Annual Report for 1999

NSF Science and Technology Center
for Computer Graphics and Scientific Visualization

Brown University

California Institute of Technology

Cornell University

University of North Carolina

University of Utah

Table of Contents

1. Executive Summary

The major goals of our STC are to establish a better scientific foundation for future computer graphics and to help create the basic framework for future interactive graphical and multimedia environments. As we move onto the next generation of computing systems, we will need to improve computational speeds for display, incorporate physical behavior into our models, extend the definitions of our models to incorporate manufacturing processes, move beyond the current generation of WIMP (windows, icons, menus, and pointing) user interfaces into post-WIMP user interfaces, scale our systems to handle more complex environments, reduce design cycle times, and store, manage, access, and transmit larger amounts of data. Finally, it is necessary to guarantee the validity and accuracy of our simulations according to each application's needs, particularly in medical, scientific, and engineering areas.

To achieve these goals, our comprehensive strategic plan is focused on three basic areas of computer graphics: modeling, rendering, and user interfaces. We have made significant progress in each of these domains in the past year. Two basic applications have helped focus and direct these areas: scientific visualization and telecollaboration. The Center's research thus expands applications' capabilities while being focused in useful directions by the needs of these applications. The Center also works to improve standards efforts. Its broad knowledge of the state of the art of computer graphics continues to prove helpful in directing standards efforts towards good solutions while preventing premature standardization in open research areas.

The principal characteristic of our research is improvement in the accuracy and fidelity of models used in computer graphics. This goal requires generality in our representations and simulations. As contrasted with the previous two decades of computer graphics research, we are now focusing on experimental validation rather than simply "looking good." We have built test environments and models and are comparing simulations to measured physical behavior in order to determine the precise accuracy of current approaches. This traditional strategy of experimentally validating scientific hypotheses is necessary to establish the fundamental bases for future improvements in computer graphics technology. But this strategy is relatively new to the field of computer graphics and represents a significant shift in methodology.

A second characteristic is our focus on efficiency. The field is moving inexorably towards more complex environments and their increasing demands for interactivity and time-critical computing, especially for virtual environments, in which significant lag can cause motion sickness. Time-critical computing (or TCC) is the idea that an approximate result on time is better that a fully accurate result too late. Procedures for improving computational speeds and computing within a known length of time depend on predictability and on the determination of error bounds. Thus, the goals of accuracy and computational efficiency are intimately related, indeed inseparable. The drive for efficiency leads to both a better scientific foundation and a stronger framework for future applications.

Finally, while it is helpful to organize the research of the Center by dividing it into categories, a great deal of synergy and overlap exists between the various research areas. For example, user interface technology begins to affect modeling technology when scientists developing new modeling methods strive to develop techniques with more user-oriented parameters.

Our Center is distributed across five states and three time zones, has no single dedicated building, and operates as a virtual collaboratory aided by a custom communication infrastructure built on dedicated T-1 lines. Through collaborative efforts, shared research, common classes, and group discussions the Center continues to grow unified; even with little face-to-face physical contact, many of the participants in the Center have become true colleagues.

2. Research Accomplishments and Plans

2.A Modeling

A.1 Participants

Faculty

Alan Barr, Elaine Cohen, Samuel Drake, Henry Fuchs, Richard Riesenfeld, Peter Schroeder

Research Staff

Mark Bloomenthal, David Breen, Russ Fish, Caroline Green, Loring Holden, David Johnson

Postdoctoral Scholar

Mathieu Desbrun

Programming Staff

Mark Montague

Graduate Students

Cindy Ball, Maret Bower, Marcel Gavriliu, Tran Gieng, Anil Hirani, Matthew Kaplan, Sean Mauch, Mark Meyer, Donald Nelson, Thomas V. Thompson II, Zoe Wood

Undergraduate Students

Yury Goldfeld, Solomon Kutnicki, Jingyi Yu

A.2 Recent Accomplishments and Plans

Computer Graphics modeling research remains a key activity at all five sites of the Center. Advances in model representation and model creation continue to drive research in rendering, interaction, visualization and performance while our advanced modeling and manufacture capabilities facilitate telecollaboration research.

Our primary objectives are to develop new methods to create, modify, and represent increasingly complex and/or realistic models. This includes research in geometric modeling, but also includes modeling in relation to design, physically based modeling, and modeling methods with level sets.

The Center's modeling work is becoming increasingly interdisciplinary. Most of the modeling results are developed from robust mathematical principles, achieving much of the original vision of STC --- to put graphics on a more "solid" foundation.

A.2.1 Geometric Modeling

Sketch-N-Make

In the largest single collaboration in the Center, Brown, UNC, and Utah have developed a prototype *art-to-part* system that allows users to quickly design non-trivial, dimensioned, machined metal and plastic parts. These parts can then be automatically manufactured on a machining center with the aid only of a technician who prepares and loads the stock and cutting tools.

The Sketch-N-Make art-to-part system automatically transforms part designs into detailed manufacturing process plans using a set of *process plan templates*. The process plan templates represent schema that guide the automatic creation of process plans by applying a series of geometric modeling modifications and transformations to the shape features of part designs. Recent developments in the Sketch-N-Make system include extensions to the process plan templates resulting in further extensions to the class of manufacturable parts. Now, in addition to the original target class of prismatic parts, the templates can be used to manufacture parts with features on multiple faces of the workpiece and with features requiring four axis indexing operations. Functional parts from this wider part class have been designed and manufactured using the Sketch-N-Make system, including camera mounting assemblies for the face-to-face display discussed in the **Telecollaboration** section. We are currently undergoing user evaluation of the system to plan the next phase of development.

Implicit Fairing of Irregular Meshes using Diffusion and Curvature Flow

In this project, we have developed methods [desb99a] to rapidly remove rough features from irregularly triangulated data intended to portray a smooth surface. The main task was to remove undesirable noise and uneven edges while retaining desirable geometric features. The problem arose mainly when creating high-fidelity computer graphics objects using imperfectly measured data from the real world.

Our approach contains three novel features: an implicit integration method to achieve efficiency, stability, and large time-steps; a scale-dependent Laplacian operator to improve the diffusion process; and finally, a robust curvature flow operator that achieves a smoothing of the shape itself, distinct from any parameterization. In consequence, we have been able to take very noisy 3D-scanned data and produce smooth and good-looking results out of it.

Geometric Conversion Methods for Level Set Modeling

Level Set Methods are newly-emerging techniques which are promising for simulation and modeling. In the fields of modeling and visualization, they have been used to segment range data, filter and segment volumetric data, interpolate (morph) solid models, and automatically create blends and fillets on complex surfaces. One of the greatest advantages of level set models is that they robustly support changes in topology, unlike surface-based methods.

To more fully exploit the power of level set methods and the investment made to date in computer-aided design, robust conversion methods are needed for transforming conventional geometric models into a level set representation. Last year we developed a method for converting CSG models into a level set representation, a distance volume [bree99a]. This work has been extended to include triangle meshes. We have begun work on converting volume datasets generated by MRI and CAT scans into distance volumes.

Color Shading Level Set Models

We have developed a 3D morphing algorithm based on level set methods. This algorithm provides a powerful approach to interpolating solid objects of different topology, requiring little or no user input. Since the fundamental representation of these level set models is volumetric, and does not contain a specific surface representation, it is difficult to color shade and texture map the polygonal surfaces that are extracted from the level set volumes. We have developed a color shading method to overcome this problem [bree99b], which is based on the color volumes and closest point volumes produced during the scan conversion. The derived polygonal surface may be color shaded by conceptually imbedding it within the color and closest-point volumes. We have demonstrated our color shading capability on a series of offset surfaces extracted from several distance volumes, and on one morphing sequence.

Physically Based Modeling

The goals for our physically based modeling research are to develop robust mathematical methods and a PBM ‘‘language”; the intent is to imitate the success of Postscript, but for 3D mechanics. In this way, we will enable nonexpert people to specify, design, control and build predictive computational models of physical systems of rigid, flexible, and fluid objects.

There is a new part of the research activity, involving a focus on real-time PBM computations. The techniques will not sacrifice robustness, although the user can select lower accuracies to speed up the calculations. In this way, PBM can also be used for semi-immersive visualization and simulation of mechanical designs and animations, such as on the Responsive Workbench.

Interactive-Speed Physical Simulations

We have developed stable and efficient algorithms for animating mass-spring systems. An integration scheme derived from implicit integration allows us to obtain interactive realistic animation of any mass-spring network. We alleviate the need to solve a linear system through the use of a predictor-corrector approach. Combined with an inverse dynamics process to implement collisions and other constraints, this method provides a simple, stable and tunable model for deformable objects suitable for virtual reality. We have implemented this technique in a VR environment, and several interactive demos demonstrate this approach [desb99b].

Engineered Modeling

Large, complex design problems require new methods to create and organize the models. We have implemented a set of *domain encapsulation assistants* to aid in such designs. An example is our *structural detailing assistant*, which processes rough skeletal designs into a detailed set of support trusses. These trusses may be optimized by functional considerations, such as the expected loads during motion. This process has been demonstrated on the design of an animatronic Godzilla. The use of domain assistants cut the design time from weeks to days. We plan to expand the number of domain assistants available for designers.

