Enhancing Interactive Particle Visualization with Advanced Shading Models

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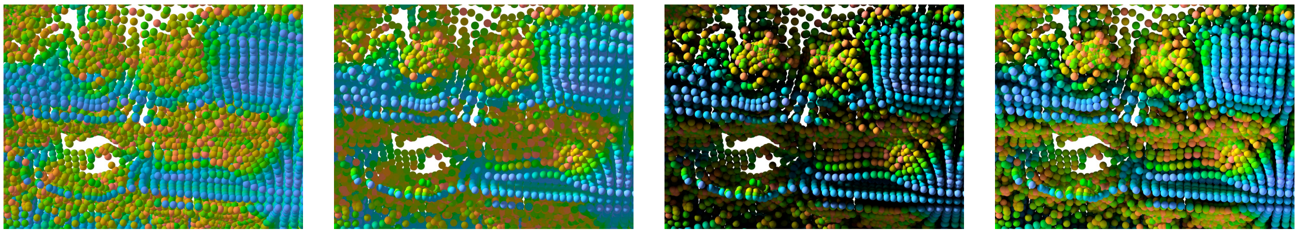


Figure 1: *Comparing shading models.* When shading a surface, purely local models do not consider contributions from other surfaces in the environment (left). These models are often augmented with shadows to enhance cues about shape and relative position (middle-left). However, the constant ambient term used to approximate indirect illumination often obscures details in shadowed regions, providing ambiguous or conflicting information. More accurate shading models, for example, ambient occlusion (middle-right) and physically based diffuse interreflection (right), provide better perceptual cues in these regions.

Abstract

Particle-based simulation methods are used to model a wide range of complex phenomena and to solve time-dependent problems of various scales. Effective visualization of the resulting state should communicate subtle changes in the three-dimensional structure, spatial organization, and qualitative trends within a simulation as it evolves. We take steps toward understanding and using advanced shading models in the context of interactive particle visualization. Specifically, the impact of ambient occlusion and physically based diffuse interreflection is investigated using a formal user study. We find that these shading models provide additional visual cues that enable viewers to better understand subtle features within particle datasets. We also describe a visualization process that enables interactive navigation and exploration of large particle datasets, rendered with illumination effects from advanced shading models. Informal feedback from application scientists indicates that the results of this process enhance the data analysis tasks necessary for understanding complex particle datasets.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture; J.4 [Computer Application]: Social and Behavioral Sciences

Keywords: particle visualization, local shading, ambient occlusion, diffuse interreflection

1 Introduction

Particle methods are commonly used to simulate complex phenomena in a wide variety of scientific domains. These methods are particularly attractive because they can be used to solve time-dependent problems on scales from the cosmological to the microscopic. Frequently, millions of particles are required to capture the behavior of a system accurately, leading to very large, very complex datasets. Effective visualization of the resulting state should communicate subtle changes in the three-dimensional structure, spatial organization, and qualitative trends within a simulation as it evolves. Unfortunately, the proper way to convey this information is not well-understood.

Visualization systems typically employ local shading models, such as the Phong model [1975] or similar variations, when rendering large datasets. Local models are efficient and do not introduce shading artifacts that could be misinterpreted as artifacts in the underlying data. Additionally, these models often provide cues about the orientation of a surface because the local properties at a given point are considered during shading. Other surfaces in the environment are not considered, however, so effects from the interaction of light with these surfaces are either ignored or crudely approximated.

We submit that global illumination effects may aid attempts to comprehend the important characteristics of complex particle datasets. In contrast to purely local models, global illumination captures effects from occluding geometry (cast shadows), diffuse and specular interreflection (indirect illumination), and the focusing of reflected or refracted light (caustics). Some of these effects may provide important visual cues that lead to enhanced perception of complex shapes with subtle features. Figure 1 compares the results of Phong shading (with and without shadows) to those obtained using ambient occlusion and physically based diffuse interreflection. We investigate the impact of these advanced models using a formal user study, and find that they often provide additional visual cues that enable viewers to correctly evaluate subtle differences in particle configurations.

Unfortunately, more sophisticated shading models that simulate global effects are computationally expensive, and current algorithms are not particularly well-suited to interactive use. We therefore seek efficient methods to include these effects in interactive applications. In our current approach, the computational limitations of more accurate shading models are mitigated by precomputing and storing illumination effects in per-particle texture maps, called precomputed luminance textures (PLTs). The PLTs are mapped to the particles during interactive visualization to approximate the illumination in the scene. This straightforward process enables the interactive navigation and exploration of large particle datasets, rendered with illumination effects from advanced shading models.

2 Background and Related Work

Successfully determining the impact and feasibility of advanced shading models in interactive rendering of large particle datasets requires integrating and extending knowledge from the perception, scientific visualization, and computer graphics communities.

