage plot' representation of a protein back-  
19 bone [50, 51]. Other options are to depict thermal vibrations of atoms through  
20 multi-layered semi-transparent surfaces [52] or to use voxel maps for selected  
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22 215 flexible elements such as loops or domains in proteins [53]. Recently, Schulz *et*  
23 *al.* [54] presented approaches to map uncertainty values like positional uncer-  
24 tainty or flexibility to the cartoon representation of a protein using geometric  
25 distortion and transparency. Figure 4 depicts flexibility using a motion blur  
26 effect.

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32 220 Another approach is to enrich common representations by adding cues in-  
33 dicating flexibility. Bryden *et al.* [55] used glyphs combining arcs and arrows  
34 to illustrate directional molecular flexibility for clusters of atoms that exhibit a  
35 synchronized rotational motion. Fioravante *et al.* [56] used color or cone glyphs  
36 to depict motional correlations in proteins, based on principal component anal-  
37 ysis and covariance clustering.  
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41 Yet another approach is to use abstractions to recapitulate the observed  
42 motion. Dabdoub *et al.* [57] draw pathlines of selected atoms to visualize the  
43 dynamics of a molecule and add more visual cues through semi-transparent  
44 ribbons displaying the movement of bonds. This approach allows the viewer to  
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46 230 follow short parts of a trajectory, yet the visual representation might quickly  
47 get confusing for very complex movements.  
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## 7. Multi-scale Visualization

Driven by advances in experimental methods [4], in computational modeling [18], and in integrative approaches [58], the size and complexity of molecular systems amenable to structural biology is rapidly increasing. This, in turn, is creating new visualization challenges.

Inspired by David Goodsell’s pioneering depictions of biomolecular landscapes [59], several recent initiatives in computer graphics have taken on the challenge of constructing such models [12]. These models can be useful both for research [60, 61] as well as communication [62].

To facilitate navigation in such complex and crowded landscapes, a range of multiscale molecular visualization techniques have been developed; these are described in a recent survey from Miao *et al.* [63]. A key method is to automatically adapt the level of molecular detail, depending on the proximity of the camera. Thus, Parulek *et al.* proposed a continuous and visual abstraction to pass from a very precise protein surface to a simple vdW representation as a function of the distance between the scene and the user’s point of view [64] (see figure 4). A similar approach was used to represent DNA origami structures at different scales [65] (see figure 4). Such seamless transformations can also be applied to pass efficiently from one protein depiction to another for illustrative purposes [10] (see figure 1).

These developments pave the way towards systems that enable interactive exploration of molecular-scale models of entire cells [66, 67] (see figure 4).

## 8. New Software Platforms for Molecular Graphics

Currently, most molecular graphics tools that structural biologists use as a mainstay are implemented as dedicated, stand-alone applications. However, this is set to change.

Recent advances in web technology are driving rapid developments in web-based molecular graphics tools, as outlined in several recent reviews [69, 70, 71]. One of the main drivers has been the WebGL API, which gives native support

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8 for GPU hardware-acceleration for molecular graphics web-apps, such as NGL  
9 Viewer [72], LiteMol [73], and Jolecule [74]. Other driving technologies include  
10 WebWorkers (e.g., used in NGL Viewer to calculate molecular surfaces off the  
11 main thread), WebSockets (e.g., used to facilitate interactive visualization of  
12 molecular dynamics trajectories [75]), and WebVR. In turn, this new genera-  
13 265 tion of molecular graphics web-apps are being re-deployed as components on  
14 many other web sites. For example, they are used by the world-wide Protein  
15 Data Bank [76] on each of its three web sites (rcsb.org, pdbe.org, pdbj.org). Ad-  
16 ditionally, they are used by the SwissModel [77] and Aquaria [78] resources to  
17 facilitate access to millions of 3D structures derived from large-scale modeling.  
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23 Currently, however, most web-based molecular graphics tools do not yet offer  
24 the full range of functionality available with more established, stand-alone tools  
25 (e.g., Chimera, VMD, etc.). This may soon change, driven by open-source, col-  
26 laborative projects such as the recently launched Mol\* initiative (molstar.org),  
27 aimed at developing a common framework for web molecular graphics.  
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31 Another relatively new software platform for molecular graphics is the Unity  
32 3D game engine, which has been used to create the molecular editor Unity-  
33 Mol [68] and MolecularRift [79], a tool for drug design. Developing in Unity  
34 can greatly simplify deployment to AR and VR devices (e.g., Oculus Rift,  
35 Hololens) [80].  
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38 Finally, molecular graphics is increasingly being used within professional  
39 animation software platforms. For the open-source, 3D modeling tool Blender,  
40 the plugin BioBlender facilitates use of biomolecular structures [81], while the  
41 Pyrite plugin facilitates use of molecular dynamics simulations [82]. For the  
42 commercial 3D modeling tool Autodesk Maya, the plugin Molecular Maya ([83])  
43 285 facilitates use of biomolecules.  
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## 48 9. Conclusion

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51 We believe that increased adoption of some of these promising methods has  
52 significant potential to advance structural biology by improving how structural  
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290 biologists see and think about their data.

By covering references to state of the art surveys written by well recognized teams in the field, the perspective may further provide an entry point to contact computer graphics researchers to implement new rendering techniques which will definitely benefit structural biology.