A.2.2 Virtual Prototyping of Assemblies

Our development of a force-feedback environment for interacting with CAD models has progressed to the point where a designer can feel, move, and grasp trimmed NURBS models. This work has spurred research on time-critical minimum distance computations [john99b], fast geometric interrogation algorithms, and 3D interaction. These operations provide the groundwork for a future design system where complex assemblies can be designed and tested without having to resort to physical prototypes.

Rolling Contact

An extension of the minimum distance computation is to satisfy the constraints of maintaining contact once it has been made. We have initiated research into this topic and are developing a method using a relative surface velocity formulation. These rolling contacts support interesting assemblies, such as a cam-follower, for testing in the virtual prototyping environment.

Extremal Distance

When models undergo contact, collision detection is not enough to determine the collision response. A measure of the interpenetration is needed to give the direction and magnitude of the forces that should be applied to separate the models. The extremal distance [nels99b] is one such measure, and is structured similarly to the minimum distance equation. We have developed methods for initiating and tracking the extremal distance between two parametric surfaces at haptic rates.

Variational Design

We have developed a fast constraint solver based on augmented coordinates. Using this method, we have started work on a design variation system [nels99a], which will allow exploration and optimization of mechanical assemblies, testing of reachability and workspace, and interactive adjustment of design parameters. These tasks extend the functionality of current virtual prototyping systems.

3D Paint

The work in virtual prototyping has enabled development of a texture painting tool for models [john99a]. When textures are directly placed on a model, they may undergo distortion from the “stretched” surface. Traditionally, for custom textures, the distortion is overcome by painting from a particular view and then projecting the texture down to the surface. Our haptic technique allows a natural painting style directly on the model. Adaptive sampling maintains a proper, distortion-free brush size. An additional advantage is that the haptic cues allow painting in regions that may be difficult to orient for traditional texture painting.

A.2.3 Research in Mathematical Representations

We are continuing our work in mathematical representations of surfaces and computer-graphics objects. To understand the complex requirements of modeling and explore more general mathematical approaches, we are developing new methods and modeling primitives and also use known mathematical methods in new computer graphics applications. This relates to projects at all sites of the Center, including:

- Differential geometry applied to computer graphics
- Wavelets and multiresolution representation of surfaces
- Representing and manipulating complex models of manifolds and/or torn surfaces
- Inverse methods for determining potential functions

Offset Models for NURBS

Offset surfaces may have complex self-intersections that limit their usefulness in design. We have developed methods for pruning the undesirable internal loops of an offset surface, returning a proper boundary representation model. These offset models are useful in computer-aided manufacture, as they represent the gouge-free limit for cutting tool paths.

Interval Analysis Research

In this work we are developing an orders-of-magnitude improved method in finding numerical bounds for the range of a multivariate polynomial over arbitrary input intervals. The new method is based on Taylor forms and we have proven that it always performs better than previous methods. We also have proven theorems about the order of the excess of the bounds generated, and shown that given a polynomial one can find another polynomial that exactly describes the improvement over the natural extension. We are applying this new method to problems in computer graphics and simulation, including collision detection, ray tracing, and isosurface extraction.

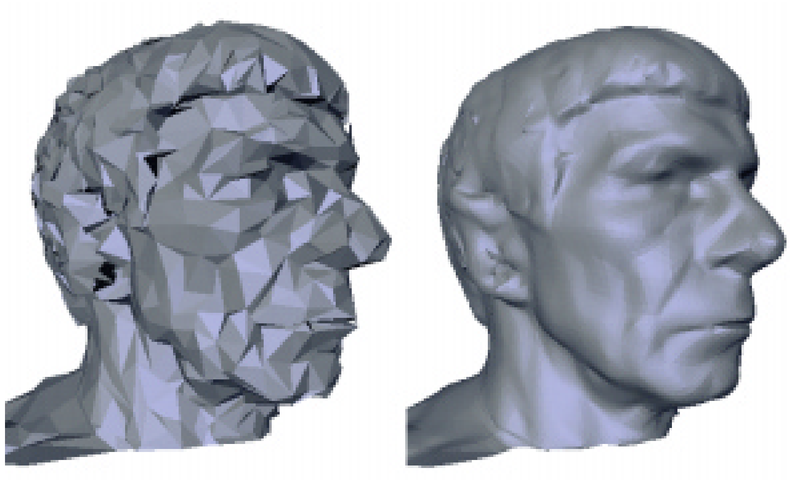


Figure 1: On the left, the original low resolution Spock mesh has 12,000 vertices. We linearly oversampled this initial mesh, and applied our new smoothing operators, using one integration step. Note that the noise in the rough features is significantly reduced, while the underlying shape is preserved.

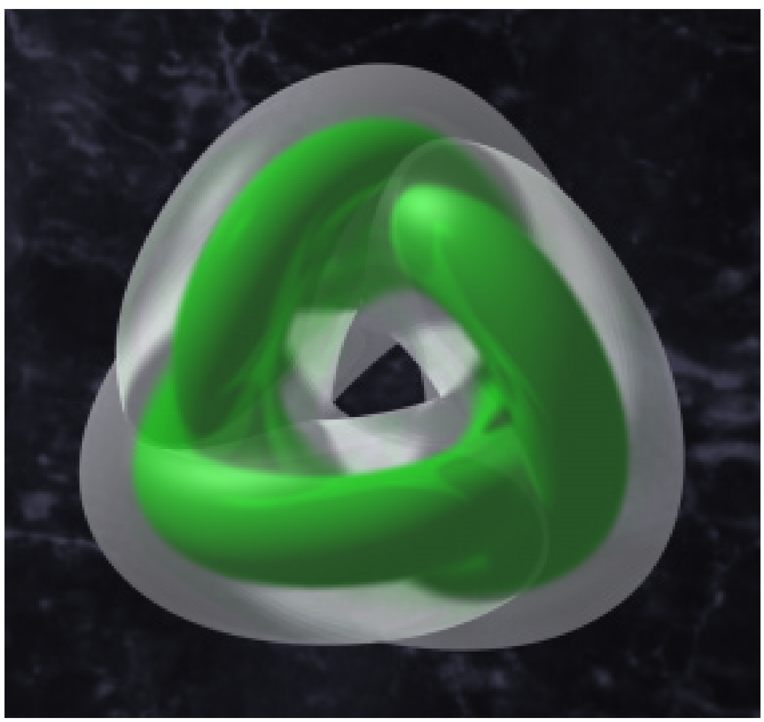


Figure 2: The translucent surface is an offset model of the inner green knot. Normally, the offset would contain numerous self-intersections and loops, making it difficult to use. This “cleaned” offset model is useful in modeling and manufacture.

2.B Rendering

B.1 Participants

Faculty

Gary Bishop, Elaine Cohen, Nick England, Henry Fuchs, Donald Greenberg, Charles Hansen, John F. Hughes, Anselmo Lastra, Lars Nyland, John Poulton, Richard Riesenfeld, Peter Shirley, Brian Smits, Kenneth Torrance

Research Staff

J. Ferwerda, S. Pattanaik, H. Sheldon, B. Trumbore, S. Westin

Post-doctoral Fellows

P. Dutre, E. Lafortune

Graduate Students

C.F. Chang, S. Fernandez, A. Gooch, B. Gooch, D. Hart, B Insko, H. Li, W. Mark, L. Markosian, W. Martin, D. McAllister, C.McCue, A. Neelamkavil, M. Oliveira, V. Popescu, F. Pellacini, A.J. Preetham, P. Rademacher, M. Ramasubramanian, P. Sloan, M. Stark, P. Tole, W. Wynn

Undergraduate Students

J.D. Northrup

Collaborators

Daniel Aliaga, Lucent Technologies Bell Laboratories
Ronen Barzel, Pixar
Lubomir Bourdev, Adobe Systems
Tom Lyche, University of Oslo
Stephen Marschner, Microsoft Research

B.2 Recent Accomplishments and Plans

Realistic image synthesis is an important area of research in computer graphics and a central research thrust for the Center since its inception. The goal of realistic image synthesis is to produce synthetic images visually and measurably indistinguishable from an actual scene. Earlier work attempted to simulate this realism by modeling only the direct illumination of the scene by light sources, but this approach failed to capture many important visual cues: indirect illumination, soft shadows, color bleeding, and caustics.

Global illumination algorithms developed in recent years have been able to accurately render these effects in addition to direct illumination. These algorithms physically simulate light reflection and the complex light interactions between surfaces in the environment. Unfortunately, these simulations make global illumination algorithms computationally very expensive, with execution times many orders of magnitude slower than simple direct illumination algorithms. Much of the rendering research of the Center is directed toward improving the efficiency of computing global illumination.