2.1 Shape, Shading, and Perception

Surface shading depends not only on an object's shape, but also upon its material properties, the surrounding environment, and the observer's viewpoint. Local shading models provide certain perceptual cues because some of these properties are considered during shading. More advanced models, however, employ more accurate representations of these elements, and thus reproduce the surface shading more accurately. Though shading alone is thought to be a relatively weak source of metric information about shape [Todd and Mingolla 1983; Erens et al. 1993], it has been suggested that the non-metric cues provided by shading, in combination with other cues, can provide powerful information for shape perception [Todd and Reichel 1989]. It has also been shown that the shading patterns provided by both diffuse and specular interreflections influence shape perception [Christou et al. 1996; Norman et al. 2004], but these effects require global information that is not captured by local shading models.

Ambient occlusion [Zhukov et al. 1998; Landis 2002] replaces the constant ambient term used by local models with an occlusion metric. Under this model, surface shading more closely reflects the solid angle subtended by a uniformly diffuse light source as visible from each point. Simply stated, valleys are shadowed but peaks are not. In contrast, full global illumination simulates light that is scattered indirectly from other surfaces in the environment in addition to that reaching a given point directly from the source, often in a physically correct way. Global illumination algorithms provide the most accurate approximation to the actual illumination in a scene, but they are currently too computationally expensive to be used in an interactive system without introducing additional approximations.

Perceiving spatial relationships is a fundamental task in scientific visualization applications and is influenced by the primary and pictorial cues. Shadows are a well-studied pictorial cue that provide important information about shape and relative position [Kersten et al. 1996; Wanger et al. 1992], and are often beneficial in scientific visualization applications [Rheingans and Landreth 1995]. The top panel of Figure 2 illustrates one example from particle visualization. While shadows may clarify the organization of objects within a scene, they often introduce other ambiguities that result from the crude approximation to indirect illumination employed by local shading models, as the bottom panel of Figure 2 demonstrates.

Many studies have examined the fidelity of computer generated images with respect to physical objects [Meyer et al. 1986; Rushmeier et al. 1995; McNamara et al. 2000; Rademacher et al. 2001; McNamara 2005]. These studies are concerned with the perception of illumination per se, rather than how it affects the perception of spatial relationships, so the impact of global illumination effects on these relationships remains largely unquantified.

The impact of diffuse interreflection has been studied in the context of virtual environments [Hu et al. 2000; Madison et al. 2001; Hu et al. 2002] and predictive rendering applications [Ferwerda et al. 2004], however. Though the perceptual effects of indirect illumination are more subtle than those induced by shadows, these effects convey equally strong information about the spatial relationships among objects in computer generated images. Several other studies also suggest that the human visual system is sensitive to the effects of indirect illumination [Gilchrist and Jacobsen 1984; Bloj et al. 1999; Langer 2001], indicating that the use of such effects in particle visualization may be beneficial.

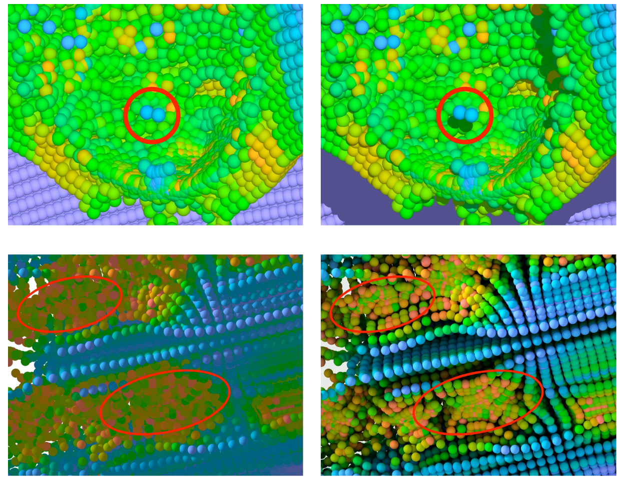


Figure 2: *Use of shadows in particle visualization.* Shadows help to disambiguate the relative position of objects in complex particle datasets (top panel). However, the crude approximation to indirect illumination tends to obscure geometric detail in shadowed regions (bottom panel).

2.2 Particle Visualization

Particle-based simulation methods are used to model complex physical phenomena from scientific domains such as astronomy, chemistry, and physics. Although this work is motivated by the need to visualize the results of structural mechanics simulations, our approach is applicable to particle data from other domains as well.

Investigators often use particle visualization to assist efforts in data analysis and feature detection, as well as in debugging ill-behaved solutions. Particles can be represented directly by simple, iconic shapes called glyphs. For many applications, a sphere or an ellipsoid is a natural representation of an individual particle. Glyph-based representations are able to preserve the fine details within the data while maintaining the large-scale three-dimensional structure of the entire domain. The resulting visualizations are particularly useful for the data analysis and code development tasks that scientists often perform.

