

Visibility Equalizer

Cutaway Visualization of Mesoscopic Biological Models

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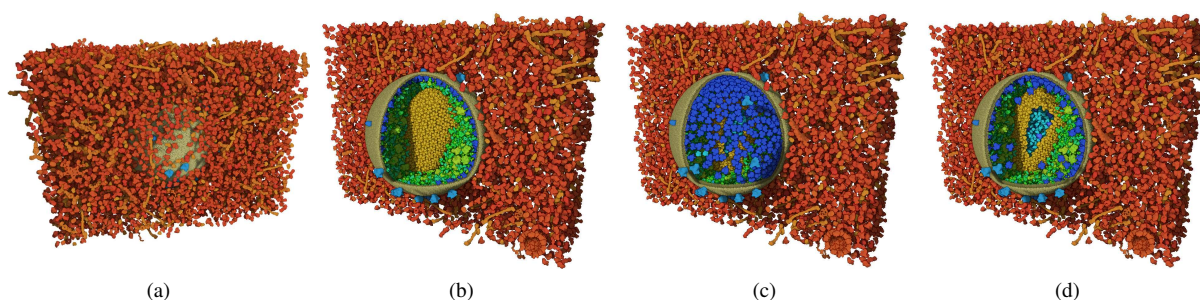


Figure 1: The workflow of our method for a model of HIV surrounded with blood plasma proteins. (a) Entire dataset is shown. The blood serum (shown in red) is occluding the virus. (b) Clipping objects are added to selectively clip molecules to reveal the HIV capsid. (c) The illustrator decides to show more of the matrix protein (shown in blue), so their clipping is disabled. However, they are now occluding the view of the capsid. (d) The probabilistic clipping has been used to selectively remove those matrix proteins occluding the capsid, but some of them are left in the scene to indicate the presence of this type of protein on the virus membrane. The capsid has been clipped with view-space clipping to reveal its internals.

Abstract

In scientific illustrations and visualization, cutaway views are often employed as an effective technique for occlusion management in densely packed scenes. We propose a novel method for authoring cutaway illustrations of mesoscopic biological models. In contrast to the existing cutaway algorithms, we take advantage of the specific nature of the biological models. These models consist of thousands of instances with a comparably smaller number of different types. Our method constitutes a two stage process. In the first step, clipping objects are placed in the scene, creating a cutaway visualization of the model. During this process, a hierarchical list of stacked bars inform the user about the instance visibility distribution of each individual molecular type in the scene. In the second step, the visibility of each molecular type is fine-tuned through these bars, which at this point act as interactive visibility equalizers. An evaluation of our technique with domain experts confirmed that our equalizer-based approach for visibility specification was valuable and effective for both, scientific and educational purposes.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Viewing algorithms

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1. Introduction

Molecular biology is an emerging field that is characterized by rapid advances of the current state of knowledge. New discoveries have to be communicated frequently to a large variety of audiences. However, due to their complexity and mesoscopic scale, it is hard to directly convey the discoveries of molecular phenomena. Therefore illustrations that depict models of these mesoscale structures are the most widely used form of communicating them.

The traditional pipeline for creating scientific illustrations of molecular structures starts with gathering the required knowledge for building models that convey the newly discovered insights. Illustrators then create sketches, in which the relevant internal and external regions of these structures are uncovered. To achieve this, occlusion management techniques, such as *cutaways* are applied. Cutaways remove specific outer parts of the organism model, so that internal structures become visible. When biologists come up with new findings that are not depicted in the existing illustration, the conceptual layout of the original illustration might not be valid anymore. The whole illustration process has to be repeated, in the worst case from the beginning, which is cumbersome and time consuming.

Considering the rapid evolution of knowledge in the field of biology, it is necessary to adapt the traditional illustration pipeline so that new information can be plugged in easily and resulting illustrations can be updated in a very short time. Virtual 3D models of cells and other mesoscale molecular structures can be utilized for these purposes. Biologists have designed tools, such as *cellPACK* [JAAA*15], to procedurally generate 3D models that represent the structure of micro-organisms such as viruses, or entire cells at atomic resolution. Based on a set of input parameters, individual molecules are assembled into these complex organic static structures. The parameter set consists of a specification of molecular ingredients, concentrations as well as spatial distribution that define where are the instances distributed in a given compartment. The resulting 3D models, in most complex cases, may consist of thousands of ingredients, which in turn, may result in millions of molecule instances and billions of atoms. The instances are densely packed within the predefined compartments, to replicate the actual molecular crowding phenomenon prevailing in living organisms. Due to the high density of these scenes, inner structures that are essential for conveying the functioning of the organism, remain hidden. It is therefore important to develop visualization techniques that would procedurally reproduce the occlusion management methods used in traditional illustration. Currently, this is achieved by placing clipping objects in the scene, which remove specified parts of the displayed model. However, illustrators have to make sure that the essential information, e.g., the ratio of multiple molecular ingredients is represented, and not either hidden in the volume or clipped away (Fig. 2a). To do this, they would need to visually in-

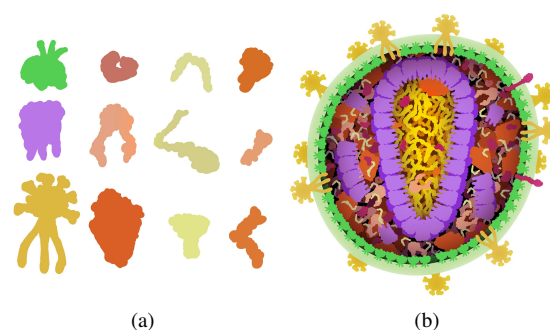


Figure 2: Which of the proteins shown in (a) are visible in the illustration shown in (b) and which are not?

spect the presence of each single ingredient in the resulting visualization (Fig. 2b).