B.2.1 Physically Based Rendering

Light Reflection Models

In 1997 the Center published a simplified representation for bidirectional reflectance distribution functions (BRDFs) of materials, which describe how light is scattered at an object's surface. Research published this year has extended our ability to measure the BRDF of various surfaces, including living human skin, using only a digital still camera, an electronic flash, and a Cyberware 3D scanner [mars99]. The measurements are quick (less than 20 minutes for a complete measurement), complete (giving hundreds of thousands of samples over the full hemisphere), and have been verified against measurements on the gonioreflectometer in the Cornell Light Measurement Lab.

The Center has also developed an inexpensive analytic model that approximates full spectrum daylight for rendering various atmospheric conditions [pree99]. Sunlight and skylight are rarely rendered correctly in computer graphics, both because of high computational expense and the fact that precise atmospheric data are rarely available. These conditions have been parameterized using terms that users can either measure or estimate. An inexpensive analytic model that approximates the effects of atmosphere has been fielded in a number of conditions and intermediate results verified against standard literature from atmospheric science.

Light Transport Algorithms

The Center's research in rendering algorithms is moving from polygon to pixel algorithms, to parallel computation, and to the use of more sophisticated perceptual thresholds for defining when enough computation has been performed to achieve the desired fidelity.

A system has been developed for ray tracing trimmed NURBS surfaces. The components are drawn largely from the existing literature, but their combination within a single framework is novel. Details of an efficient implementation, including issues such as parallelizing and storage costs, have been addressed for ready implementation in general ray tracing programs.

Two research projects have resulted in improved methods for computing shadows in three-dimensional scenes. While computing shadows from a single point source is relatively simple and goes back to the early days of graphics when the light source was moved away from the eye position, the accurate representation of shadows resulting from area light sources is quite complicated.

Studying the generalized prism-like constructions generated by the emitter and the occluder in a four-dimensional (shadow) space has revealed a simpler intrinsic structure of the shadow than the more complicated 2D projection onto a receiver [star99]. A closed form expression for the spline shadow irradiance function has been derived to reduce an evaluation over a 4D domain to an explicit formula involving only 2D faces on the receiver, derived from the scene geometry. This leads to a straightforward computational algorithm and an interactive implementation. Moreover, this approach can be extended to scenes involving multiple emitters and occluders, as well as curved emitters, occluders, and receivers.

An alternative approach explores better methods for calculating the visibility between any surface point in a scene and an area light source [hart99]. Since changes in visibility between a surface point and an area light source are the cause of penumbra and umbra regions on the receiver surface, an efficient processing of the visibility function is often the key for rendering fast and accurate soft shadows. Once the visibility has been processed, the illumination can then be computed by integrating the incoming radiance function due to the light source, taking into account the bidirectional reflectance distribution function at the receiving surface. Soft shadows and other shading effects are generated with high accuracy in less time than with existing shading algorithms.

Perceptually Based Techniques

Center researchers have developed a novel physical error metric that correctly predicts the perceptual threshold for detecting artifacts in scene features [rama99]. Built into this metric is a computational model of the human visual system's loss of sensitivity at high background illumination levels, high spatial frequencies, and high contrast levels (visual masking). An important feature of the model is that it handles the luminance-dependent processing and spatially-dependent processing independently. This allows precomputation of the expensive spatially-dependent component, making the model extremely efficient.

Temporal extension to the model is very important and would be useful for dynamic image sequences such as animations or architectural walkthroughs. This framework is also especially suited for software architectures that switch between model-based and image-based rendering. These systems render and transform objects as image layers (image-based rendering) instead of re-rendering their geometry (model-based rendering). By precomputing a threshold model from the scene and using it as perceptual guide for establishing distortion criteria, the performance of hybrid rendering systems could be improved by identifying locally higher acceptable distortions due to loss of visual sensitivity.

B.2.2 Image Based Rendering (IBR)

Traditional models of three-dimensional scenes have become so complex that most of the polygons are smaller than one pixel in the final image. The computational and bandwidth advantages of specifying large, coherent regions with triangular polygons are disappearing. At the same time, textures captured from photographs or other methods vastly enhance image quality and the impression of model complexity, yet produce a relatively fixed additional computation demand at any given resolution. Sets of depth-enhanced images can also be used to produce new images from arbitrary viewpoints.

A number of projects at Center sites are developing image-based rendering techniques as well as approaches which combine image-based rendering and traditional model-based rendering. One project has decomposed global illumination into view-dependent (diffuse) and view-independent (non-diffuse) components [bast99]. The view-independent component uses a traditional precomputed geometry-based radiosity solution that is rendered using standard graphics hardware. The view-dependent component is then decomposed into "what is reflected" (radiance with depth) and "how it is reflected" (BRDF), and precomputed and rendered using image-based approaches. This approach produces glossy reflections in constant time (per reflector) independent of the scene complexity.

Other recent work in the Center focuses on the improvement upon LDIs (layered depth images, as proposed by Shade et al., SIGGRAPH 98), which serve to merge multiple reference images under a single center of projection, while maintaining the simplicity of warping a single reference image. The original concept, however, did not consider the issue of sampling rate, which is a factor of the LDI tree [chan99]. While rendering from the LDI tree, one only has to traverse the LDI tree to the levels that are comparable to the sampling rate of the output image.

An alternative approach trades off storage space for frame rate by using images to replace distant geometry [alia99]. The preprocessing algorithm automatically chooses a subset of the model to display as an image so as to render no more than a specified number of geometric primitives. An optimized layered-depth-image warper displays images surrounded by geometry at run time. Both empirical and theoretical results indicate reductions of approximately an order of magnitude in geometric complexity can be achieved using a practical amount of memory by today's standards.

Also involving layered depth images was work done on image-based objects [oliv99], which offers compact, image-based representation for three-dimensional objects with complex shapes that can be rendered with correct perspective from arbitrary viewpoints using a list-priority algorithm. Objects are represented by six layered depth images sharing a single center of projection. They can be scaled, and freely translated and rotated, for use as primitives to construct more complex scenes. Due to their minimum storage requirements and rendering simplicity, image-based objects can find potential uses in games, virtual museum applications, and web catalogs.

Recent research at UNC explores the impact of the laser rangefinder on computer graphics [nyla99]. The laser rangefinder's ability to acquire dense range data of familiar environments, coupled with a digital color camera, enable researchers to create panoramic color photographs where every pixel has an accurate range value.

B.2.3 Non-Photorealistic Rendering (NPR)

A rendering is an abstraction that favors, preserves, or even emphasizes some qualities for a particular functional purpose while sacrificing, suppressing, or omitting other characteristics that are not the focus of attention. While most computer graphics rendering activities have been concerned with photorealism, i.e., trying to create an image that looks like a high-quality photograph, several recent Center research projects have investigated new approaches to rendering for efficient visual communication of shape, structure, or less tangible expressive characteristics.

When constructing 3D geometry for use in cell animation, the reference drawings of the object or character often contain various view-specific distortions, which cannot be captured with conventional 3D models. Center-affiliated work on view-dependent geometry [rade99] introduces the concept of a view-dependent model, which consists of a base model, a set of key deformations (deformed versions of the base model), and a set of corresponding key viewpoints (which relate each 2D reference drawing to the 3D base model). This method interpolates the key deformations to generate a 3D model that is specific to any arbitrary viewpoint, thereby capturing the view-dependent distortions as an object moves from the artistic 2D world to the geometric 3D world.

For technical illustration the elucidation of structure and technical information is the preeminent motivation. This calls for a different kind of abstraction in which technical communication is central, but art and appearance are still essential instruments toward this end. Recent Center research has extended previous work on static technical illustrations to support a dynamic environment [gooc99]. This display environment includes all of the benefits of computer generated technical illustrations, such as a clearer picture of shape, structure, and material composition than traditional computer graphics methods. It also takes advantage of the three-dimensional interactive strength of modern display systems, including new algorithms for real time drawing of silhouette curves. Current non-photorealistic lighting methods have been augmented with new shadowing algorithms based on accepted techniques used by artists and on studies carried out in human perception.

Applying traditional illustration techniques for depicting 3D scenes can greatly increase the expressive power of 3D computer graphics. These techniques typically involve an overall reduction of visual detail, together with enhancement of the most important details like facial features and object outlines. With careful stylization just a few strokes can be made to evoke a sense of complex geometry, such as leafy bushes or flowing, glossy hair.

The development of art-based methods for depicting virtual scenes has the potential to bring a wide range of new looks to computer graphics, and also to reduce the cost of modeling complex scenes. If the rendering style evokes the complexity of the scene indirectly, the underlying scene geometry might be relatively simple. This is the approach taken in [kowa99], as described more fully in the Interaction section.