Several efforts have investigated techniques to render large numbers of spheres efficiently, from using massively parallel processors [Krogh et al. 1997] and visualization clusters [Liang et al. 2004] to designing custom hardware [Zemcik et al. 2003]. Another aspect of particle visualization is the choice of shading model used during rendering. Though most scientific visualization techniques use local shading models, there has been some recent interest in the use of more sophisticated models for volumetric data [Ebert and Rheingans 2000; Kniss et al. 2003; Stewart 2003; Wyman et al. 2006]. Unfortunately, these techniques are not directly applicable to particle visualization.

We seek practical methods for including effects from advanced shading models in an interactive particle visualization process. Our current approach leverages the work of Arvo [1986] to enable interactive navigation and exploration of large particle datasets, rendered with effects like indirect illumination. In this approach, texture maps capture complex illumination effects rendered in a preprocessing phase, and these textures are then applied to geometry during interactive rendering.

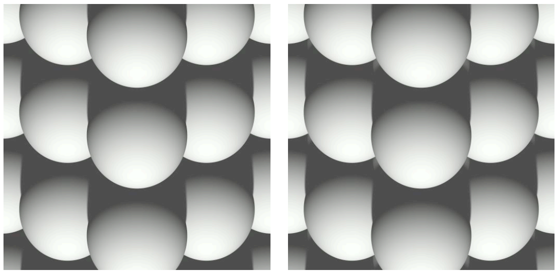


Figure 3: *An image pair from the pilot study.* Similar, but not identical, particle configurations were rendered using Phong shading and shadows. Different configurations were created by inserting extra particles into the hollow regions of a 4x4x4 cube; for example, the configuration depicted in the right image of this pair contains an additional 15 particles.

3 Experimental Study

We investigate the impact of two advanced shading models, ambient occlusion and physically based diffuse interreflection, with a formal user study designed to answer the following question: does either ambient occlusion or physically based diffuse interreflection provide additional visual cues that enable viewers to accurately resolve subtle differences between particle configurations in the cases for which a local shading model, augmented with shadows, fails to do so? The results show that both ambient occlusion and diffuse interreflection aid viewers in correctly evaluating the structure and spatial relationships within particle datasets when the cues from local shading and shadows are insufficient.

3.1 Pilot Study

We first conducted an experiment to identify specific cases in which local shading and shadows left viewers unable to distinguish differences between simple particle configurations.

Setup. In this experiment, 34 images of 10 similar, but not identical, particle configurations were rendered using Phong shading and shadows under several viewing and lighting conditions. Only the underlying geometry depicted in each image differed; all other parameters were held constant. The viewing and lighting conditions were chosen such that the differences in the resulting images were subtle or, in many cases, imperceptible.[1] One pair of images used in this experiment is depicted in Figure 3.

Eight participants (seven male, one female) with varying levels of computer graphics experience were selected from the student and faculty populations at our university. Each participant had normal or corrected-to-normal vision, and all were naive to the purpose of this experiment.

Procedure. Using a simple web-based interface, the two images in each pair were displayed, side-by-side, on a 23-inch Apple Cinema Display (1920x1200 resolution, 0.258 mm dot pitch) under normal office lighting conditions. These conditions were chosen to mimic those in which investigators typically view such images. Each participant viewed the image pairs in a random order, and, for each pair, answered the following question:

> Does the particle configuration depicted in the left image differ from that depicted in the right image?

[1]We define *imperceptible* to mean that all pixel values in a difference image computed from the two images in a given pair are zero.

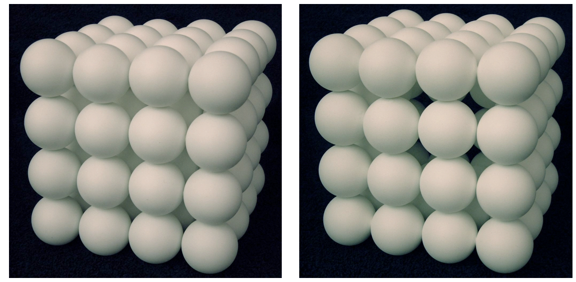


Figure 4: *Physical particle models.* One model is comprised of 64 table tennis balls arranged in a 4x4x4 cube (left), while the other is comprised of 56 table tennis balls also arranged in a 4x4x4 cube, but with the 8 balls in the center having been removed (right).

Participants chose one of two answers: (1) Yes, the particle configurations differ; or (2) No, the particle configurations are the same. The question and answers were displayed below each pair of images. Participants were given as much time as they required to study the images and make their choice. Once satisfied, the desired answer was selected and recorded, and the next pair was loaded. This process was repeated until all 34 pairs had been viewed exactly once.