To alleviate this process, we present our first contribution. We display a stacked bar for each molecular type that encodes the ratio of visible, clipped, and occluded instances of the respective type for the current viewpoint and clipping setting. During the process of placing clipping objects in the scene, these bars therefore continuously reveal, which molecular types are underrepresented or overrepresented. This enables the illustrator to modify the placement of the clipping objects in such a way that every molecular type is adequately represented in the scene. We call this the coarse-level of the visibility specification process.

To preserve important structures that would be removed through clipping objects, such as cutting planes, traditional illustrations also often reintroduce parts of them in front of the revealed cross sections. In Figure 2b, for instance, the glycoproteins (yellow molecules) of the HIV particle which are not occluding the object of interest, in this case the capsid containing the RNA, are left in the illustration to communicate their presence on the surface of the virus (2a). In this way, the main components of the virus particle can be illustrated in a single image. The process of fine-tuning the visibility is extremely time-consuming, as the illustrator has to manually pick individual molecular instances to be reintroduced or removed from the scene.

To significantly speed up this visibility fine-tuning process, we propose a novel method for clipping instances using a fuzzy approach. In addition to either, entirely show or remove instances of a given ingredient, we offer the possibility to show only an arbitrary number of them. The main purpose of this approach is to increase the visibility of hidden structures by removing redundant parts of occluding instances while preserving some of them. An analogy of this approach can be drawn with “Screen-Door Transparency”, which is a trivial way to obtain transparency in computer graphics, by placing small holes in a polygon to reveal what is present behind. Additionally, we propose the novel metaphor of the

visibility equalizer for controlling efficiently this effect. To explain its role, we use the metaphor of hi-fi sound reproduction where on a basic level, the *volume control* is used for adjusting the output sound *uniformly* on all frequencies. Such a mechanism corresponds to our coarse-level visibility specification through the clipping objects, where all molecular types are uniformly removed from the clipped regions. However, hi-fi sound systems also allow users to fine-tune the sound through an *equalizer*. With an equalizer, the volume of each individual frequency band can be adjusted separately to achieve a desired sound reproduction. In the sense of this of metaphor, the visibility of each molecule type can be regarded as a frequency band—represented as the stacked bars that form our visibility equalizer. To achieve a similar level of fine-grained control for the visibility of the molecule types, we make these bars interactive—thus allowing the user to interact with the equalizer. Individual intervals on each bar can be dragged to increase or decrease the visibility of the individual molecular types within the scene, given the specified clipping objects. When interacting with the visibility equalizer, the artist or biologist can intuitively achieve expressive cutaway designs in a fraction of the time that would be needed for manual visibility adjustments.

2. Related Work

Related work can be categorized into occlusion management techniques and molecular visualization. We will concentrate on the former, according to the focus of this paper.

2.1. Occlusion Management

Related occlusion management techniques can be categorized into object centric approaches and transfer function based approaches. In object centric approaches, the geometry or parts of the volume that are obstructing one or more particular objects of interest are (partially) removed. In transfer function based approaches, the user assigns importances to intervals of the volume data values.

Object Centered Approaches. Cutaway and ghosting techniques were first introduced by Feiner & Seligmann [FS92] in 1992. Their work inspired several follow-up approaches [DWE02, DWE03, WEE03, VKG04, VKG05, KTH*05] that were later summarized in the survey by Viola & Gröller [VG05] under the collective term of *smart visibility* techniques. They coined this term to describe expressive visualization techniques that smartly uncover the most important features of the displayed data, i.e., cutaway views, ghosted views, and exploded views.

Krüger et al. [KSW06] developed a system that applies transparency and shading to enable focus&context visualization in volume data sets with a simple point&click interface. Li et al. [LRA*07] propose a cutaway design based on the geometry of the occluder in contrast to previous approaches that were based on the occludee. Burns & Finkelstein [BF08]

applied the concept of importance-driven cutaways for volume data to polygonal models. Lawonn et al. [LGV*16] extend this approach to present a composite technique that combines the visualization of blood flow with the surrounding vessel structures. Baer et al. [BGCP11] published a perceptual evaluation of smart visibility techniques for two ghosted view approaches in comparison to semi-transparent approaches. The results clearly favored the ghosted view techniques. Sigg et al. [SFCP12] propose an approach for automatic cutaway box placement with optimized visibility for target features that are specified as degree-of-interest functions during interactive visual analysis of the volume data. Lidal et al. [LHV12] defined five design principles for cutaway visualization of geological models. The approach by Diaz et al. [DMNV12] preserves the relevant context information in volume clipping by allowing the user to extrude segmented surfaces such as bone structures from the clipping plane.

Since these approaches are object centered, they deal with (partial) occlusion of individual objects. For our data, partial or even complete occlusion of individual molecules is not an issue. The data is not composed of large singular entities such as polygonal or segmented volumetric objects where each single one has a semantic meaning. Instead, there are thousands or hundreds of thousands of instances that stem from only a couple of dozen molecule types. Therefore it does not matter if individual instances are occluded, as long as the structures that they form are preserved. Our approach is therefore fundamentally different from existing occlusion management approaches as it combines principles from object centered and transfer function based approaches.

Transfer Function Based Approaches. Transfer function based approaches are related as our data resembles volumetric data in the sense that it consists of a dense point cloud. However, instead of continuous attribute values distributed over voxels, our data features a discrete number of molecule types. This characteristic enables our visibility equalizer approach. The context-preserving volume rendering model [BGKG05] uses a function of shading intensity, gradient magnitude, distance to the eye point, and previously accumulated opacity to selectively reduce the opacity in less important data regions. Contours of surfaces that would be removed due to opacity, remain visible as the amount of illumination received is taken as a measure whether a point should be visible or not. Burns et al. [BHW*07] propose a multimodal approach that combines CT scan data and real-time ultrasound data. Importance driven shading is used to emphasize features of higher importance that have been revealed through the ghosting.