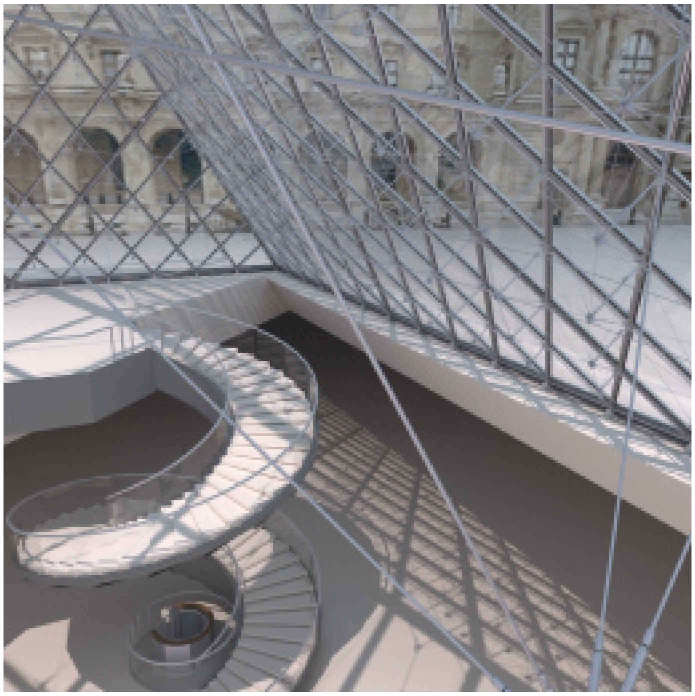


Figure 3: Perceptually-based adaptive global illumination solution using approximately 10% of the samples per pixel as a reference global illumination solution [rama99]

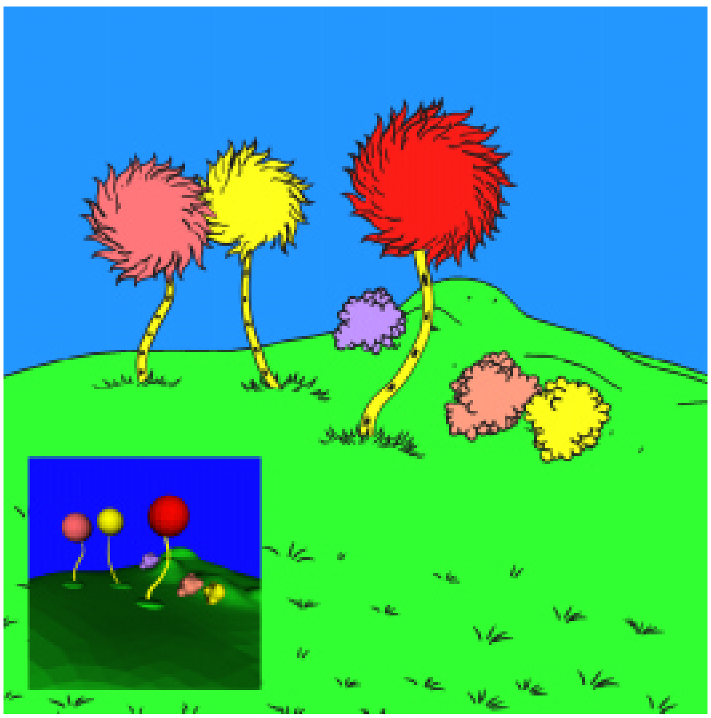


Figure 4: Applying techniques from art and illustration to expand the expressive power of 3D computer graphics [kowa99] (1999 SIGGRAPH Proceedings cover image)

2.C Interaction

C.1 Participants

Faculty

Al Barr, John Hughes, Peter Schroeder

Research Staff

Andrew Forsberg, Loring Holden, Barb Meier, Tim Miller, Anne Spalter, Robert Zeleznik

Graduate Students

Dan Fain, Michael Kowalski, Lee Markosian, Mark Meyer

Undergraduate Students

Jonathan Cohen, David Karelitz, Thomas Crulli, J. D. Northrup, Philip Stone

C.2 Recent Accomplishments and Plans

As the economic importance of efficient interaction grows, the Center has continued to devote substantial effort to it, especially in areas where we have application-domain expertise, such as modeling and shared-workspace environments, as well in more general areas such as haptics and speech recognition that are applicable to multiple application domains.

Object-Centric Interface Design for Virtual Environments

We have developed a new interaction metaphor for object-centric tasks in the form of a prototype VR system, ALCOVE. ALCOVE is an adjustable, desktop, two-screen display system. Through analytic calculations, we quantitatively demonstrated the benefits of restructuring the interaction volume offered by current systems. Our metrics show that many applications' interaction volumes increase by factors of 1.5 to 2.6 times when using ALCOVE. We also conducted an informal user task analysis and evaluations of previous VR systems that qualitatively support this improved interaction volume as well as demonstrate the need for a shift from room and desk-sized systems to desktop units. We also created some testbed applications that benefit from this object-centric design and analyzed some of the advantages and shortcomings of our system.

The ALCOVE system is designed to easily integrate into common work environments. In addition to the design and performance metrics that we have derived, we have also examined various possible VR technologies and analyzed their usefulness in different situations. One of the most promising new technologies for projection based virtual reality is plasma display technology. Recognizing this, we have analyzed the potential benefits and problems associated with plasma display panels and constructed our prototype ALCOVE unit from these plasma displays. We are currently working with display manufacturers to bring these display devices to the level needed for mainstream computing and virtual environment usage.

Tools for Free-form Modeling and "Texturing"

We are developing interactive tools with which an artist can apply her skills to define both shapes and the rendering styles used to depict them. Using our system, the user sculpts complex surfaces by first sketching their underlying masses (such as muscle shapes). She then "oversketches" these masses with a smooth surface that approximates their collective shape. Our recent papers on curve drawing [cohe99] and "skin" [mark99] address particular sub-problems that arise from this approach. The next step will be to generalize the curve-sketching technique and apply it toward an interface for sketching a new class of "soft" primitives, essentially letting a user draw the model that s/he is imagining, and having the computer make reasonable (and over-rideable) inferences about the shape.

Speech recognition

We are continuing to work on computer speech recognition, speech production, and sound localization. We are extending an articulation-based recognizer based on factorial hidden Markov models and system trained with measured data. We are still developing techniques to analyze and optimize the interaction of early and late processing components in recognition models, and investigating spatialized sound reproduction techniques for virtual environments. This work may, if sufficiently successful, be incorporated into our multi-modal VR interfaces research instead of the off-the-shelf speech system that we have been using until now.

Responsive Workbench

We have been continuing to design interaction tools and metaphors on the workbench, and are continuing our collaboration with JPL for the NASA Genesis mission (to be launched in 2001). We have been evaluating advantages and alternate virtual environment designs. We will continue to use our testbed applications like the JPL trajectory planner to evaluate new interaction toolkits as well as demonstrate the practical benefits of VR technology.

Cave – Accomplishments

On May 25, 1999 The Technology Center for Advanced Scientific Computing and Visualization (TASCV) officially opened (see http://www.chronicle.com/free/99/05/99052601t.htm). The center was started with a $1M NSF MRI awarded to six departments at Brown University (Applied Math, Physics, Chemistry, Geology, Cognitive Science, and Computer Science).

The center houses the new Cave at Brown University -- a fully immersive display environment. Our four-wall Cave has 8-foot by 8-foot display surfaces. This display environment is balanced with an IBM SP supercomputer for computation and a Cavegraphics computer for image generation. The opening of this facility sets the stage for future user interface research. At this point, we have established much of the infrastructure needed to begin Cave-based UI research.

Cave - Plans

We will explore gestural and multi-modal user interfaces designed for a Cave-like environment. We haven't been able to due this prior to the Cave installation because it is such a different experience from working at a desktop monitor or responsive-workbench-like display. Two projects are already under way-- Room Designer (a system for populating a room or building environment with furniture) and a user study designed to more quantitatively and qualitatively understand when selection of objects is best done with speech versus gestural techniques.

Two other applications will drive our Cave research: We will be designing novel user interfaces to help explore very large datasets (gigabyte and terabyte in size). This effort will be initiated by an investigation into the research problems associated with large dataset visualization. And we will also use the Cave facility as part of our telecollaboration research -- as a prototype of an Office of the Future (see **Telecollaboration**).

Haptics

We have begun to abstract some haptic user interface principles [mill99] from our 3D haptic sketch-based polygonal modeling testbed, as well as from examination of successful haptic interfaces of the real world. In most haptics work, there is something to be simulated, and the challenge is in creating fast-enough simulations. In contrast, in our work a task to be performed by a user is given, and we must determine what to simulate to allow and aid that task. We will perform user studies to investigate the effect of learning and explicit teaching of strategies on human performance with and preference for haptic user interfaces.

Multi-Modal Interfaces

We are currently exploring the use of multimodal interfaces for 3D graphics applications, specifically virtual environments. We use hand gestures and speech input as our input modalities and are investigating how these interfaces can be used in scientific visualization and interior design. We are also planning a series of experiments to investigate how effective these interfaces are in terms of user performance and preference.

Color Choosing

In today's graphics software it is often surprisingly difficult to choose a desired color. Once a color is selected and used in a design, it is often even harder to adjust it and its relationships to other colors. We seek to make this process easier to control and more enjoyable by providing better underlying color space representations (see **Scientific Visualization**) and new interface tools.