Results and discussion. Cases in which more than 50% of the viewers answered “No” are the ones in which we are interested. Of the 34 image pairs, 28 met this criteria. In several of these cases, as many as 90% or more of the participants failed to distinguish a difference in the particle configurations. Two obvious conclusions are drawn from the results:

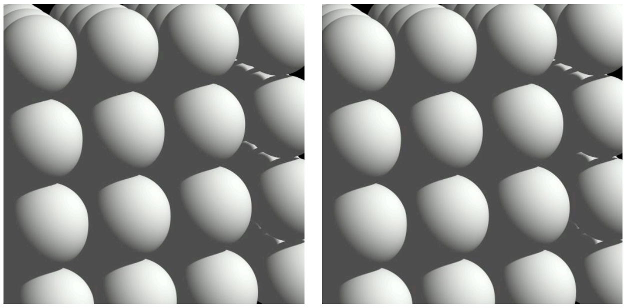
- Local shading models sometimes provide visual cues that enable viewers to distinguish between differences in particle configurations, even in the presence of shadows.
- Local shading models sometimes fail to provide visual cues that enable viewers to distinguish between differences in particle configurations.

We stress that the cues provided by local shading models are often sufficient, even in the presence of shadows. While we believe that the use of global effects like indirect illumination can be beneficial, we recognize that local shading models often suffice. In this study, we are interested in those cases where the available visual cues are not sufficient, and these cases are examined more closely in the main experiment.

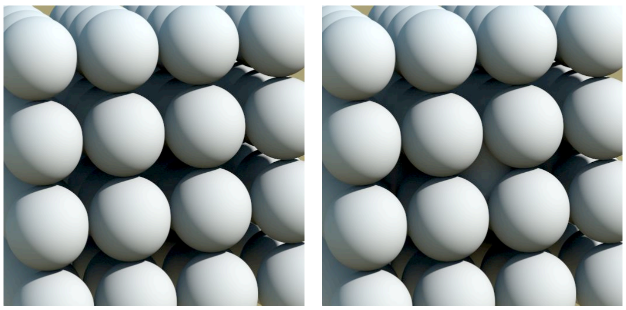
3.2 Main Experiment

Our main experiment is designed to determine the impact of two variants of indirect illumination (ambient occlusion and physically based diffuse interreflection) on a viewer’s ability to correctly evaluate the three-dimensional structure and spatial relationships in particle datasets. We explore this problem using a shape matching task in which participants choose from between two images the one that depicts a physical particle model.

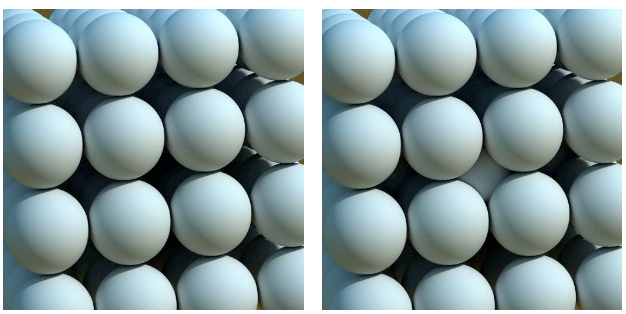
Physical particle models. Physical particle models were constructed by assembling standard table tennis balls into configurations common of the interesting features in particle datasets. Once assembled, the models were painted with several coats of flat spray paint to more closely model the properties of an ideal Lambertian surface and minimize specular illumination effects such as highlights or reflections. Photographs of these models are depicted in Figure 4.



(a) Phong shading



(b) Ambient occlusion



(c) Diffuse interreflection

Figure 5: *Example images from the main experiment.* The 28 image pairs identified in the pilot study were re-rendered using ambient occlusion and physically based diffuse interreflection. Here, the configuration depicted in the right image of each pair contains an additional five particles, one of which is clearly visible under ambient occlusion and diffuse interreflection.

An important assumption motivating the experimental design is that participants are more readily able to comprehend the three-dimensional structure and spatial relationships of physical objects than those in computer generated images. We believe this assumption is reasonable because, in the physical world, all of the known and unknown perceptual cues are potentially available for participants to use when observing an object's shape and structure. Asking each participant several questions concerning the shape and structure of the physical models before beginning the actual task verified that this assumption was, indeed, reasonable.

Hypothesis. Ambient occlusion and physically based diffuse interreflection provide additional visual cues that enable viewers to correctly evaluate the three-dimensional structure and spatial relationships of particle configurations for which local shading models, enhanced with shadows, fail to do so.

Setup. For this experiment, the 28 image pairs identified in the pilot study were re-rendered using ambient occlusion and physically

Method	Min/Max	Mean	Standard Deviation	Standard Error
LS	11/16	14.125	1.959	0.693
AO	15/22	19.250	2.765	0.796
DI	19/26	22.750	2.252	0.977

Table 1: *Characterizing task performance*

based diffuse interreflection. Only the shading model changed; all other parameters were identical to those used in the pilot study. In each pair, exactly one image depicted the physical model while the other depicted a similar, but not identical, particle configuration. Figure 5 depicts one such pair rendered using Phong shading, ambient occlusion, and physically based diffuse interreflection.