In his PhD thesis [Vio05], Viola presents an optimization strategy for automatically assigning visual mapping to voxels so that segmented objects in the volume are visible as specified by the user. Correa et al. [CM11] used a similar approach for applying visibility directly to voxels, without

the notion of segmented objects. In our approach, we control visibility by interacting with the stacked bars of the visibility equalizer to modify the clipping object properties for each individual molecule type. Ruiz et al. [RBB*11] propose an approach for automatic transfer function optimization by minimizing the informational divergence between a user specified target distribution and the visibility distribution captured from certain viewpoints.

Transfer function based approaches are well suited for volumetric data that contains segmentable structures, such as the organs or bones in a medical scan. For molecular data this only holds partially true, as some types of molecules do indeed form continuous structures that could be made visible with a transfer function (e.g., membranes, nucleus). On the other side, within these structures there is a more noise-like distribution of these molecules that cannot be segmented into solid structures.

2.2. Multi-Scale Visualization of Molecular Structures

Lindow et al. [LBH12] were the first to introduce a fast method for the real-time rendering of large-scale atomic data on consumer level hardware. They utilize instancing on the GPU to repeat these structures in the scene. For each molecule type, a 3D grid of the atoms is created and stored on the GPU. Falk et al. [FKE13] further refined the method with improved depth culling and hierarchical ray casting to achieve faster rendering performance for even larger scenes.

A novel and more efficient approach for rendering large molecular datasets was later on introduced by Le Muzic et al. [LMPSV14], which is based on brute-force rasterization rather than ray-tracing. To reduce the number of drawn geometries they rely on the tessellation shader to perform dynamic level-of-detail. Their approach allows switching between different degree of coarseness for the molecular structures on-the-fly, thus allowing the entire scene to be rendered in a single draw call efficiently, approaching zero driver overhead. As a follow up, they developed and released cellVIEW [LAPV15], a tool designed for rendering large-scale molecular scenes, which was implemented with Unity3D, a popular 3D engine. cellVIEW was primarily developed to showcase large molecular structures generated with cellPACK [JAAA*15], a tool developed to procedurally generate accurate and multi-scale models of entire viruses and cells.

Our visibility equalizer technique is built-upon cellVIEW, and is an attempt to improve the navigation and exploration of large molecular scenes generated with cellPACK. cellVIEW leverages GPU computing and parallel programming to enable real-time rendering and therefore, to provide a smooth and responsive user-experience, the visibility equalizer was developed with the same programming paradigm.

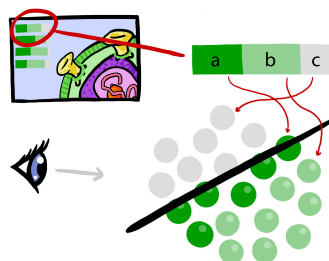


Figure 3: Illustration of the visibility equalizers. Each molecular ingredient has its own stacked bar showing (a) instances visible from the current viewpoint, (b) occluded instances, (c) instances clipped away by the clipping objects.

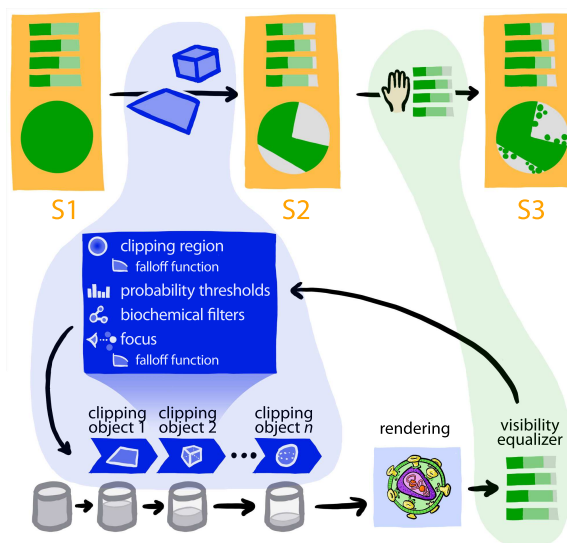


Figure 4: The workflow of our method. The data can be displayed either without any clipping ($S1$), with deterministic clipping defined by the clipping objects ($S2$), or probabilistic clipping specified through the visibility equalizer ($S3$). Lower part (technical overview): each clipping object filters the output of the previous one. The rendered image is used to update the visibility equalizer. Interaction with the bars updates the scene to match the specification in the visibility equalizer.

3. Overview

The two main components of our method are the *clipping objects* and the *visibility equalizer*. We distinguish between object-space object clipping and view-space object clipping. Object-space clipping discards elements according to their distance to a geometric shape. View-space clipping discards elements according to whether or not they occlude certain objects in the current viewport. The role of the visibility equalizer is to override the behaviour of the clipping objects. The visual encoding of the visibility equalizer is illus-

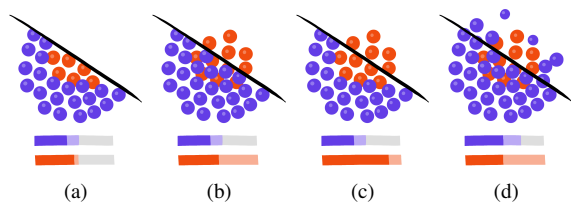


Figure 5: Interaction with the visibility equalizer. (a) increasing the visibility ratio of the red molecules, reduces the occluding blue molecules. (b) completely decreasing the clipping ratio of the red molecules. (c) partially decreasing the clipping ratio of the blue molecules. (d) combining the steps from a and b to increase the overall visibility of the red molecules.

trated in Figure 3. It contains a series of stacked bars, one for each molecular species, which can be manipulated by user-interaction. The stacked bars show three quantitative information for a given type of ingredient: *a* - the ratio of visible instances to the total number of instances; *b* - the ratio of occluded instances to the total number of instances; *c* - the ratio of discarded instances to the total number of instances. By dragging the light green bar, the number of instances affected by the object-space clipping is modified, while dragging the dark green bar modifies the number of instances affected by the view-space clipping. Figure 4 depicts the workflow of our method as a state-machine. We demonstrated three possible states, denoted as *S1*, *S2*, and *S3*.