295 To further help realizing this goal, we would also encourage readers to consider participating in scientific events that bring structural biologists together with researchers working in computer graphics — meetings such as VIZBI [84], BioVis [85], and MolVA [86].

## 300 **References**

- [1] C. Levinthal, Molecular model-building by computer, *Scientific American* 214 (6) (1966) 42–52, cited By 131. doi:10.1038/scientificamerican0666-42.
- [2] R. Langridge, T. E. Ferrin, I. D. Kuntz, M. L. Connolly, Real-time color graphics in studies of molecular interactions, *Science* 211 (4483) (1981) 661–666.
- [3] Electron Microscopy Solutions, 2017 nobel prize in chemistry (2017). URL <https://www.fei.com/cryo-em/>
- [4] Y. Cheng, Single-particle cryo-EM-How did it get here and where will it go., *Science* 361 (6405) (2018) 876–880.
- [5] J. S. Richardson, beta-Sheet topology and the relatedness of proteins., *Nature* 268 (5620) (1977) 495–500.
- [6] M. L. Connolly, Analytical molecular surface calculation, *Journal of Applied Crystallography* 16 (5) (1983) 548–558.
- 315 [7] W. Humphrey, A. Dalke, K. Schulten, VMD: visual molecular dynamics, *Journal of Molecular Graphics* 14 (1) (1996) 33–38.

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6  
7  
8 [8] M. Tarini, P. Cignoni, C. Montani, Ambient occlusion and edge cueing  
9 to enhance real time molecular visualization., *Visualization and Computer*  
10 *Graphics, IEEE Transactions on* 12 (5) (2006) 1237–1244.
- 11  
12  
13 320 [9] G. Cipriano, M. Gleicher, Molecular surface abstraction, *Visualization and*  
14 *Computer Graphics, IEEE Transactions on* 13 (6) (2007) 1608–1615.
- 15  
16 [10] M. Van Der Zwan, W. Lueks, H. Bekker, T. Isenberg, Illustrative molecular  
17 visualization with continuous abstraction, in: *Computer Graphics Forum*,  
18 Vol. 30, Wiley Online Library, 2011, pp. 683–690.
- 19  
20  
21 325 [11] M. Chavent, B. Lévy, B. Maigret, MetaMol: High quality visualization  
22 of Molecular Skin Surface, *Journal of Molecular Graphics and Modelling*  
23 27 (2) (2008) 209–216.
- 24  
25  
26 [12] T. Klein, L. Autin, B. Kozlikova, D. S. Goodsell, A. Olson, M. E. Groller,  
27 I. Viola, Instant Construction and Visualization of Crowded Biological En-  
28 vironments., *IEEE Trans Vis Comput Graph* 24 (1) (2018) 862–872.
- 29  
30 330  
31 [13] J. S. Richardson, D. C. Richardson, Doing molecular biophysics: Finding,  
32 naming, and picturing signal within complexity, *Annual Review of Bio-*  
33 *physics* 42 (1) (2013) 1–28.
- 34  
35  
36 [14] M. L. CONNOLLY, Solvent-Accessible Surfaces of Proteins and Nucleic-  
37 Acids, *Science* 221 (4612) (1983) 709–713.
- 38  
39 335  
40 [15] T. D. Goddard, T. E. Ferrin, Visualization software for molecular assem-  
41 blies, *Current opinion in structural biology* 17 (5) (2007) 587–595.
- 42  
43  
44 [16] S. I. O’Donoghue, D. S. Goodsell, A. S. Frangakis, F. Jossinet, R. A.  
45 Laskowski, M. Nilges, H. R. Saibil, A. Schafferhans, R. C. Wade, E. West-  
46 hof, et al., Visualization of macromolecular structures, *Nature methods* 7  
47 340 (2010) S42–S55.
- 48  
49  
50 [17] G. T. Johnson, S. Hertig, A guide to the visual analysis and communica-  
51 tion of biomolecular structural data, *Nature reviews. Molecular cell biology*  
52 15 (10) (2014) 690–698.
- 53  
54  
55  
56  
57  
58  
59  
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51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65
- 345 [18] W. Im, J. Liang, A. Olson, H.-X. Zhou, S. Vajda, I. A. Vakser, Challenges  
in structural approaches to cell modeling., *Journal of molecular biology*  
428 (15) (2016) 2943–2964.
- [19] M. Chavent, B. Lévy, M. Krone, K. Bidmon, J.-P. Nominé, T. Ertl,  
M. Baaden, Gpu-powered tools boost molecular visualization, *Briefings in*  
350 *Bioinformatics* (2011) bbq089.
- [20] J. D. Hirst, D. R. Glowacki, M. Baaden, Molecular simulations and visual-  
ization: introduction and overview, *Faraday discussions* 169 (2014) 9–22.
- [21] B. Kozlíková, M. Krone, M. Falk, N. Lindow, M. baaden, D. Baum, I. Viola,  
J. Parulek, H. C. Hege, Visualization of Biomolecular Structures: State of  
355 the Art Revisited, *Computer Graphics Forum* 36 (8) (2017) 178–204.
- [22] M. Krone, B. Kozlíková, N. Lindow, M. Baaden, D. Baum, J. Parulek,  
H.-C. Hege, I. Viola, Visual analysis of biomolecular cavities: State of the  
art, *Computer Graphics Forum* 35 (3) (2016) 527–551. doi:10.1111/cgf.  
12928.
- 360 [23] T. Simões, D. Lopes, S. Dias, F. Fernandes, J. Pereira, J. Jorge, C. Bajaj,  
A. Gomes, Geometric detection algorithms for cavities on protein surfaces  
in molecular graphics: A survey, *Computer Graphics Forum* 36 (8) (2017)  
643–683. doi:10.1111/cgf.13158.
- [24] M. Krone, J. E. Stone, T. Ertl, K. Schulten, Fast visualization of gaussian  
365 density surfaces for molecular dynamics and particle system trajectories,  
*EuroVis-Short Papers* (2012) 67–71.
- [25] J. E. Stone, M. Sener, K. L. Vandivort, A. Barragan, A. Singharoy,  
I. Teo, J. V. Ribeiro, B. Isralewitz, B. Liu, B. C. Goh, J. C. Phillips,  
C. MacGregor-Chatwin, M. P. Johnson, L. F. Kourkoutis, C. N. Hunter,  
370 K. Schulten, Atomic detail visualization of photosynthetic membranes with  
GPU-accelerated ray tracing, *Parallel Computing* 55 (2016) 17–27.