Our color "nudger" and "selector" widgets use gestural 3-axis marking menus to allow the user to vary hue, saturation, and brightness with simple motions of the mouse or tablet pen. The nudger is a gradient-based widget in which users can make continuous changes by dragging. The selector uses discrete swatches that must be clicked individually and is designed for initial selection of colors. We use the Munsell color space to drive both, guaranteeing perceptually consistent changes: i.e., when a user changes a color's value, the hue and saturation remain constant (this is not the case in current commercial software and is the source of much confusion).

While the nudger and selector operate on single colors, we've also developed tools that operate on groups of colors, adjusting relative value-contrast and saturation-contrast of the group. We are about to undertake a user study to compare our widgets and the use of the Munsell space to standard color manipulators and standard spaces (namely HSV). Additionally, there is an educational component, interactive applets for the Web, to this color project.

Although manipulation tools are important, we also believe in expertise: we are developing expert palette interfaces that provide preselected collections of colors united around a theme or particular application. Users can use these as provided, or adapt them to their particular needs. We are designing free-form palettes (most programs use rigid grids of color swatches) that allow the user move swatches to any location, change swatch sizes, and easily create and delete gradients between swatches. We are also developing expert palettes that link to other palettes and that provide textual information about the reasons for the color choices and their suggested uses.

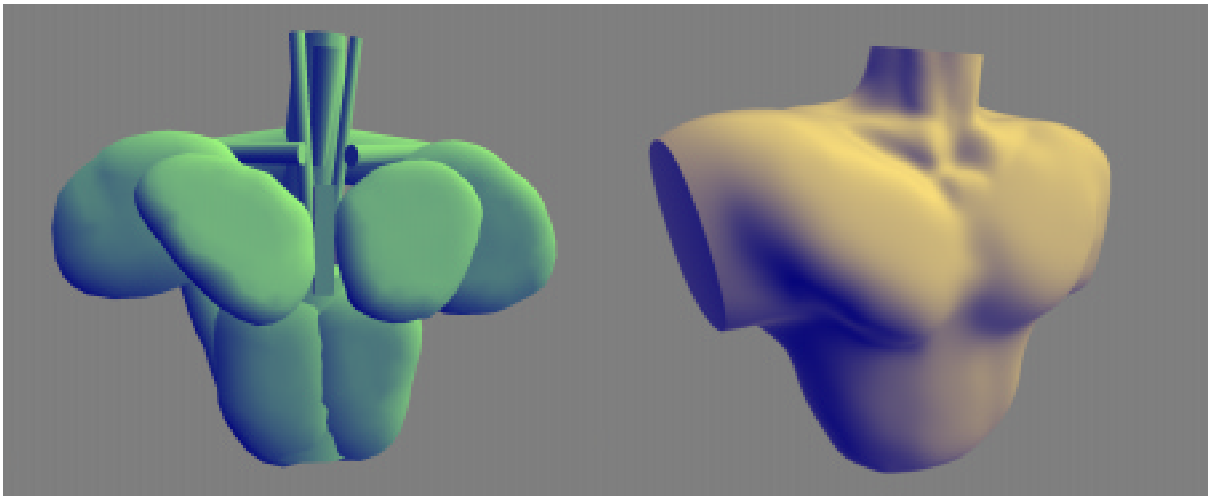


Figure 5: The torso was constructed by specifying underlying masses (left) and then by putting a "skin" over the masses to create the finished torso (right).

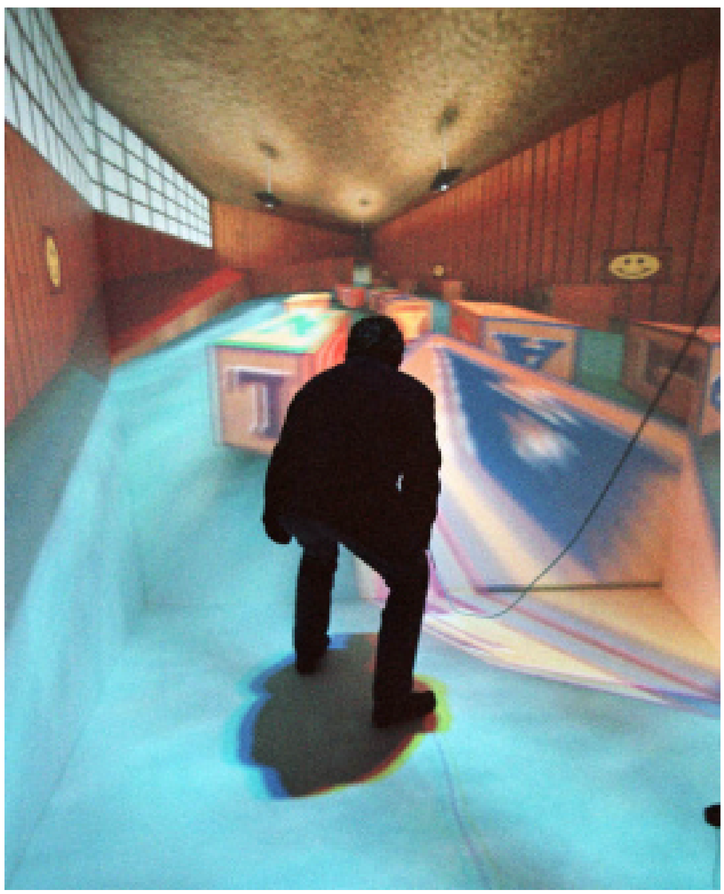


Figure 6: The Technology Center for Advanced Scientific Computing and Visualization at Brown University contains a Cave, pictured here, in which we will explore gestural and multi-modal user interfaces. (Associated Press picture)

2.D Scientific Visualization

D.1 Participants

Faculty

Chris Johnson, Andy Van Dam, Peter Schroeder, Henry Fuchs, Charles Hansen, David Laidlaw

Research Staff

Anne Spalter, Tim Miller, Barb Meier

Graduate Students

James Durkin, Gordon Kindlmann, Zoe Wood, Peter-Pike Sloan, Jeremy Ackerman, Gentaro Hirota, Michael North, David Karelitz, Philip Stone

D.2 Recent Accomplishments and Plans

The Center has wide-ranging accomplishments in scientific visualization that have significant impact on the fields of science, medicine, and engineering. The Center's strategy is two-fold: conduct fundamental research in the field of scientific visualization and we apply the Center's skills in its four core research areas to scientific visualization projects, many of which, involve scientists and engineers from outside the Center.

The Center has continued to increase its profile in Scientific Visualization by delivering invited talks and publishing papers in scientific visualization journals and conferences, such as the IEEE Transactions on Visualization and Computer Graphics and the annual IEEE Visualization conference. This past year at the IEEE Visualization '98 Conference, Center garnered two awards: Best Paper Award for Interactive Ray Tracing for Isosurface Rendering by Steven Parker, Peter Shirley, Yarden Livnat, Charles Hansen, and Peter-Pike Sloan from the University of Utah and Best Panel Award for David Laidlaw's (Brown/Caltech) panel on visualization and perception. One of Professor Laidlaw's images was chosen as the cover image for Visualization '98 proceedings.

Accomplishments for the past year in scientific visualization include a wide variety of research- and applications-oriented results.

Multiresolution Methods for Visualization and Computational Modeling (intersite collaboration between Caltech and Utah)

This intersite collaboration examines the feasibility of applying advanced multiresolution geometric modeling, numerical simulation, and visualization approaches to advance the state-of-the-art of algorithms in this area. This past year we have succeeded in advancing our research efforts on several fronts whose results, in part, appear in SIGGRAPH '99 papers, a journal article, an inverse problems conference proceeding article, and the ACM Solid Modeling Symposium.

In the past year we have had a breakthrough in realizing smooth function space hierarchies on irregular meshes. So far all smooth function space hierarchies were based either on tensor product settings or on the semi-regular (sometimes referred to as subdivision connectivity) settings appearing in subdivision. In practical applications this limits us to the subdivision setting and has been the reason for our remeshing work (see below). In practice it is often desirable to work with the original finest level mesh, such as those produced by marching cubes extraction of iso-surfaces or meshes arising from 3D scanner technologies. The main problem with these settings is that whatever technique is applied, it must take careful account of the underlying unknown parameterization. We have been able to develop irregular smoothing operators that take this parameterization into account. Using such a smoothing operator, which is still linear, opens up the whole range of signal processing applications to irregular meshes and in particular provides a new avenue to construct smooth shape functions for FEM settings.

Immersive Color Space Visualization

The Center is conducting research on color space visualization using the cave environment at Brown University (part of the TCASCV). The current system uses a variety of visualization techniques to study different color spaces, including RGB, HSL, CIExyY, CIELab, and Munsell. A particular challenge in choosing and developing visualization techniques has been the need to convey appearance and properties of 3D volumes without using transparency (which would alter the color being represented). One method we have developed for this purpose consists of falling "snow flakes" that pass through the color space and change color depending on their location within it. The user gets a sense of the colors throughout the space and yet no part of the space is permanently obscured. The user controls the number and flow rate of the flakes and can also freeze them completely.