S1: The scene is displayed without any clipping. The visibility equalizer shows that no molecules are clipped, and provides the described visibility information for each molecular ingredient.

S2: Clipping objects are added to filter-out elements according to the distance to a clipping object's shape. Each time the scene is refreshed, visible and clipped instances are counted and the values of the visibility equalizer are updated accordingly.

S3: The user overrides the behaviour of a clipping object, by interacting with the visibility equalizer as illustrated in Figure 5. Upon modification of the Visibility Equalizer values, the scene is updated and re-rendered to match with the user specified clipping properties.

4. Object-Space Clipping

Clipping objects define how instances shall be discarded depending on their location or type. They can operate either in object-space or in view-space. In this Section, we will explain in details how clipping objects operate in object-space.

4.1. Clipping Object Distance

Clipping objects are associated with geometric shapes to specify a region of the domain which is influenced by the clipping. Our system currently supports the following set of primitive shapes: plane, cube, sphere, cylinder and cone. We compute the distance between the instance centroids and the clipping region to find out which ones lie inside that region. To accelerate the computation, we solve the problem analytically using a mathematical description of the clipping region as a 3D signed distance field (SDF).

Due to the architecture of the rendering technique which is employed, the instances information (position, rotation, type, radius, etc.) is already stored on the GPU in large buffers using a structure of array layout. To speed up the clipping operation and avoid data transfer costs, the distance is computed in parallel in a compute shader program, prior to the rendering, with one thread allocated per instance. The position, rotation, scale and geometry type of every clipping object must be additionally uploaded to the GPU in order to define the correct clipping region SDF. In a single thread and for each clipping object, the required information is fetched from the video memory and is used to compute the signed distance between an instance and the clipping object. Should an object be clipped, a dedicated flag in a GPU buffer will be updated, and that flag will be read during the rendering to discard the clipped instance.

4.2. Clipping Filtering

A clipping object also comprises a set of parameters that override the clipping state of instances based on their type. This filtering operation is performed if an instance is located inside the clipping region, in the same compute shader program described in Section 4.1. The first parameter controls the percentage of discarded instances in the clipping region for a given type. We refer to this value as *object-space clipping probability*. This value can be increased or decreased by dragging the light green bar in the visibility equalizer. Clipping objects are applied in serial, the output of a clipping object constitute the input of the next one. It is important to mention that with multiple clipping objects, interaction with the light green bar in the visibility equalizer will only affect the clipping probability of the selected clipping object.

Upon start-up of the system, each instance is given a uniformly distributed random number comprised between 0 and 1, and which will remain unchanged. Then, for each instance, we compare this value with the clipping probability in the computer shader program. In case the constant random number is higher than the clipping probability, the instance is marked as discarded, and will not be rendered. For example, if the clipping probability value is equal to zero, all instances in the clipping region will be clipped, if the value is equal to one, no instance will be clipped. A value between zero and one thus allows to control the degree of fuzziness of a clipping, as explained in Figure 5.

The other parameters allow users to control the clipping based on properties such as the size of the molecules (weight) and their overall number (concentration). Via the user interface and for a given clipping object, the user defines ranges that correspond to the desired concentration and molecular weight. Instances whose properties lie outside these ranges are simply discarded and will not be rendered.

4.3. Falloff Function

To further increase control over the object-space clipping, we use a falloff function. The falloff function is used to gradually modulate the effect of the clipping with respect to the distance from the clipping shape. The farther away from the clipping surface an instance is, the higher his clipping probability will be. The object-space clipping probability of a molecule on the 3D position p is multiplied by the falloff function $f(p)$. The falloff function is defined as follows:

$$f(\vec{p}) = 1 - \min(1, (d(\vec{p})/d)^c) \quad (1)$$

where $d(p)$ is the distance to the clipping surface from the point p . The function is parametrized by d and c , where d is the maximum distance up to which the object-space clipping probability takes effect, while c specifies the exponent of the falloff function. It is worth mentioning that the falloff function will override the user-defined clip-ratio, and will modify the values displayed in the visibility equalizer. The molecules of the blood serum (shown in red) are gradually removed from the bottom to the top. In this way, the information about the concentration of these molecules is illustrated at the bottom of the scene, while the visibility of the HIV particle (blue and green) is increased towards to top of the scene.

5. View-Space Clipping

While object-space clipping with geometric shapes allows for a high degree of flexibility, it may also require cumbersome manual operations for more complex set-ups. We therefore provide additional functionalities to selectively remove occluding instances in front of a set of ingredients specified as object of focus, to ensure them a maximum degree of visibility. The focus state can be manually specified via the visibility equalizer by ticking a dedicated checkbox in front of the stack bars.

5.1. Occlusion Queries

When an ingredient type is set as focus, occluding instances of a different type may be selectively removed to reveal the occludees. To determine which are the occluding instances, we perform occlusion queries. Nowadays, modern graphics hardware is able to perform occlusion queries easily using the fixed-function API. However this method requires one draw call per query, which may induce driver overhead with several thousands of queries. We compute the queries

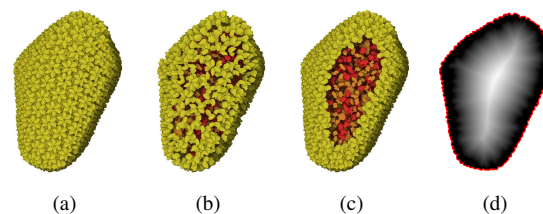


Figure 6: View-space clipping, (a) shows the full HIV Capsid, (b) shows the uniformly distributed clipping, (c) demonstrates the aperture effect and (d) shows the results of the 2D distance transform of the clipping mask.

manually instead using a custom shader program, because it allows the queries to be computed in a single GPU draw call, thus approaching zero driver overhead. In-depth technical details about this approach are described by Kubisch & Tavenrath [KT14].