Eight new participants (five male, three female) with varying levels of computer graphics experience were selected from the student and faculty populations at our university for this experiment. As before, each participant had normal or corrected-to-normal vision, and all were naive to the hypothesis and purpose of this experiment.

Procedure. The image pairs were displayed using the same web-based interface, monitor, and lighting conditions as in the pilot study. Each participant viewed the image pairs in a random order, and the ordering of each image in a given pair (left or right) was also randomized. For each pair of images and the corresponding physical model, participants answered the following question:

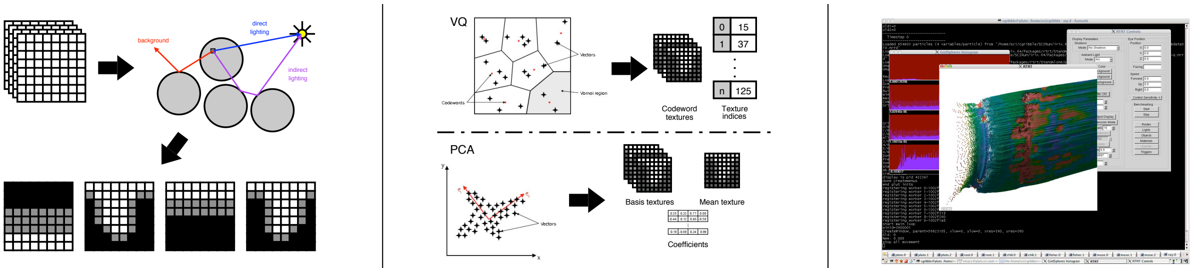
> Which image in this pair, the left or the right, depicts the particle configuration that most closely matches the physical model?

Participants chose one of two possible answers: (1) The left image depicts the particle configuration that most closely matches the physical model; or (2) The right image depicts the particle configuration that most closely matches the physical model. The question and answers were displayed below each pair of images. The participants were given as much time as they required to study both the physical model and the images before making their choice. Once satisfied, the desired answer was selected and recorded, and the next pair loaded. This process was repeated until all 84 pairs had been viewed exactly once.

Results and discussion. We have hypothesized that ambient occlusion and diffuse interreflection enable viewers to correctly evaluate the structure and spatial relationships of particle configurations for which Phong shading and shadows fail to do so. The results of this experiment are characterized using the descriptive statistics in Table 1. As expected, performance under local shading and shadows is essentially at chance (50% of the responses were correct), while performance under the more advanced shading models improved, with 69% correct under ambient occlusion and 81% correct under diffuse interreflection.

We examine the results more closely using inferential statistics. Specifically, repeated measures analysis of variance indicates a significant impact of shading model on task performance ($F(2,14) = 28.385$, $p < 0.001$), and the Tukey-Kramer test shows a significant difference between local shading with shadows and ambient occlusion ($p < 0.01$) and between local shading with shadows and diffuse interreflection ($p < 0.001$). However, the difference between ambient occlusion and diffuse interreflection is only moderately significant ($p < 0.05$). We draw two conclusions from these results:

- Using ambient occlusion and physically based diffuse interreflection significantly increases the number of correct responses in this task when compared to the Phong shading model augmented with shadows.



(a) Texture generation (b) Texture compression (c) Interactive visualization

Figure 6: *Major phases of the PLT particle visualization process.* Luminance textures are generated using a Monte Carlo path tracer (a); solid black textures are removed and the remaining textures are compressed using VQ or PCA (b); and, finally, PLTs are mapped to the particles during interactive visualization (c).

- Understanding the conditions for which the computationally less expensive ambient occlusion model provides sufficient visual cues to successfully complete this task requires further investigation.

Although we have attempted to account for potential problems by carefully considering the experimental constraints, the results must be interpreted in light of the following issues. First, capturing the structural characteristics of complex simulations in simple physical models is problematic. Great care was taken to construct models that represent some of the features often seen in particle data, but the task of actually assembling the models precluded the inclusion of certain features (for example, detached or overlapping particles). Second, while the viewpoints used in the rendered images attempt to minimize the presence of other cues that could be used during the task (silhouette edges, for example), it is possible that these cues played a role in some viewers' ability to choose the correct image. This issue was mitigated by testing several viewpoint and lighting conditions for each particle configuration. Finally, though we consider only white, ideal Lambertian surfaces in the current study, specular highlights sometimes provide cues that aid shape perception [Blake and Bulthoff 1991; Norman et al. 1995], and we suspect that the use of color mapping may also provide useful cues.

4 System Implementation

We believe the results of the preceding study indicate that the use of advanced shading models may be beneficial in the context of particle visualization. The approach to interactive visualization that we describe here will serve not only as a data analysis and exploration tool for application scientists, but also as a testbed for exploring the impact of these models in an interactive particle visualization process.