Using immersive visualizations in the cave, as well as on a responsive workbench-like display and desktop versions, we have been able to gain a better intuitive understanding of the geometry and topology of these spaces and the mappings between them. Such knowledge is important for understanding the relationships between underlying color spaces and the interfaces and functionality provided in graphics software packages. This knowledge also is vital for exploring the tradeoffs made in color space conversions. In the course of these explorations, an anomaly has been discovered in the representation of displayable RGB colors in Munsell space: a notch in a blue area that shows several points of maximal saturation, instead of the usual single one.

Improved Selection and Manipulation in Immersive VR

The Center has created a new interaction style for immersive VR that we call "projective manipulation." Projective manipulation extends established cursor-based desktop 3D interaction techniques to immersive VR. For example, to select a distant object, the user positions a finger in front of his or her eye so that the fingertip appears to be on top of the distant object. Ignoring stereo information, the user’s fingertip is tantamount to a 2D cursor in desktop interaction. Part of this work has been done in collaboration with the User Interface Group at the University of Virginia. Preliminary results from pilot usability studies indicate that manipulating projections is more effective than techniques that require the user to intersect objects in 3D.

Augmented Reality for Image-Guided Surgical Procedures

The Augmented Reality (AR) work at UNC focuses on visualization for image-guided surgery. The research group works on two applications: ultrasound-guided needle biopsy of the breast and laparoscopic interventions. Tracking and head-mounted display technology is the same for both applications. We have been using a recently integrated Flashpoint 5000 optoelectronic tracker from Image-Guided Technologies to track the head and all tools such as ultrasound probe, laparoscopic camera, biopsy needle, laparoscopic depth extraction device. The successors of the UNC/Utah lightweight monochrome stereo video-see-through HMD have been a Kaiser Electro-Optics ProView30 and (more recently) a ProView XL35 HMD. Though bulkier, these units provide full color display at up to 1024x768 pixels.

In the area of breast biopsy, we are preparing our system for human subject experiments to be conducted (probably in early 2000) under separate funding from NIH (led by Stephen M. Pizer, the funding source for most of this project). Among other enhancements, our system has been ported from the older Onyx1 Infinite Reality (with Sirius Video) platform to the new Onyx2 Reality Monster (with DIVO digital video capture) platform.

In the area of laparoscopic visualization, we have been investigating the possibility of developing a miniaturized internal depth extraction device using a structured light projector and small cameras, with all optical paths carried into the patient through conventional laparoscopic assemblies. Kurtis Keller has begun manufacturing a prototype device.

We have also conducted an experiment in which ultrasound and laparoscopic visualizations are combined with pre-operative imagery. The merged visualization was our first attempt in creating a much more visually complex AR environment. While applying this visualization to a phantom model of a human with an internal lesion to be biopsied, our physician collaborator (Dr. Tony Meyer) successfully extracted a sample from the lesion, using guidance from the AR view showing the lesion both in the pre-op CT imagery and in the live ultrasound scan. The attached image shows the view through the HMD during this experiment.

Remote Microscope Control, with the Collaboratory for Microscopic Digital Anatomy (CMDA)

The Center has completed its participation in the research and development of a networked, interactive collaborative microscopy research environment, the Collaboratory for Microscopic Digital Anatomy (CMDA), with the National Center for Microscopy and Imaging Research (NCMIR) and the San Diego Supercomputer Center (SDSC). An interactive volume rendering software environment has been constructed, providing an intuitive interface that allows non-expert users to visualize their EM tomography data quickly and easily. This rendering system exploits an algorithm created at the Center, which generates transfer functions that emphasize boundary regions in biological data. This algorithm was recognized as the best research contribution at the 1998 ACM SIGGRAPH Volume Visualization Symposium.

Remote Microscope Control, with the Collaboratory for Microscopic Digital Anatomy (CMDA)

During the fifth and final year of the CMDA grant the Center plans to integrate its recent research contributions into the operational CMDA software system. The use of Center-developed rendering tools and visualization aids by microscopy researchers will allow us to fully evaluate the effectiveness of these advanced techniques for EM tomography data and in a non-expert user environment. Such experience should allow us to improve these techniques and point the way towards new research challenges. In addition to integration and evaluation activities, we will be focusing our further research efforts on new direct volume rendering techniques, with the emphasis on bridging the gap between fast but approximate and slower but higher accuracy methods through the use of a metric-driven progressive refinement approach.

Augmented Reality for Image-guided Surgical Procedures

The medical AR group plans to construct a new video-see-through HMD, this time using commercial higher-resolution color displays, in preparation for human subject breast biopsy experiments to be conducted under separate funding from NIH. A number of further enhancements are planned for the system before that, such as fully integrating an optical tracking device and parallelizing time-critical portions of the code.

Educational Visualization Applications

We plan to continue exploration of the blue notch and other characteristics of importance to the use of graphics software, such as navigational paths through the color spaces that can be taken advantage of by color pickers. We also plan to view histograms of art and design works in the spaces to see whether such visualizations are useful for analysis or prediction of the success of different types of visual communication.

We plan to use these color space models, mappings, and visualization techniques for an educational project that guides users through a virtual color science museum in which they interact with guided exhibits (see **Exploratories** in the **Outreach** section).

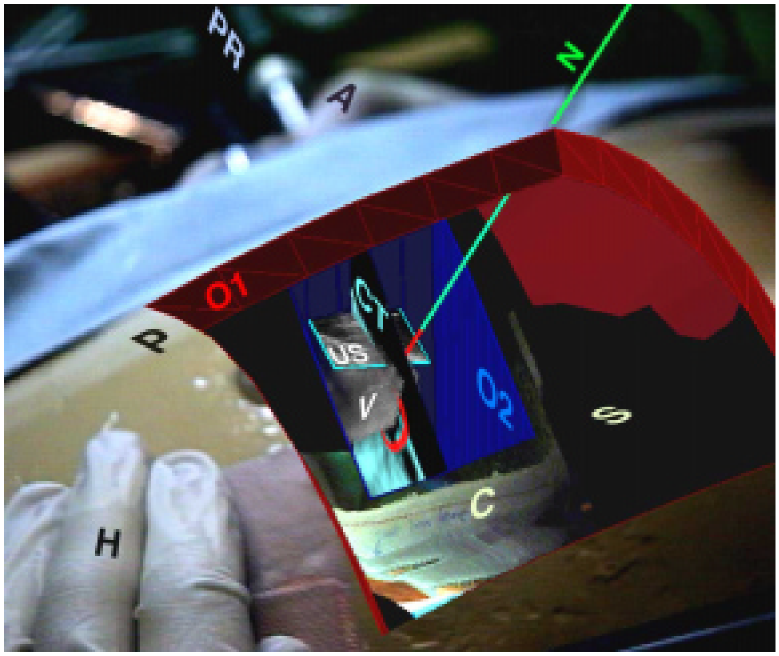


Figure 7: Live video-see-through augmented reality view shown in stereoscopic head-mounted display of experimental UNC system designed to assist surgeons with image-guided interventions. The letters are not part of the original image and were added for explanation: (P) is a mock-up of a patient's abdomen, and (H) is the user's hand. A superimposed computer-generated opening (O1) allows the surgeon to look into the patient. Inside O1 the system displays an internal surface (S) consisting of pre-acquired geometry textured with live video from a tracked laparoscopic camera (not visible). A plastic container (C) represents the target organ liver. The surgeon looks into the liver by means of a second, inner computer-generated opening (O2). Inside O2 the system displays a pre-operative CT slice (CT), on which the dark target lesion has been annotated by the physician with a red outline. Live intra-operative ultrasound is displayed as a textured polygon (U/S), which moves with the tracked ultrasound probe (PR) operated by an assistant's hand (A). Volumetric ultrasound data (V) can be emitted through freehand scanning with PR. The user has inserted a tracked biopsy needle, shown as a green line (N) into P. Inside O1 and O2 the red extension of N represents the predicted (straight-line) trajectory of the needle. Using this three-dimensionally integrated visual feedback, the user attempts to guide N into the target lesion in order to extract a sample.

2.E Telecollaboration

E.1 Participants

Faculty

Sam Drake, Henry Fuchs, Rich Riesenfeld, Brent Seales (visiting from the University of Kentucky), Greg Welch

Research Staff

Mark Bloomenthal, Russ Fish, Andy Forsberg, Loring Holden, Andrei State, Herman Towles, Robert Zeleznik

Graduate Students

Michael Brown (visiting from the University of Kentucky), Wei-Chao Chen, David Gotz, Zhu He, Aditi Majumder, David Marshburn, Gopi Meenakshisundaram, Andrew Nashel, Charles Pisula, Ramesh Raskar, Ruigang Yang

Undergraduate Students

Caroline Green

Collaborators

Ruzena Bajcsy, University of Pennsylvania/National Science Foundation

Jaron Lanier, Advanced Network & Services, Inc.

E.2 Recent Accomplishments and Plans

Telecollaboration has been a driving force in the Center since its birth. Not only does it allow collaborators at remote sites to interact with each other in a face-to-face way that was previously prohibited by geography, but deficiencies in current systems fuel ongoing research efforts to improve the telecollaborative experience. Thus, we are both users and developers of this technology.