We first render all the focused ingredients to an off-screen texture. This texture will then serve as a depth-stencil mask for the occlusion queries. There can be several ingredient types constituting the object of focus for a given clipping object. Thereafter, we render the bounding spheres of the potential occluders in a single draw call, on top of the depth-stencil mask. Thanks to early depth-stencil functionality, available on modern graphics hardware, fragments that will pass the test and be executed are guaranteed to belong to an occluder. We then update the clipping state of the occluding instance by updating its corresponding occlusion flag stored in the main video memory directly from the fragment program.

5.2. Clipping Filtering

Similarly to the object-space clipping, we provide an additional parameter to control the degree of fuzziness of the view-dependent clipping, which we refer to as *view-space clipping probability*. This value is set by the user for each ingredient type, and is modified by dragging the dark green bar in the visibility equalizer. The view-space clipping probability is evaluated after an instance was flagged as occluder in the same shader program mentioned in Section 4.2. We compare the clipping probability with a random number, initially defined and described in Section 4.2. If the random number is higher than the clipping probability, the instance will remain as clipped, otherwise it will be displayed. This will however result in a uniformly distributed number of visible occluders over the object of focus. Such a distribution might not always be the best design choice, because it fragments heavily the overall structure of the occluders and makes it difficult to see the occludees, as shown in Figure 6b.

We propose an alternative technique for fuzzy removal of

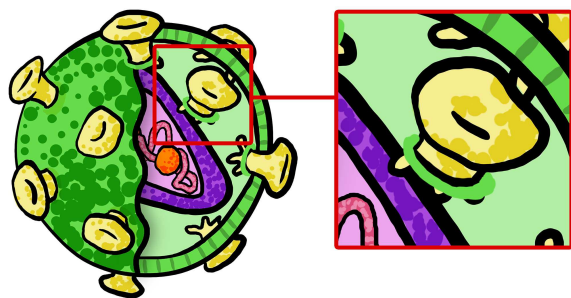


Figure 7: Caption.

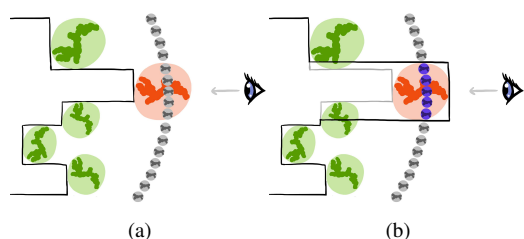


Figure 8: The principle of the depth-bias used for contextual anchoring. The bar chart represents the depth of the mask in one dimension. Elements in grey and red correspond respectively to potential occluders and occludees. (a) Without contextual anchoring, the depth of occluders (grey) is overlapping the depth of the mask and will therefore be discarded. (b) With contextual anchoring, the depth of the occludees (red) is shifted so that context elements (purple) no longer overlap the focus and remain unclipped.

occluding instances, which we dub *aperture effect*. We define an additional parameter, the aperture coefficient, which controls the 2D distance from the instance to the edges of the occludees mask, below which occluding instances shall be clipped. A visual explanation of the aperture effect is shown in Figure 6c. To enable this effect we compute the 2D distance transform of the occludees mask which we store in a separate off-line texture. We use the GPU Jump Flooding Algorithm by Rong & Tan [RT06] to interactively recompute the 2D distance field every frame. After the computation of the distance transform, the texture stores the distance to the contours of the shape for each pixel. Then, while computing occlusion queries in the fragment shader, we simply look-up the distance for the current fragment, and discard instances according to the user-defined aperture coefficient.

5.3. Contextual Anchoring

When observing still images of cut-away scenes, it might be challenging to perceive the depth of objects correctly, despite using lighting-based depth cues. We propose an additional method for depth guidance, which we call *contextual an-*

choring. The concept is to override the results of clipping, to preserve elements located in a close range to non-clipped elements, and that would normally be clipped. By introducing contextual anchoring, the viewer, assuming that he is aware of what the context elements are, will intuitively understand where instances are located. We were able to procedurally reproduce this effect by applying a depth bias to the occlusion queries computation for selected focused molecules. This bias will ensure that contextual elements will no longer overlap the focus and will therefore be preserved as illustrated in Figure 8.

6. Equalizing Visibility

The visibility equalizer comprises a series of stack bars that convey important visibility information for each ingredient type. The three colors correspond respectively to the number of visible, occluded and clipped instances, as explained in Figure 3. In order to fill the stacked bars with correct values, we must count the number of clipped and visible instances, and this operation must be repeated on every update.

6.1. Counting Clipped Instances

We perform the counting of the clipped instances on the GPU, in a dedicated compute shader program, since all the data already reside in the video memory. We priorly declare a dedicated buffer on the GPU to hold the number of clipped instances for each ingredient type, and which shall be cleared before each counting operation. Counting the clipped instances is a rather straightforward task since the clipping state of each instance is routinely computed and stored in a dedicated GPU buffer. Once the clipping routine is performed, we simply browse through all the instances, and in case an instance was flagged as clipped, we increase the counter in the GPU buffer that corresponds to the number of clipped instances for the given type. It is important to use an atomic increment operation for the counting to avoid concurrent accesses to the same counter value from different threads.