Our current approach consists of three distinct phases. First, precomputed luminance textures (PLTs) are generated by sampling the illumination across the surface of each particle using a Monte Carlo path tracer. The storage requirements of PLTs are reduced by compressing the textures using vector quantization (VQ) or principal components analysis (PCA). Finally, the PLTs are mapped to the particles during interactive visualization. This process is depicted in Figure 6.

4.1 Texture Generation

To compute the luminance textures, samples in the (u,v) parameter space of a given texture are generated and mapped to the current particle. Rays originating at these points are traced through the scene according to the user-specified shading model, and the resulting luminance values are stored in the corresponding texel. This process continues until a PLT has been generated for each particle.

We use a straightforward latitude-longitude mapping from the (u,v) parameter space of the textures to the world space coordinates of the particle surfaces. This mapping was chosen because of its simplicity and low overhead. A uniform area mapping may permit fewer samples to be used; however, for 16×16 textures, at most 65% more samples would be required under the current mapping to achieve an equivalent or better sampling density for all texels. We have found that a relatively low resolution texture (16×16 texels) with a small number of samples per texel (typically less than 50) and 8-bit luminance values capture the illumination adequately.

4.2 Texture Compression

PLTs typically require a large amount of memory, even for relatively low resolution textures. For example, using a 16×16 texture, the PLTs for a single time step with one million particles consume over 244 MB of memory, or more than 20 times that consumed by the particle positions. The requirements for datasets with multiple time steps quickly become prohibitive.

Removing the textures of particles that receive no light is often a simple, but effective, means to reduce the size of the PLTs for datasets exhibiting densely packed particles. The textures corresponding to these particles are solid black and are removed using a simple post-processing utility. Additionally, because particles within some local vicinity typically exhibit similar illumination patterns, we explore two texture compression schemes to exploit this redundancy. One is based on vector quantization, the other on principal component analysis.

Vector quantization. VQ maps k-dimensional vectors in the space $\mathbb{R}^k$ to a set of k-dimensional vectors $C=\{c_i : i=1,2,\ldots,N\}$. The set of vectors C is called the codebook, and each c_i is a codeword. Associated with each codeword is a Voronoi region defined by $V_i=\{x\in\mathbb{R}^k : \|x-c_i\|\leq\|x-c_j\|\ \forall i\neq j\}$. We use VQ to compress the PLTs by treating each texture as a k-dimensional vector, where k corresponds to the product of the width and height of the texture.

There are two basic steps to compressing textures using VQ. First, vector pairs that minimize the distortion among the input vectors are found. The distortion is a measure of the distance between two vectors, x and y: $d(x,y)=\sum_{i=1}^{k}(x_i-y_i)^2$. Next, the minimum distortion pair is merged by computing the centroid of its vectors. The set of vectors that remain are then used in subsequent iterations. These steps are repeated until the desired number of codewords or a user-specified error threshold has been reached, which results in an optimal codebook.

We use a variant of the exact pairwise nearest neighbor (PNN) algorithm [Ward 1963] to construct the initial codebook; specifically, we use the optimized algorithm described by Fränti et al. [2000]. We also use the double distortion [Torres and Huguet 1994] and partial distortion [Bei and Gray 1984] tests to enable early termination of the search based on the current distortion measure. Nevertheless, the execution times of our VQ compression algorithm are extremely long, requiring many hours of computation to achieve even moderate compression ratios (see Section 5.2).

Principal component analysis. Texture compression based on PCA is another alternative. PCA uses statistical techniques to compute an orthonormal set of basis vectors in which the PLTs, treated as k-dimensional vectors, can be expressed. By storing only a subset of these vectors, the mean vector, and the associated per-object coefficients, an approximation to the original set of PLTs can be reconstructed during rendering.

The algorithm consists of three basic steps. First, the mean vector, $m_x = E\{x\}$, and the covariance matrix, $C_x = E\{(x - m_x)(x - m_x)^T\}$, are computed. An ordered set of (λ_i, e_i) pairs, where λ_i is the eigenvalue that corresponds to the eigenvector e_i, are computed from C_x using matrix SVD. These eigenvectors serve as the PLT basis vectors. Finally, the per-object coefficients are determined by computing the dot product of each input vector with each basis vector.

PCA-based compression is lossy. However, PLTs often exhibit a large degree of redundancy, so reasonable reconstructions can be obtained while dramatically reducing the texture storage requirements. Though PCA introduces an additional element of approximation, we have not found this approximation to be noticeable, even for a relatively small number of basis textures (see Figure 8 and Section 5.2).

4.3 Interactive Visualization

Using PLTs in the interactive visualization process proceeds by calculating the appropriate (u, v) texture space coordinate of a visible point, querying the four values required to bi-linearly interpolate the final luminance value at that point, and multiplying the resulting value by the color of the particle.