- 1  
2  
3  
4  
5  
6  
7  
8 [26] T. D. Goddard, C. C. Huang, E. C. Meng, E. F. Pettersen, G. S. Couch,  
9 J. H. Morris, T. E. Ferrin, UCSF ChimeraX: Meeting modern challenges  
10 in visualization and analysis, *Protein science : a publication of the Protein*  
11 *Society* 27 (1) (2018) 14–25.  
12 375
- 13  
14 [27] B. T. Phong, Illumination for computer generated pictures, *Communica-*  
15 *tions of the ACM* 18 (6) (1975) 311–317.
- 16  
17  
18 [28] J. F. Blinn, Models of light reflection for computer synthesized pictures,  
19 *SIGGRAPH Comput. Graph.* 11 (2) (1977) 192–198. doi:10.1145/  
20 965141.563893.  
21 380
- 22  
23 [29] M. Krone, G. Reina, S. Zahn, T. Tremel, C. Bahnmüller, T. Ertl, Implicit  
24 sphere shadow maps, in: *Pacific Visualization Symposium, IEEE*, 2017, pp.  
25 275–279.
- 26  
27  
28 [30] I. Yu, A. Cox, M. H. Kim, T. Ritschel, T. Grosch, C. Dachsbacher, J. Kautz,  
29 Perceptual influence of approximate visibility in indirect illumination, *ACM*  
30 *Transactions on Applied Perception (TAP)* 6 (4) (2009) 24.  
31 385
- 32  
33  
34 [31] D. A. Szafrir, A. Sarikaya, M. Gleicher, Lightness constancy in surface visu-  
35 alization, *IEEE transactions on visualization and computer graphics* 22 (9)  
36 (2016) 2107–2121.
- 37  
38  
39 [32] J. E. Stone, K. L. Vandivort, K. Schulten, Gpu-accelerated molecular visu-  
40 alization on petascale supercomputing platforms, in: *Proceedings of the 8th*  
41 *International Workshop on Ultrascale Visualization, UltraVis '13, ACM*,  
42 New York, NY, USA, 2013, pp. 6:1–6:8. doi:10.1145/2535571.2535595.  
43 URL <http://doi.acm.org/10.1145/2535571.2535595>  
44
- 45  
46  
47 [33] S. Grottel, M. Krone, K. Scharnowski, T. Ertl, Object-Space Ambient Oc-  
48 clusion for Molecular Dynamics, in: *IEEE Pacific Visualization Sympo-*  
49 *sium*, 2012, pp. 209–216. doi:10.1109/PacificVis.2012.6183593.  
50  
51  
52  
53  
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58  
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60  
61  
62  
63  
64  
65
- [34] G. Johnson, L. Autin, D. Goodsell, M. Sanner, A. Olson, ePMV embeds  
molecular modeling into professional animation software environments,  
Structure 19 (2011) 293–303. 400
- [35] R. M. Andrei, M. Callieri, M. F. Zini, T. Loni, G. Maraziti, M. C. Pan,  
M. Zoppè, Bioblender: A software for intuitive representation of surface  
properties of biomolecules, CoRR.
- [36] F. M. Richards, Areas, Volumes, Packing, and Protein Structure, Annu.  
Rev. Biophys. Bioeng. 6 (1977) 151–176. doi:10.1146/annurev.bb.06.  
060177.001055. 405
- [37] M. Krone, K. Bidmon, T. Ertl, Interactive visualization of molecular surface  
dynamics., IEEE Trans Vis Comput Graph 15 (6) (2009) 1391–1398.
- [38] N. Lindow, D. Baum, S. Prohaska, H.-C. Hege, Accelerated visualization  
of dynamic molecular surfaces, Computer Graphics Forum 29 (3) (2010)  
943–952. 410
- [39] M. Krone, M. Falk, S. Rehm, J. Pleiss, T. Ertl, Interactive exploration of  
protein cavities, Computer Graphics Forum 30 (3) (2011) 673–682.
- [40] A. Jurcik, J. Parulek, J. Sochor, B. Kozlikova, Accelerated Visualization of  
Transparent Molecular Surfaces in Molecular Dynamics, in: IEEE Pacific  
Visualization Symposium, 2016, pp. 112–119. doi:10.1109/PACIFICVIS.  
2016.7465258. 415
- [41] P. Hermosilla, M. Krone, V. Guallar, P.-P. Vázquez, À. Vinacua, T. Ropin-  
ski, Interactive GPU-based generation of solvent-excluded surfaces, The  
Visual Computer 33 (6-8) (2017) 869–881. 420
- [42] N. Lindow, D. Baum, H.-C. Hege, Ligand Excluded Surface: A New Type  
of Molecular Surface, IEEE Transactions on Visualization and Computer  
Graphics 20 (12) (2014) 2486–2495. doi:10.1109/TVCG.2014.2346404.