6.2. Counting Visible Instances

In order to count the number of visible instances for a given view-point, we first need to generate an instance-buffer, which is a texture that contains, for each pixel, the unique instance id of the rendered molecule. We first start to flag visible instances in a post-processing shader, by browsing all the pixels of the instance-buffer. In case an instance is present in the instance-buffer, it is guaranteed to have at least one pixel visible on the screen, and it is therefore flagged as visible in a dedicated GPU buffer. To store the number of visible instances per type, we also need to declare an additional GPU buffer, which must be priorly cleared each time visible instances are counted. In a second stage, similarly to the counting of the clipped instances, we browse through all

the instances in a dedicated compute shader, while fetching the visibility information which was previously computed. Should an instance be flagged as visible, the counter that corresponds to the number of visible instances for the given type will be increased using an atomic increment operation. Once the information about the number of visible and clipped instances is obtained, the data is then transferred to the CPU, and used to update the visibility equalizer.

7. Results

To showcase the capabilities of our method, we applied it to three different mesoscale molecular scenes. We use cellVIEW [LAPV15] for the rendering, which is a tool designed to efficiently render large molecular scenes on the GPU and is implemented in Unity3D. The different datasets are generated by the domain experts with cellPACK [JAAA*15], a modeling tool for procedural generation of large biomolecular structures. cellPACK summarizes and incorporates the most recent knowledge obtained from structural biology and system biology to generate comprehensive mesoscale models. Based on experimentally obtained data (e.g. data such as proteins structure, concentration and spatial distribution), the tool is able to generate entire models of viruses and cells via a packing method based on collisions constraints.

The first dataset is a model of an HIV particle in blood serum. Figure 9a shows this dataset clipped with a single plane. The contextual anchoring is applied to reintroduce parts of the clipped membrane (grey) around the envelope proteins (blue). The second dataset is a model of *Mycoplasma mycoides*. Figure 9b shows how probabilistic clipping is used to reduce visual clutter to illustrate the positions of the ribosomes (shown in blue) within the cell. The third dataset, shown in Figure 9c is a model of an immature HIV. Here, we applied several clipping objects to reveal the internal structure of the virus. The blood serum (blue) has been preserved around the particle using the probabilistic clipping to illustrate how it encloses the HIV particle. The visibility equalizer is displayed as well, showing the ratios of visible and clipped-away instances of the individual molecular ingredients. The white boxes to the left of each stacked bar are used to mark the given ingredient or compartment as focus.

In Figure 10, we show an example of a single clipping plane used to reduce the concentration of the blood serum molecules, so that the HIV proteins are visible. However, to avoid misleading the viewer about the actual concentration of the blood molecules, we render clipped proteins with a ghosting effect. It illustrates what the actual concentration is, while the visual clutter caused by the blood serum is significantly reduced. Figure 10 illustrates that this can be done in different ways according to the vision of the artist.

The Visibility Equalizer is designed to offer a fast and responsive user experience and therefore it is designed to limit

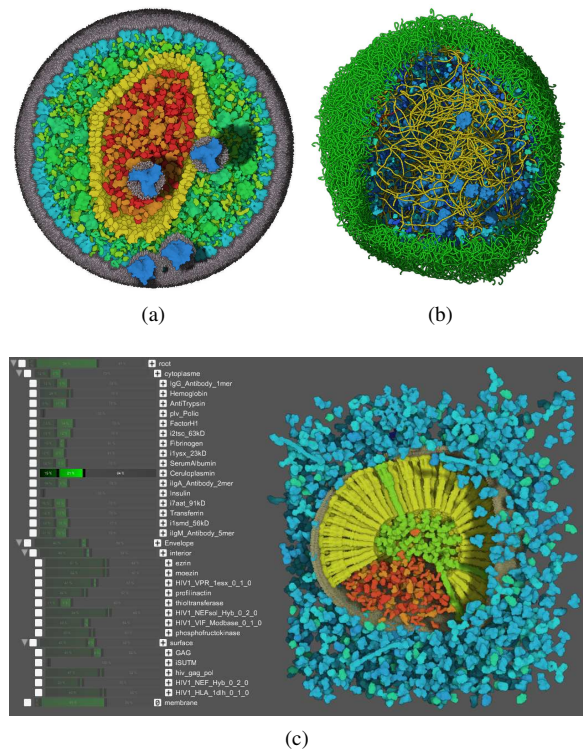


Figure 9: (a) HIV clipped with a plane. Contextual anchoring is used to indicate the proximity of envelope proteins (dark blue) with the lipid membrane (grey). The dark spots represent shadows projected into interior proteins. (b) *Mycoplasma mycoides* with ribosomes (blue) shown. (c) Internal structures of an immature HIV model are shown by several clipping objects. On the left, the visibility equalizer is shown.

the computational overhead. The computation of the object-space clipping, compared to the rendering task performed by cellVIEW, is very light-weight and does not impact the overall performance. The view-space clipping, however, requires more computational work which could impact the responsiveness. Therefore, a good strategy is to limit the number of view-space clipping objects, especially for very large scenes with up to several million instances. Indeed, for computing occlusion queries, occluders and occludees must be additionally rendered, which adds extra work to the rendering pipeline. For this reason, only the bounding spheres of the molecules are rendered rather than their entire structures, which may consist of hundreds or thousands of spheres, in order to guarantee a minimum computational overhead. Moreover, the 2D distance transform which is needed for the aperture effect, also requires additional computation, but since it is computed in parallel on the GPU, we are able to