Texture compression adds some additional work. VQ maps the original textures to a smaller set of codeword vectors using an integer index. In this case, the four luminance values are obtained by first determining the index of the codeword to which the texture of a particular particle has been mapped. The appropriate values of the codeword are then interpolated, and texture mapping proceeds normally. In contrast, PCA computes a set of orthonormal bases in which to express the PLTs, so the appropriate texels must be reconstructed before interpolating their values and assigning a color to the given pixel. Reconstruction requires a dot product between the per-object coefficients and the basis vectors. While this additional computation introduces some overhead, we have found that the impact on interactive performance is relatively small (see Table 3 and Section 5.3).

5 Results

Informal feedback from application scientists indicates that our method, which allows interactive navigation and exploration of large particle datasets, rendered with effects like indirect illumination, enhances the data analysis and feature detection tasks necessary for understanding complex particle datasets. For example, Figure 7 compares the results of a typical visualization using Phong shading and shadows with those using the PLTs. The size and depth of the crack in this dataset become much more clear with diffuse interreflection effects captured by PLTs.

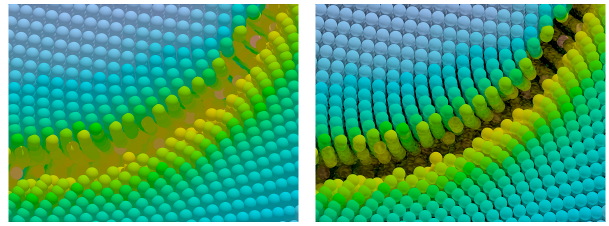


Figure 7: *Visualizations of a particle dataset.* The size and depth of the crack in this dataset are difficult to judge under Phong shading and shadows (left), but become more clear with three bounces of diffuse interreflection captured by PLTs (right).

Dataset	Particles [millions]	Texture Size [MB]	Run Time [hh:mm]
Bullet002	0.5	139.04	01:27
Bullet007	0.5	134.06	01:13
Container010	0.9	233.13	03:53
Container012	0.9	232.29	06:07
HMX128	0.8	203.68	02:01
HMX173	0.8	197.64	02:07
Sphere006	0.2	52.26	00:24
Sphere022	0.2	52.00	00:26

Table 2: *Texture generation statistics*

To quantify the performance of our approach, we use several time steps from four datasets of varying sizes and complexity. The results reported in this section were gathered on an eight processor, 16 core Opteron machine with 64 GB of physical memory.

5.1 Texture Generation

Textures were generated using physically based diffuse interreflection, 16×16 textures, and 49 samples per texel on the test machine. Table 2 reports the size of the resulting PLT data files, as well as the time required to generate the textures. For two of the datasets, Container012 and HMX173, ambient occlusion textures were also generated. Ambient occlusion is less computationally expensive than diffuse interreflection, so the preprocessing time required to generate these PLTs is considerably less: 140 minutes and 34 minutes, respectively.

5.2 Texture Compression

The need for texture compression is motivated by the data in Table 2. Many simulations contain tens or hundreds of time steps, so the memory demands of the PLTs for such large datasets would quickly overwhelm all but the most resourceful machines. Texture compression begins by removing the textures of particles that receive no light. Although both compression schemes correctly remove these redundant textures, doing so prior to compression potentially reduces the run time of the compression algorithms. The reductions achieved by removing solid black textures is highly dependent on the properties of a particular dataset, however. For the datasets tested, reductions ranged from roughly 0% (Bullet002) to 66% (HMX173).

The PLT data size is further reduced by compressing the textures using either VQ or PCA and a user-specified compression ratio. Both VQ and PCA are effective schemes. While the textures compressed with VQ exhibit lower mean distortion than those compressed with PCA, this quality comes at a price: our current VQ algorithm requires tens of hours on the test machine to achieve even moderate

Dataset	Phong [fps]	Uncompressed [fps]	VQ [fps]	PCA [fps]
Bullet002	5.21	6.89	6.89	6.15
Bullet007	6.01	7.82	7.82	6.87
Container010	1.54	2.91	2.91	2.79
Container012	0.67	1.28	1.28	1.25
HMX128	0.73	1.12	1.12	1.11
HMX173	0.73	1.11	1.11	1.01
Sphere006	3.60	6.57	6.57	5.89
Sphere022	3.12	5.34	5.34	4.88

Table 3: *Impact on interactive visualization performance*

compression ratios (for example, 2:1 or 4:1). Fortunately, execution times for PCA compression are very reasonable, typically just tens of seconds. Though the mean distortion exhibited by the PCA compressed textures is somewhat higher, this error does not appear to have a noticeable impact on the resulting visualization, as shown in Figure 8. Moreover, for a fixed number of input vectors, the execution time decreases as the number of basis vectors decreases, so PCA favors large compression ratios.