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60  
61  
62  
63  
64  
65
- [43] H. Edelsbrunner, Deformable Smooth Surface Design, *Discrete & Computational Geometry* 21 (1) (1999) 87–115. doi:10.1007/PL00009412.
- [44] M. Hadwiger, P. Ljung, C. R. Salama, T. Ropinski, Advanced Illumination Techniques for GPU Volume Raycasting, in: *ACM SIGGRAPH Asia Courses*, 2008, p. 166. doi:10.1145/1508044.1508045.
- [45] A. Knoll, I. Wald, P. Navratil, A. Bowen, K. Reda, M. E. Papka, K. Gaither, Rbf volume ray casting on multicore and manycore cpus, in: *Computer Graphics Forum*, Vol. 33, Wiley Online Library, 2014, pp. 71–80.
- [46] L. E. Kay, New views of functionally dynamic proteins by solution nmr spectroscopy, *Journal of molecular biology* 428 (2) (2016) 323–331.
- [47] S. Bottaro, K. Lindorff-Larsen, Biophysical experiments and biomolecular simulations: A perfect match?, *Science* 361 (6400) (2018) 355–360.
- [48] P. Rheingans, S. Joshi, Visualization of molecules with positional uncertainty, in: *Data Visualization '99*, 1999, pp. 299–306.
- [49] J. Schmidt-Ehrenberg, D. Baum, H.-C. Hege, Visualizing dynamic molecular conformations, in: *IEEE Visualization*, 2002, pp. 235–242.
- [50] R. Koradi, M. Billeter, K. Wüthrich, MOLMOL: A program for display and analysis of macromolecular structures, *J. Mol. Graph.* 14 (1) (1996) 51–55. doi:http://dx.doi.org/10.1016/0263-7855(96)00009-4.
- [51] W. Rieping, M. Habeck, M. Nilges, Inferential Structure Determination, *Science* 309 (5732) (2005) 303–306.
- [52] C. H. Lee, A. Varshney, Representing thermal vibrations and uncertainty in molecular surfaces, in: *SPIE Conference on Visualization and Data Analysis*, 2002, pp. 80–90.
- [53] J. Cortes, S. Barbe, M. Erard, T. Simeon, Encoding molecular motions in voxel maps, *IEEE/ACM Trans. Comput. Biol. Bioinform.* 8 (2) (2011) 557–563.