The Center's telecollaboration effort includes several multi-site research groups, many funded by the Director's Reserve, whose degree of research coordination would be impossible without the telecollaboration technology being developed and applied. To achieve the long-term goal of enabling distant collaborators to work together as if present in a common space, fundamental in-depth research in all of the Center's core areas of modeling, rendering and interaction is required, to further develop scene construction and acquisition, reconstruction and display, and interaction techniques for virtual environments. Undertakings in these areas of the past year are described below.

E.2.1 The Office of the Future

As stated in last year's Annual Report, the cornerstone of the Center's telecollaboration research is the Office of the Future. Based on the observation that work generally is accomplished in one office either alone or with one or two other people, OOTF aims to go beyond the desktop WIMP (windows-icons-mouse-pointer) metaphor; its long-term goal is to be an immersive environment where it would appear to its users that they are in adjacent offices with a "window" cut out of the common wall. Technically, the fundamental concept is to replace lights with projectors so that surfaces can be lit with the imagery of the opposing location. It is thus necessary to know where every camera pixel is positioned in that other scene, where every projector pixel is struck in your scene, where surfaces are located, their reflection properties and other such detail, given a casual arrangement of cameras and projectors. Below described are recently developed methods of how to acquire and manipulate such information.

Seamless Projection Overlaps

Recent Center work [rask99b] bore an alternative method of high-resolution Spatially Immersive Displays (SID), generally involving wide field of view (WFOV) image generation through multiple projectors. Past models of such have used non-overlapping projections (e.g. CAVE), side-by-side overlapping projections with precise electro-mechanical setup (e.g. flight simulators) or a WFOV projector with expensive optics and computer hardware. Center researchers found that through image warping and intensity blending, it is possible to solve the basic problem of registering and blending of two projections at a time. Using proper calibration and rendering methods, this work is even applicable when the projection displays are not walls or the projection axes are not orthogonal to display surfaces.

Real-Time Depth Warping for 3-D Scene Reconstruction

Other Center work aided projected stereo imaging by 3-D scene reconstruction via real-time depth warping [seal99]. The work, using ideas of depth from structured light and from stereo vision, explores a new depth-recovery technique that is targeted for two realms: visualization on non-regular screen surfaces and real-time depth recovery in an unknown scene. This method uses projected imagery from a light source such as a Digital Light Projector that forms a closed loop with a camera system that iteratively re-images the projected imagery, warps it and re-projects it in order to compensate for distortion as a result of scene geometry. Since the projected imagery, when recaptured by the synchronized cameras, exhibits warping solely due to depth variations in the scene, the captured image can be compared to the projected image in order to solve for the depth geometry that induced the warp.

E.2.2 National Tele-Immersion Initiative

Work being done on the Office of the Future is also sponsored by the National Tele-Immersion Initiative, with which two Center sites are affiliated. For the past two years, the notions involved in OOTF have been refined with help of NTII and its component researchers. An undertaking of Advanced Network & Services, NTII has the broad aim of enabling users at geographically distributed sites to collaborate in real time in a shared, simulated environment as if they were in the same physical room. This new paradigm for human-computer interaction is the ultimate synthesis of networking and media technologies to enhance collaborative environments and, as such, it is the greatest technical challenge for Internet2.

E.2.3 Face-to-Face Video Teleconferencing

An exciting new avenue of telecollaboration is taking form in face-to-face video teleconferencing, a televideo environment of which the ultimate goal is for a participant is able to experience eye contact with his or her life-size collaborator at a remote location. With the same basic idea as the Office of the Future, the ultimate goal of this system is to create a sense of presence compelling enough to the users so that they appear to be sitting across a table from one another. Currently in the prototype stages at two Center sites and presently in Office NOW!, an NSF office equipped with the same cameras-projectors setup, this system is composed of a camera (soon to be replaced by a mini-camera cluster), a whiteboard display surface, and a projector. The whiteboard serves not only as the display screen for the projected life-size image of the remote collaborator, but it also operates as a concealer for the camera, mounted behind it on a bracket made by the Sketch-N-Make group and aimed at the person in the “sweet spot,” i.e. a particular point in his or her office. Since the cameras are positioned so that each person looks straight into them, and their projected images are displayed on whiteboards propped across the table from their collaborator, the desired effect is that the working environment created is much more comfortable and intimate than other current states of video telecollaboration.

There is much room for improvement and refinement in the current setup. For example, eye contact and a wider field of vision are longer-term goals of researchers. A “mini-camera cluster,” which was designed and manufactured by the Sketch-N-Make group and is more thoroughly discussed in Section E.2.4, has been a step forward towards the wider field of vision goal, increasing the user’s view from around thirty horizontal degrees to more than ninety.

Problems have arisen, however, which fuel Center research. For example, lighting is extremely important in this situation; it is necessary for each user to be well lit, but at the same time it is quite undesirable to have any light other than the projector’s fall on the display screen. This is currently remedied by a series of track lights strategically focused away from the display board and towards the user. It’s also problematic to have light from the projector picked up by the camera. This problem is being solved by placing a Utah-manufactured screen with alternating 0.5 millimeter spaces and horizontal louvers, with faces angled so that light from the projector is either reflected back to the user or absorbed between in the slats. Future cameras, with physical dimensions that may be much smaller, also hold promise in solving this problem.

E.2.4 Sketch-N-Make Design and Manufacture Group

Recent strides were made in the Sketch-N-Make Design and Manufacture Group due to the Center’s telecollaborative capacity. As mentioned in last year’s Modeling section, Brown, UNC and Utah have developed *Sketch-N-Make*, a prototype art-to-part system that allows users to quickly design non-trivial, dimensioned, machined metal and plastic prismatic parts. These parts can then be automatically manufactured on a machining center with the aid of a technician who prepares and loads the stock and cutting tools.

Last year, the Center both integrated and extended Brown’s gestural UI framework to work effectively with Utah’s Alpha_1 modeling system. In addition, a family of stereotyped process plan templates was developed that work in concert with a restricted but non-trivial class of mechanical parts, (i.e. prismatic parts with a single machining access direction), a combination that allows high-level UI geometry to be transformed automatically into high level mechanical features, placed within the context of an appropriate process plan template. These features could then be used to automatically derive computer numeric control (CNC) code that drives a machining center during manufacture.

This year brought a milestone to the process by which parts are made. For the first time, a mechanical part, designed at UNC with Sketch-N-Make and manufactured at Utah, was produced without any physical interaction between collaborators. A miniature version of the WFOV camera cluster, designed in the Jot environment at UNC and manufactured at Utah, will presently link the offices of a Center PI and an NSF executive. Using three cameras whose video streams are digitally merged, the mini-camera cluster will play a large part in the imminent research on Face-to-Face Video Teleconferencing.

Figure 8: Two members of the Office of the Future team “virtually” shake hands, recreating a spontaneous interchange between two naïve participants during a demo. In the foreground is the OOTF environment, while the people in the back are in the room to which OOTF is tele-connected.

Figure 9: Here, the Face-to-Face Videoteleconferencing system is at work. In the foreground is a UNC collaborator, sitting in the office of Henry Fuchs, conversing with collaborators at Utah who are life size and appear to be across the table from her.

3. Education and Human Resources

The Center runs a wide range of programs to develop human resources in science and engineering. We have continued to emphasize our programs for women and minority groups, and have also begun a focus on efforts that bring the Center's resources to wider audiences.

Highlights:

- The Exploratories Web-based educational applets project was part of five different venues at SIGGRAPH '99. A series of exploratories applets are also being distributed, via Advanced Network & Services' ThinkQuest '99 CD, to virtually every secondary school in the US and many abroad (over 225,000 CDs will be sent out). `http://www.cs.brown.edu/exploratory/`
- The SAM I AM program, which brings graphics and visualization software and expertise to Pasadena public schools, has reached over 1000 students and 30 teachers in grades 6-12 of the largely minority Pasadena public school system. Software companies, including Adobe Systems, have donated software for this effort.
- Several years ago, a high school teacher in a Center program began an interactive biology Web site called The Virtual Cell. The site is now funded through additional grant money, has won awards and recognition through various Web ranking pages, is being translated into other languages, and receives over 2000 hits a week. `http://personal.tmlp.com/jimr57`

3.A Recent Accomplishments

A.1 Graduate Programs

Center graduate students see and interact with one another in the all-site televideo seminar. In addition, they have the opportunity to meet in person in Center graduate student workshops. Incoming students have cited the Center as a reason for applying to Center university graduate programs and exposure to the Center often leads undergraduates to consider graduate school at one of the other Center sites.

All-Site Graduate Televideo Seminar

The Center is in the sixth year of its pioneering all-site televideo seminar, attended and taught by all five sites. The seminar is offered for credit at three of the sites and is attended by approximately 70 students a year. A unique feature of the Center graduate experience, this seminar provides access to information and people well beyond the scope of any single university. Graduate students also use the televideo system as part of a research lab without walls to discuss collaborative work. Lecture titles and abstracts for the 1998-99 academic year seminar can be found at:

`http://www.cs.brown.edu/stc/education/course98-99/home.html`

All-Site Graduate Student Workshops

The Center's popular graduate student workshops are in their fourth year, with participants from each of the sites gathering at a different Center location each time.