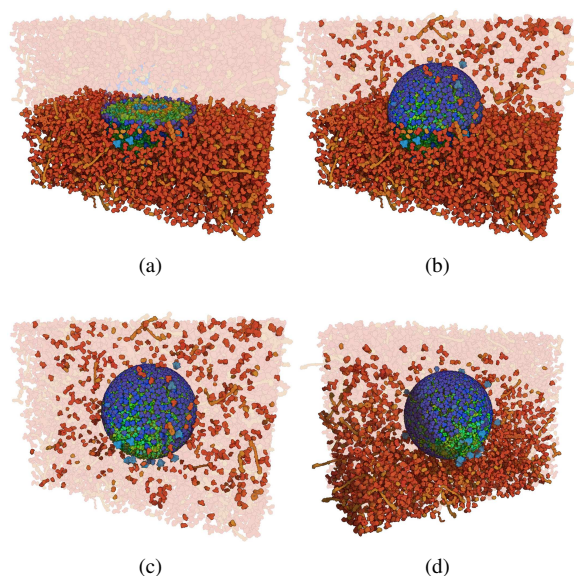


Figure 10: The cutaway molecules are indicated through the ghosting effect. (a) Part of the scene is removed by a clipping plane. (b) The amount of cutaway molecules has been decreased through the probabilistic clipping, which caused some of the cutaway molecules to be reintroduced into the scene. (c) The blood serum (red molecules) are removed by probabilistic clipping in the entire dataset. (d) A falloff function is used to gradually change the influence of the probabilistic clipping.

guarantee a very low computational overhead for this operation too. ** Todo add concrete numbers **

8. User Feedback

We evaluated the usefulness of our tool by collecting informal user feedback from two domain experts in biological illustration and molecular biology, respectively. In both cases, we did a remote walk-through introduction of our software, while collecting first impressions. Additionally, we gave them an executable version of the software and asked them to write a short summary of their experience after trying the tool by themselves. We first sent an early version of our tool to a biomedical illustrator with a strong academic background in chemistry. His overall feedback was very positive, he enjoyed the responsiveness of the tool, and the novel concept of fuzziness and gradient clipping. Here is a quote from his written feedback:

“...in my opinion it can be a very useful toolkit for an illustrator in the biomedical field...It also seems very promising for interactive teaching and also for animation purposes... One very useful feature of the software is the possibility to “cut” planes of interest of a particular space, and keeping

the information of all “layers” by creating a “gradient” of concentration of the ingredients of the displayed molecular recipe. A visualization that resembles an “exploded model” but for biological assembly and it can be achieved without manually selecting every instance you would like to hide.”

Secondly, we interviewed an expert in the domain of molecular biology and visualization. For this second interview the overall feedback was also quite positive. He greatly enjoyed how easy and fast it was to perform clipping, and also enjoyed the polished user interface for manipulating the cut object parameters. He also wished for several additional features to improve the usability of the tool, such as filtering based on biomolecular properties and rendering the ghosts of the clipped instances. These features have since been implemented in the current version of the software, as seen in Figure 10. Here is a quote from the written feedback we collected:

“...The aperture cutting feature is especially useful for exploring a feature or object in the context of a crowded molecular environment. The ability to retain a subset of the clipped objects (“fuzzy clipping”) is an interesting feature that could be very useful under certain circumstances. The feature is useful if one wants to get an impression of reducing the concentration of some of the molecular ingredients, or of what a gradient of certain molecular ingredients would look like.”

9. Conclusion and Future Work

In this paper, we presented a novel method for authoring cutaway illustrations of mesoscopic molecular models. Our system uses clipping objects to selectively remove instances based on their type and location. To monitor and fine-tune the process, we introduce the visibility equalizer. It keeps the user informed about the number of molecular instances removed by the clipping objects, or occluded in the current viewport. Moreover, the visibility equalizer allows the users to directly override the behaviour of the clipping objects in order to fine-tune the visibility of molecular ingredients within the scene.

The visibility equalizer concept demonstrates a scenario where a visualization metaphor, such as the stacked bar chart in our case, can serve as a user interface for performing a specific task, in our case to manipulate 3D data to authorize cutaways. The proposed method allows the users to create comprehensive illustrations of static biological models in real-time. This was confirmed by gathering feedback from domain experts. While the concept was applied to a specific domain, we also wish to develop other examples where the (information) visualization acts simultaneously as an interface to steer the view.

There are several follow-up ideas which we would like to focus on in the future, to strengthen data exploration and showcasing with cellVIEW. Firstly, we would like to explore automatic clipping mechanisms to assist the user with

the placement of clipping-objects based on the nature of the scene and shape analysis. Secondly, we would also like to try our visibility equalizer concept with time-dependent datasets and enhance it to provide the means for authoring animations of clipped datasets.

Our Visibility Equalizer method is built on top of cellVIEW and Unity3D, which are both free to use for non-commercial use, the source code is publicly available, as well as the showcased scenes modelled with cellPACK (<https://github.com/illvisation/cellVIEW>).