- 1  
2  
3  
4  
5  
6  
7  
8 [54] C. Schulz, K. Schatz, M. Krone, M. Braun, T. Ertl, D. Weiskopf, Uncer-  
9 tainty visualization for secondary structures of proteins, in: IEEE Pacific  
10 Visualization Symposium (PacificVis), 2018. doi:10.1109/PacificVis.  
11 2018.00020.  
12  
13  
14 455 [55] A. Bryden, G. Phillips, M. Gleicher, Automated illustration of molecular  
15 flexibility, IEEE Trans. Vis. Comput. Graphics 18 (1) (2012) 132–145. doi:  
16 10.1109/TVCG.2010.250.  
17  
18  
19 [56] M. Fioravante, A. Shook, I. Thorpe, P. Rheingans, Visualizing Motional  
20 Correlations in Molecular Dynamics using Geometric Deformations, Com-  
21 put. Graph. Forum 32 (3pt3) (2013) 311–320. doi:10.1111/cgf.12118.  
22 460  
23  
24 [57] S. M. Dabdoub, R. W. Rumpf, A. D. Shindhelm, W. C. Ray, Moflow:  
25 visualizing conformational changes in molecules as molecular flow improves  
26 understanding, BMC Proceedings 9 (6) (2015) 1–12.  
27  
28  
29 [58] A. Sali, H. M. Berman, T. Schwede, J. Trewhella, G. Kleywegt, S. K. Bur-  
30 ley, J. Markley, H. Nakamura, P. Adams, A. M. J. J. Bonvin, W. Chiu,  
31 465 M. D. Peraro, F. Di Maio, T. E. Ferrin, K. Grünwald, A. Gutmanas,  
32 R. Henderson, G. Hummer, K. Iwasaki, G. Johnson, C. L. Lawson,  
33 J. Meiler, M. A. Marti-Renom, G. T. Montelione, M. Nilges, R. Nussi-  
34 nov, A. Patwardhan, J. Rappsilber, R. J. Read, H. Saibil, G. F. Schröder,  
35 C. D. Schwieters, C. A. M. Seidel, D. Svergun, M. Topf, E. L. Ulrich, S. Ve-  
36 lankar, J. D. Westbrook, Outcome of the First wwPDB Hybrid/Integrative  
37 Methods Task Force Workshop, Structure (London, England : 1993) 23 (7)  
38 470 (2015) 1156–1167.  
39  
40  
41 [59] D. S. Goodsell, M. A. Franzen, T. Herman, From Atoms to Cells: Using  
42 Mesoscale Landscapes to Construct Visual Narratives, Journal of molecular  
43 biology 430 (21) (2018) 3954–3968.  
44  
45  
46 475 [60] G. T. Johnson, L. Autin, M. Al-Alusi, D. S. Goodsell, M. F. Sanner, A. J.  
47 Olson, cellPACK: a virtual mesoscope to model and visualize structural  
48 systems biology, Nature Methods 12 (1) (2015) 85–91.  
49  
50  
51  
52  
53  
54  
55  
56  
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52  
53  
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55  
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58  
59  
60  
61  
62  
63  
64  
65
- 480 [61] J. H. Iwasa, Bringing macromolecular machinery to life using 3D animation, *Current opinion in structural biology* 31 (2015) 84–88.
- [62] J. H. Iwasa, Animating the model figure, *Cell* 20 (12) (2008) 699–704.
- [63] H. Miao, T. Klein, D. Kouřil, P. Mindek, K. Schatz, M. E. Groller, B. Kozlikova, T. Isenberg, I. Viola, Multiscale Molecular Visualization., *Journal of molecular biology* 431 (6) (2019) 1049–1070.
- 485 [64] J. Parulek, D. Jönsson, T. Ropinski, S. Bruckner, A. Ynnerman, I. Viola, Continuous levels-of-detail and visual abstraction for seamless molecular visualization, in: *Computer Graphics Forum*, Vol. 33, Wiley Online Library, 2014, pp. 276–287.
- [65] H. Miao, E. De Llano, T. Isenberg, M. E. Groller, I. Bari, I. Viola, Dimsum: Dimension and scale unifying map for visual abstraction of dna origami structures, *Computer Graphics Forum* 37 (3) (2018) 403–413. [arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/cgf.13429](https://onlinelibrary.wiley.com/doi/pdf/10.1111/cgf.13429), doi:10.1111/cgf.13429.
- 495 URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.13429>
- [66] P. Mindek, D. Kouřil, J. Sorger, D. Toloudis, B. Lyons, G. Johnson, M. E. Groller, I. Viola, Visualization Multi-Pipeline for Communicating Biology., *IEEE Trans Vis Comput Graph* 24 (1) (2018) 883–892.
- [67] J. Singla, K. M. McClary, K. L. White, F. Alber, A. Sali, R. C. Stevens, Opportunities and Challenges in Building a Spatiotemporal Multi-scale Model of the Human Pancreatic  $\beta$  Cell, *Cell* 173 (1) (2018) 11–19.
- [68] Z. Lv, A. Tek, F. Da Silva, C. Empereur-Mot, M. Chavent, M. Baaden, Game on, science-how video game technology may help biologists tackle visualization challenges, *PloS one* 8 (3) (2013) e57990.
- 505 [69] F. Mwalongo, M. Krone, G. Reina, T. Ertl, State-of-the-art report in web-based visualization, *Computer Graphics Forum* 35 (3) (2016) 553–575. doi:10.1111/cgf.12929.