5.3 Interactive Visualization

Finally, we examine the impact of PLTs on interactive visualization performance. We use Phong shading with shadows as the baseline. Frame rates were measured by rendering a series of 100 frames at 1024×1024 resolution on the test machine. Table 3 reports the average frame rates obtained by these tests. (The PCA compressed PLTs used in these tests store eight basis textures.)

For all of the datasets tested, rendering performance improves significantly when using either the original or compressed PLTs. The improvement results from the ability of our technique to capture both local and global effects during texture generation, obviating the need for shadow computations during interactive rendering.

The indexing process required by PLTs in which the solid black textures have been removed or that have been compressed using VQ imposes no measurable overhead on the rendering performance. In contrast, PCA has a mild performance impact in most cases. With the datasets tested, this impact ranges from about 0% (HMX128) to roughly 12% (Bullet007). The overhead arises from the need to reconstruct an approximation to the original textures on-the-fly. As before, the use of PCA favors large compression ratios because the impact of the reconstruction process grows linearly with the number of basis vectors.

6 Conclusions and Future Work

We have demonstrated that ambient occlusion and physically based diffuse interreflection enable viewers to better evaluate the three-dimensional structure and spatial relationships within particle datasets under conditions in which local shading and shadows fail to convey this information. Specifically, we have found that these advanced models significantly increase the number of correct responses in a matching task when compared to the Phong shading model augmented with shadows.

We have also described a particle visualization process that enables interactive navigation and exploration of large particle datasets, rendered with illumination effects from advanced shading models. The computational limitations of these models are overcome by removing the illumination calculation from the interactive visualization process. During interactive rendering, precomputed luminance textures are reconstructed (if necessary) and mapped to the particles to approximate the illumination in the scene. Informal feedback from application scientists indicates that our approach enhances the data analysis and feature detection tasks necessary for understanding complex particle datasets. Moreover, our approach will prove useful not only to application scientists, but also to further studies investigating the effect of advanced shading models on an interactive visualization process.

The user study was designed to answer a very specific question. Not surprisingly, however, the results raise many more questions about the role of advanced shading models in particle visualization. For example, several questions arise in the context of feature detection: Do these models affect reaction time when specific judgments about a feature of interest are required? Do their effects enable viewers to quickly and accurately judge the depth of a crack, for example, or the degree of separation between fragments in a fractured structure? Does advanced shading affect a viewer's ability to quantify specific characteristics of a feature? Does specular interreflection play a role in these judgments? What about color mapping? Any one of these questions could be the target of a future study. Similarly, it is unclear how global illumination effects rank with other visual cues such as interactive rotation or stereo, so the role of these effects in an interactive particle visualization process is of particular interest.

We are also interested in rendering algorithms and shading models that trade fidelity for computational complexity, and vice versa. Currently, we are exploring additional techniques based on caching and lazy evaluation; acceleration structures for on-demand computation of global illumination effects; and computationally simple, perceptually-equivalent approximations to indirect illumination. Our current particle visualization process also warrants further investigation. For example, improving the performance of the texture generation phase would be valuable, and different representations for storing the precomputed illumination effects may provide more accurate results or a more compact representation. Finally, several other compression techniques, such as the centroid method or various transform coding schemes, could also be explored.

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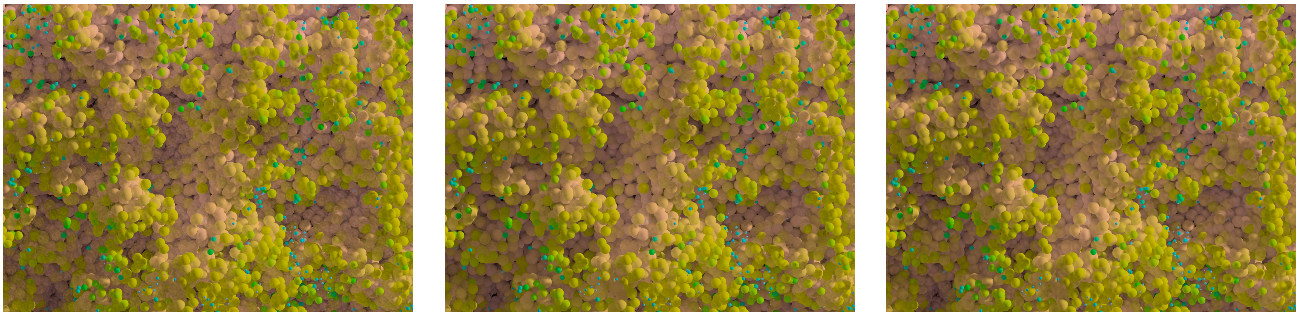

(a) Uncompressed textures

(b) VQ compressed (4:1)

(c) PCA compressed (4:1)

Figure 8: *Comparing compression schemes.* VQ and PCA are both effective PLT compression schemes. In these images, the original textures (a) have been compressed using VQ (b) and PCA (c). There is little noticeable difference among the images, even though the PLT data file size has been reduced by a factor of four.

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