References

- [BF08] BURNS M., FINKELSTEIN A.: Adaptive cutaways for comprehensible rendering of polygonal scenes. In *SIGGRAPH Asia* (Singapore, 2008), ACM, pp. 154:1–154:7. 3
- [BGCP11] BAER A., GASTEIGER R., CUNNINGHAM D., PREIM B.: Perceptual evaluation of ghosted view techniques for the exploration of vascular structures and embedded flow. *Computer Graphics Forum* 30, 3 (2011), 811–820. 3
- [BGKG05] BRUCKNER S., GRIMM S., KANITSAR A., GRÖLLER M. E.: Illustrative context-preserving volume rendering. In *Proceedings of the Seventh Joint Eurographics / IEEE VGTC Conference on Visualization* (Leeds, United Kingdom, 2005), EUROVIS'05, pp. 69–76. 3
- [BHW*07] BURNS M., HAIDACHER M., WEIN W., VIOLA I., GRÖLLER M. E.: Feature emphasis and contextual cutaways for multimodal medical visualization. In *Proceedings of the 9th Joint Eurographics / IEEE VGTC Conference on Visualization* (Sweden, 2007), EUROVIS'07, pp. 275–282. 3
- [CM11] CORREA C., MA K.-L.: Visibility histograms and visibility-driven transfer functions. *Visualization and Computer Graphics, IEEE Transactions on* 17, 2 (Feb 2011), 192–204. 3
- [DMNV12] DÍAZ J., MONCLÚS E., NAVAZO I., VÁZQUEZ P.: Adaptive cross-sections of anatomical models. *Computer Graphics Forum* 31, 7 (2012), 2155–2164. 3
- [DWE02] DIEPSTRATEN J., WEISKOPF D., ERTL T.: Transparency in interactive technical illustrations. *Computer Graphics Forum* 21, 3 (2002), 317–325. 3
- [DWE03] DIEPSTRATEN J., WEISKOPF D., ERTL T.: Interactive cutaway illustrations. *Computer Graphics Forum* 22, 3 (2003), 523–532. 3
- [FKE13] FALK M., KRONE M., ERTL T.: Atomistic visualization of mesoscopic whole-cell simulations using ray-casted instancing. *Computer Graphics Forum* 32, 8 (2013), 195–206. 4
- [FS92] FEINER S., SELIGMANN D.: Cutaways and ghosting: satisfying visibility constraints in dynamic 3d illustrations. *The Visual Computer* 8, 5-6 (1992), 292–302. 3
- [JAAA*15] JOHNSON G. T., AUTIN L., AL-ALUSI M., GOODSELL D. S., SANNER M. F., OLSON A. J.: cellPACK: a virtual mesoscope to model and visualize structural systems biology. *Nature methods* 12, 1 (Jan. 2015), 85–91. 2, 4, 8
- [KSW06] KRÜGER J., SCHNEIDER J., WESTERMANN R.: Clearview: An interactive context preserving hotspot visualization technique. *Visualization and Computer Graphics, IEEE Transactions on* 12, 5 (Sept 2006), 941–948. 3
- [KT14] KUBISCH C., TAVENRATH M.: OpenGL 4.4 scene rendering techniques. *NVIDIA Corporation* (2014). 6
- [KTH*05] KRÜGER A., TIETJEN C., HINTZE J., PREIM B., HERTEL I., STRAUSS G.: Interactive visualization for neck-dissection planning. In *Proceedings of the Seventh Joint Eurographics / IEEE VGTC Conference on Visualization* (Leeds, United Kingdom, 2005), EUROVIS'05, pp. 295–302. 3
- [LAPV15] LE MUZIC M., AUTIN L., PARULEK J., VIOLA I.: cellVIEW: a tool for illustrative and multi-scale rendering of large biomolecular datasets. In *Eurographics Workshop on Visual Computing for Biology and Medicine* (Sept. 2015), pp. 61–70. 4, 8
- [LBH12] LINDOW N., BAUM D., HEGE H.-C.: Interactive rendering of materials and biological structures on atomic and nanoscopic scale. *Computer Graphics Forum* 31, 3 (2012), 1325–1334. 4
- [LGV*16] LAWONN K., GLASSER S., VILANOVA A., PREIM B., ISENBERG T.: Occlusion-free blood flow animation with wall thickness visualization. *Visualization and Computer Graphics, IEEE Transactions on* 22, 1 (Jan 2016), 728–737. 3
- [LHV12] LIDAL E. M., HAUSER H., VIOLA I.: Design principles for cutaway visualization of geological models. In *Proceedings of Spring Conference on Computer Graphics (SCCG 2012)* (May 2012), pp. 53–60. 3
- [LMPSV14] LE MUZIC M., PARULEK J., STAVRUM A.-K., VIOLA I.: Illustrative visualization of molecular reactions using omniscient intelligence and passive agents. *Computer Graphics Forum* 33, 3 (2014), 141–150. 4
- [LRA*07] LI W., RITTER L., AGRAWALA M., CURLESS B., SALESIN D.: Interactive cutaway illustrations of complex 3D models. In *SIGGRAPH '07* (San Diego, California, 2007), ACM. 3
- [RBB*11] RUIZ M., BARDERA A., BOADA I., VIOLA I., FEIXAS M., SBERT M.: Automatic transfer functions based on informational divergence. *Visualization and Computer Graphics, IEEE Transactions on* 17, 12 (Dec 2011), 1932–1941. 4
- [RT06] RONG G., TAN T.-S.: Jump flooding in gpu with applications to voronoi diagram and distance transform. In *Proceedings of the 2006 Symposium on Interactive 3D Graphics and Games* (New York, NY, USA, 2006), I3D '06, ACM, pp. 109–116. 7
- [SFCP12] SIGG S., FUCHS R., CARNECKY R., PEIKERT R.: Intelligent cutaway illustrations. In *Visualization Symposium (PacificVis), 2012 IEEE Pacific* (Feb 2012), pp. 185–192. 3
- [VG05] VIOLA I., GRÖLLER E.: Smart visibility in visualization. In *Computational Aesthetics in Graphics, Visualization and Imaging* (2005), The Eurographics Association. 3
- [Vio05] VIOLA I.: *Importance-Driven Expressive Visualization*. PhD thesis, Institute of Computer Graphics and Algorithms, Vienna University of Technology, Favoritenstrasse 9-11/186, A-1040 Vienna, Austria, June 2005. 3
- [VKG04] VIOLA I., KANITSAR A., GRÖLLER M. E.: Importance-driven volume rendering. In *Proceedings of the Conference on Visualization '04* (Washington, DC, USA, 2004), VIS '04, IEEE Computer Society, pp. 139–146. 3
- [VKG05] VIOLA I., KANITSAR A., GRÖLLER M. E.: Importance-driven feature enhancement in volume visualization. *Visualization and Computer Graphics, IEEE Transactions on* 11, 4 (July 2005), 408–418. 3
- [WEE03] WEISKOPF D., ENGEL K., ERTL T.: Interactive clipping techniques for texture-based volume visualization and volume shading. *Visualization and Computer Graphics, IEEE Transactions on* 9, 3 (July 2003), 298–312. 3