- 1  
2  
3  
4  
5  
6  
7  
8 [70] S. Yuan, H. S. Chan, Z. Hu, Implementing webgl and html5 in macro-  
9 molecular visualization and modern computer-aided drug design, Trends  
10 in biotechnology 35 (6) (2017) 559–571.  
11 510
- 12 [71] L. A. Abriata, Web Apps Come of Age for Molecular Sciences, Informatics  
13 4 (3) (2017) 28.
- 14  
15  
16 [72] A. S. Rose, P. W. Hildebrand, NGL Viewer: a web application for molec-  
17 ular visualization, Nucleic Acids Research 43 (W1) (2015) W576, [http:](http://proteinformatics.charite.de/ngl)  
18 [//proteinformatics.charite.de/ngl](http://proteinformatics.charite.de/ngl) (last accessed: 14.02.17). doi:  
19 515 [10.1093/nar/gkv402](https://doi.org/10.1093/nar/gkv402).
- 20  
21  
22 [73] D. Sehnal, M. Deshpande, R. S. Vařeková, S. Mir, K. Berka, A. Midlik,  
23 L. Pravda, S. Velankar, J. Koča, LiteMol suite: interactive web-based vi-  
24 sualization of large-scale macromolecular structure data, Nature Methods  
25 14 (12) (2017) 1121–1122. doi:[10.1038/nmeth.4499](https://doi.org/10.1038/nmeth.4499).  
26 520
- 27  
28 [74] Jolecule - the protein viewer in the cloud, <http://jolecule.appspot.com/>  
29 (last accessed: 31.01.17).
- 30  
31  
32 [75] F. Mwalongo, M. Krone, M. Becher, G. Reina, T. Ertl, GPU-based remote  
33 visualization of dynamic molecular data on the web, Graphical Models 88  
34 (2016) 57–65. doi:[10.1016/j.gmod.2016.05.001](https://doi.org/10.1016/j.gmod.2016.05.001).  
35 525
- 36  
37 [76] H. Berman, K. Henrick, H. Nakamura, Announcing the worldwide Protein  
38 Data Bank, Nature Structural & Molecular Biology 10 (12) (2003) 980–980.  
39 doi:[10.1038/nsb1203-980](https://doi.org/10.1038/nsb1203-980).  
40 URL <http://www.nature.com/articles/nsb1203-980>
- 41  
42  
43 [77] T. Schwede, J. Kopp, N. Guex, M. C. Peitsch, Swiss-model: an automated  
44 protein homology-modeling server, Nucleic acids research 31 (13) (2003)  
45 3381–3385.  
46 530
- 47  
48 [78] S. I. O’donoghue, K. S. Sabir, M. Kalemanov, C. Stolte, B. Wellmann,  
49 V. Ho, M. Roos, N. Perdigao, F. A. Buske, J. Heinrich, et al., Aquaria:  
50  
51  
52  
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46  
47  
48  
49  
50  
51  
52  
53  
54  
55
- 535 simplifying discovery and insight from protein structures, *Nature methods*  
12 (2) (2015) 98.
- [79] M. Norrby, C. Grebner, J. Eriksson, J. Boström, Molecular rift: Virtual  
reality for drug designers, *Journal of Chemical Information and Model-*  
ing 55 (11) (2015) 2475–2484, PMID: 26558887. doi:10.1021/acs.jcim.  
540 5b00544.
- [80] A. Maes, X. Martinez, K. Druart, B. Laurent, S. Guégan, C. H. Marc-  
hand, S. D. Lemaire, M. Baaden, MinOmics, an Integrative and Immersive  
Tool for Multi-Omics Analysis, *Journal of Integrative Bioinformatics* 15 (2)  
967294.
- 545 [81] R. M. Andrei, M. Callieri, M. F. Zini, T. Loni, G. Maraziti, M. C. Pan,  
M. Zoppè, Intuitive representation of surface properties of biomolecules  
using bioblender, *BMC Bioinformatics* 13 (4) (2012) S16. doi:10.1186/  
1471-2105-13-S4-S16.
- [82] N. Rajendiran, J. D. Durrant, Pyrite: A blender plugin for visualizing  
550 molecular dynamics simulations using industry-standard rendering tech-  
niques, *Journal of Computational Chemistry* 39 (12) (2017) 748–755.  
doi:10.1002/jcc.25155.
- [83] Molecular Maya - a plugin for Autodesk Maya, [https://clarafi.com/  
tools/mmaya/](https://clarafi.com/tools/mmaya/) (last accessed: 31.01.17).
- 555 [84] VIZBI - Visualizing Biological Data, <https://vizbi.org> (last accessed:  
31.01.17).
- [85] BioVis, <http://biovis.net> (last accessed: 31.01.17).
- [86] MolVA - Molecular Graphics and Visual Analysis of Molecular Data, [http:  
//decibel.fi.muni.cz/~xbyska/molva/](http://decibel.fi.muni.cz/~xbyska/molva/) (last accessed: 31.01.17).

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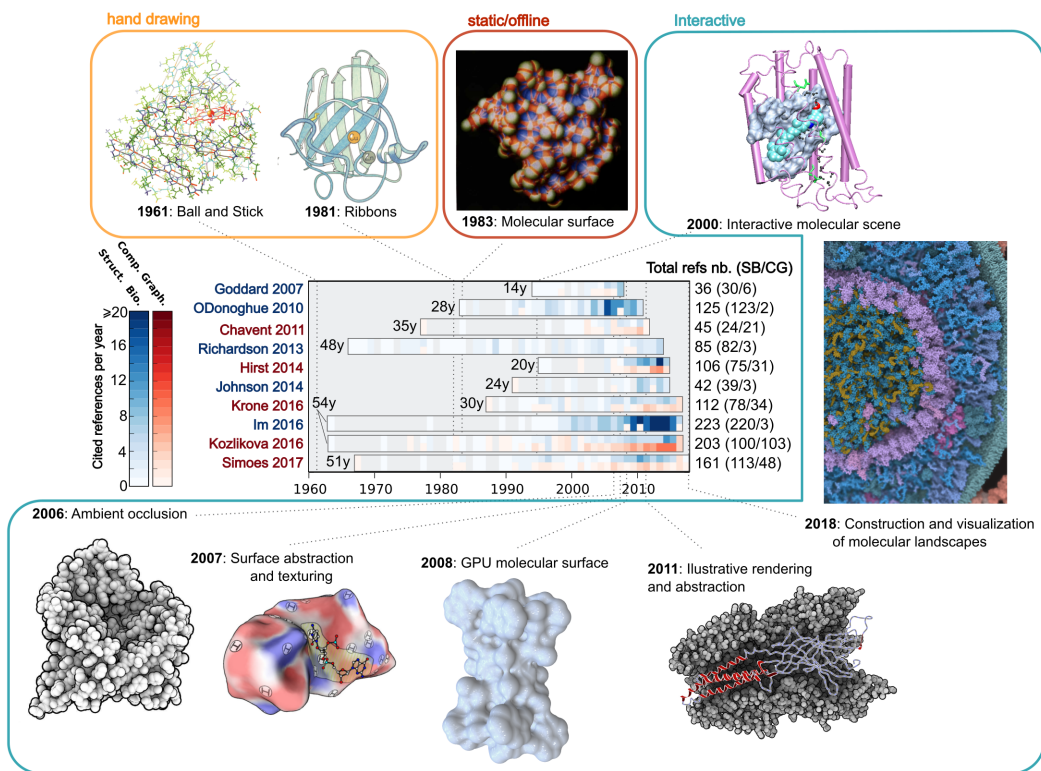


Figure 1: List of surveys presented in this article indicating their time span, number of cited references per year, total number of references, and the ratio of papers coming from the structural biology and computer graphics and visualization fields, respectively. If an article refers to both types of references for the same year, the cell is divided in two rows of different color. Blue color refers to articles oriented towards a more general (structural biology) audience while red color depicts more technical articles generally published in journals and conferences from the computer graphics community. Figures around the diagram present milestones for molecular visualizations: from hand drawings of myoglobin by Martin Geis (Illustration, Irving Geis. Used with permission from the Howard Hughes Medical Institute ([www.hhmi.org](http://www.hhmi.org)). All rights reserved) and the ribbons diagram designed by Jane Richardson [5] to more sophisticated representations like molecular surfaces. This surface was first processed as a static image [6]. During the early 90s to 2000s, with the advent of molecular viewers such as VMD, PyMOL or UCSF Chimera, it was possible to display all these representations interactively (here, a scene rendered with VMD [7]). From mid-2000s, technical developments performed in computer graphics labs are changing the way of visualizing molecular structures by better rendering molecular shapes using lighting effects such as Ambient Occlusion [8], developing new ways of rendering molecular structures [9, 10] or efficiently harnessing Graphics Processing Units (GPU) capabilities [11]. Now, it is possible to interactively construct and visualize very crowded and large systems opening the way for mesoscale models (spanning thousands of Angstroms and containing millions of molecules) with a nearly atomic resolution [12]. Unfortunately, these methods are not yet fully available to the end users such as structural biologists.

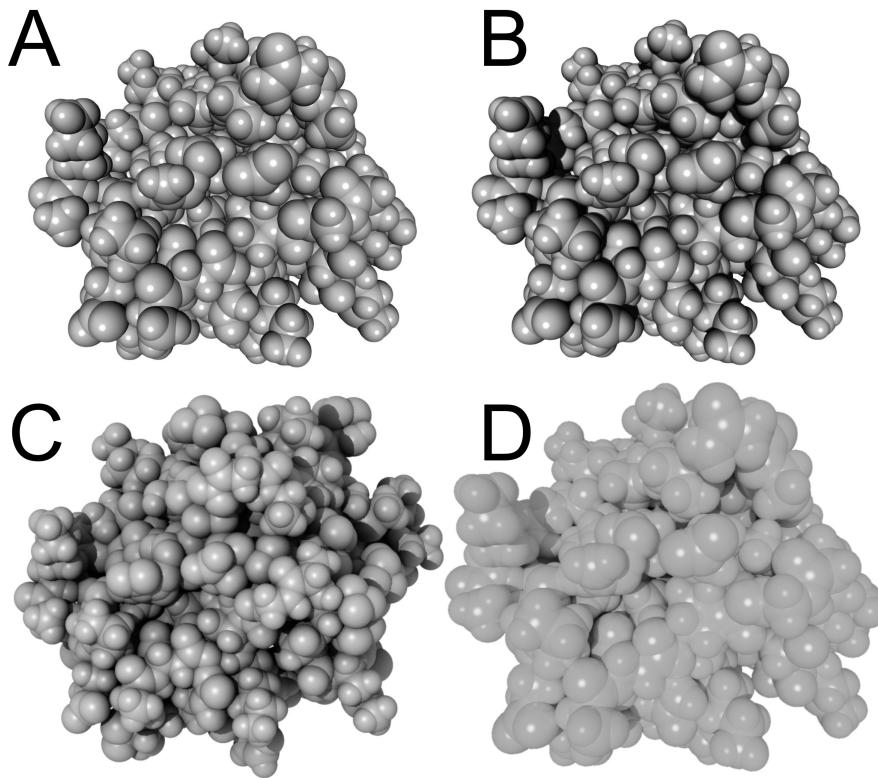


Figure 2: A- Basic Blinn-Phong (BP) rendering. B- Addition of shadows to BP rendering. C- Ambient occlusion lighting added to BP and shadows. D- Photorealistic rendering. While the three first renderings can be performed interactively, the latter still requires costly computation which currently only allows rendering static images.



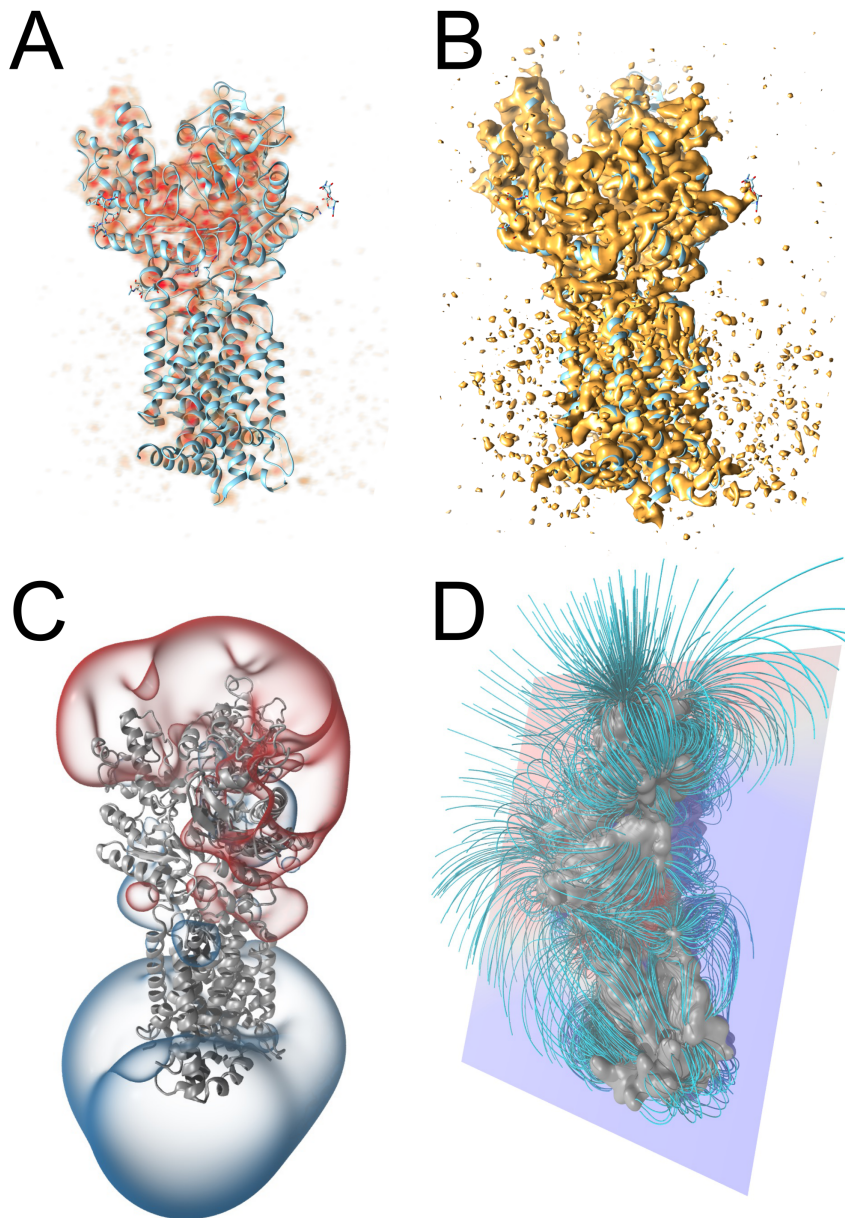


Figure 3: Examples of volume rendering for molecular data. Visualization of the cryo-EM map of a protein (PDB ID: 6D4J; EMD ID: EMD-7796) rendered using direct volume rendering (A) and isosurface (B). Electrostatic field represented as isosurface (C) and as field lines (D).

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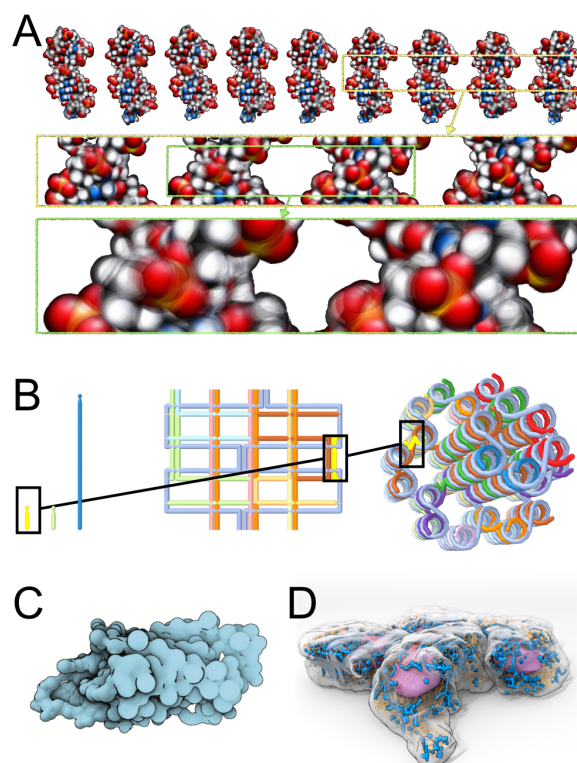


Figure 4: A- DNA dynamics depicted as time lapse-motion blurred rendering of an MD trajectory. Three levels of magnification are provided to depict dynamics at different time- and lengthscales: on the top row overall double helix motion is visible with DNA groove deformations up to the tens of Angstroms scale, in the middle row the local groove dynamics is highlighted leading to Angstrom-scale shape changes and the bottom row depicts very short timescale sub-Angstrom phosphodiester backbone vibrations. Figure generated using UnityMol [68]. B- Abstractions of DNA origami [65]. C- continuous transformation to pass from a very precise molecular surface (on the left side of the molecule) to a simplified surface representation (center), then to a VdW representation, as a function of the user's point of view [64]. D- illustrative representation of cell models [66]. Purple: nuclear surface, blue: mitochondria, yellow: microtubules. The cell surface is outlined and semi-transparent. Image from the Allen Cell Explorer: <https://www.allencell.org>