Many students compare the experience favorably with a full-fledged graphics conference and feel that they have gained a better understanding not only of the work of their distributed Center colleagues, but of the field in general. The chance to visit other Center sites and see different approaches to graphics research is felt to be particularly rewarding. See: `http://www.cs.brown.edu/stc/students/`

3.B Undergraduate Programs

Undergraduate education at all sites (with the exception of UNC, which has no undergraduate computer science program) is directly influenced by the Center. For example, in collaboration with the Department of Computer Science, the Cornell site is developing a new four-semester sequence of undergraduate courses for both CS majors and students from other departments who are looking for additional opportunities to study computer graphics. Donald Greenberg is also continuing to teach his successful *Disruptive Technologies* course in the Johnson Graduate School of Management, which draws a number of undergraduate students.

Twelve undergraduate architecture students enroll each semester in the Cornell site's Design Studio for the 21st Century course, taught in their computer graphics laboratory with full access to computing, scanning, output, and display resources. The course introduces new paradigms for the conceptual development, modeling, and rendering of architectural design. Tools are based on sketching routines, digitizing drafting tables, projection displays, and the ability to interactively modify and walk through virtual environments. This fall's studio includes a high percentage of female and minority students, including a student from the Center's Undergraduate Research Access program (described shortly below).

All-Site Graduate Televideo Seminar

Although technically a graduate course, this seminar is taken by almost as many undergraduates as graduates. See Graduate Programs, Section A.1

The Utah ACCESS Program

Started in 1990 by a Center faculty member, the ACCESS program has introduced over 150 young women to university-level research in science and technology (approximately 20 each year) by providing both academic and social support systems. During an eight-week summer course before their initial year at the University of Utah, ACCESS students get a feel for research by tackling real-world problems in a mentored setting that includes instruction, laboratory work, and team work on assigned problems. Supported by a $2,500 stipend during the academic year, ACCESS students are placed in a science, engineering, or medical research lab. The majority of the students continue to work in research labs throughout their undergraduate careers. One of the participants is continuing the doctoral program at STC school Cornell.

http://www.science.utah.edu/access.html

Undergraduate Research Access

For the past three years, we have continued contact with summer session students who have been admitted to Cornell as undergraduates. Our Undergraduate Research Access program provides opportunities for students to gain exposure to computer science and architectural design research in the Center. The students involved are primarily minority female students, but have included males and non-minority females as well. The emphasis is on developing long-term career interest in computer graphics, primarily through contact with older students and opportunities to explore high-end modeling and rendering tools.

Our goal is to mentor the students and instill in them greater confidence that they can undertake careers in computer graphics. This outreach program has been enhanced this past year by Corey Toler's leadership. Corey first came to the lab as a high school student in the summer program, pursued independent study and summer modeling work in the lab over her college career, and, in September 1999, completed her Master's degree at Cornell in computer graphics. During her tenure at Cornell, Corey has served as an excellent mentor for other women and minority students (see image accompanying this section).

Research in Center Labs for Students from Historically Black Colleges

The Center has begun a new initiative to create alliances with historically black colleges. In 1997, the Chair of Morehouse's Computer Science department, along with Morehouse's Director of Educational Technology, visited the Brown site for three days. Last summer, the Center hosted a student from Morehouse College. He worked with the Exploratories Group (see A.2.2) at Brown for four weeks and continuing to work on projects with the Center from Morehouse. This summer, the Brown site hosted a second Morehouse student who worked with the Exploratories Group for seven weeks and is continuing his efforts from Morehouse.

B.1 Undergraduate Interactive Materials Development

The Center is augmenting its intensive local hands-on outreach programs with materials development efforts. This strategy lets us build on the entire Center's outreach and educational experiences and leverage them to greatly expand our influence.

Interactive Tools for the Classroom of the Future

The Center has worked for several years on an ambitious education outreach project called Interactive Tools for the Classroom of the Future. In this project a post-doc, graduate student, and undergraduates worked together to develop visualization and physical simulation tools for science education, using a fully interactive 3D environment including object behaviors derived from the laws of physics. Based at the Cornell site, this project has drawn on Center software resources from several other sites, including UNC's OBB-Tree collision library and Brown's VRAPP library. This project and related activities have involved ten material-creators and impacted hundreds of students.

Exploratories

Exploratories are a computer-based combination of an exploratorium and a laboratory—a constructivist way of teaching and learning using two- and three-dimensional, explorable worlds in which objects have behaviors and users can interact with models of concepts and phenomena. Exploratories leverage the joint forces of computer graphics and interaction to provide efficient, powerful learning experiences that would be impractical, if not impossible, to attain with traditional means. To facilitate widespread use, the exploratories are written in Java and embedded within a hypertext (HTML) framework that facilitates both independent and guided use. Teachers may incorporate individual exploratories into existing curricula, while students may find guidance to additional resources, including related exploratories.

The Exploratory project has three major research thrusts: Content Creation, Authoring Tools, and a Design Strategy Handbook. Current exploratories incorporate a range of computer graphics subject matter taught in the Center, including linear interpolation for animation, wavelets, filter and image processing operations, color perception, matrix math for graphics, scene graphs, and more. The interactive materials are appropriate for a range of educational levels, from high school to the graduate level, but emphasize undergraduate-level courses. Applet production is going on at several sites and applets are being integrated into the Center's introductory graphics programming courses.

`http://www.cs.brown.edu/exploratory/`

The Exploratories project was part of five different SIGGRAPH '99 venues: 1. A lecture in the Electronic Schoolhouse, entitled "Exploratories: An Educational Strategy for the 21st Century;" 2. A Playground exhibit in the Electronic Schoolhouse called "The Color Playground;" 3. Use of six exploratories in the course "Why Does it Do That? 10 Mysteries of Computer Artmaking Revealed," taught by the Center's Outreach Coordinator;" 4. Use in the course "A Survey of Color for Computer Graphics,"and 5., participation in the Computer Applications Laboratory.

The Color Playground series of exploratories is being distributed on Advanced Network & Services' ThinkQuest '99 CD to every secondary school in this country and many abroad. Over 225,000 CDs will be sent out.

3.C Pre-College Programs

Opportunities offered by the Center have brought our researchers in contact with large numbers of K- 12 students and teachers. Connections have been created with groups that historically have had little interaction with university researchers and research labs. The pre-college programs are designed to contribute to the Center goal of drawing more students into computer science and computer graphics. Emphasis is increasingly on programs that encourage underrepresented groups, such as women and minorities, to participate. The experiences gained in intensive, hands-on workshops are being distilled into interactive materials that can potentially be used by thousands of students and teachers.

SAM I AM (Science and Math, Integrated Art Technologies)

The SAM I AM program brings computer graphics and visualization to the Pasadena public school system. The program supplies graphics software and instruction to leverage the existence of new computer labs that were, unfortunately, stocked with little but word processing programs. This year SAM I AM reached approximately 1000 students in grades 6-12 and 30 teachers, including many minorities—the Pasadena Public School system is 86% non-Caucasian. Special sections of the program are targeted to at-risk teenagers and female students. Software companies, including Adobe Systems, have donated software and publishers have donated magazine subscriptions to this effort.

The Utah High School Computing Institute (HSCI)

Now in its ninth year, the five-week HSCI was started by a Center co-PI and continues to provide an important regional service for 30-40 high school students each year (almost 370 since the program began) from across the entire state of Utah, including many rural areas. Just as race or gender disadvantages some students, others struggle with geographic destiny—they are simply too far away from centers of academic excellence to be exposed to a nationally recognized research lab. In addition to the summer activities in programming, computer graphics, artificial intelligence, and Web design, year-round workshops and an increasing number of Web connections keep students involved long after the initial summer program. See:

`http://www.eng.utah.edu/outreach/hsci/`

There was unprecedented Center involvement in the teaching of the Institute this year, with three Center researchers teaching units on computer graphics. Students were able to take advantage of the unique facilities of the Utah site, such as 3D rapid prototyping machines. The program continues to inspire high school students to pursue a college education and many have majored in computer science: this year, the two teaching assistants, Chad Barb and Ben Baker, who both went through the program as participants, are now undergraduates at Utah and working with the Center in a research group on user interfaces.

Virtual Cell

A product of a previous Center outreach program for high school teachers (The Summer Workshop in Computer Graphics and 3D Modeling/The Greenhouse), the Virtual Cell online interactive biology textbook project has continued to grow in scale and richness. The site has received a grant (see last year's annual report) and in April 1999 was featured in The Eisenhower National Clearinghouse for Mathematics and Science Education (ENC) "Digital Dozen" and was declared a Channel One Network Student Web site of the week. The Virtual Cell site also received The Catholic Schools of Tomorrow award from Today's Catholic Teacher Magazine, one of 12 awards given nationally. The organization flew the teacher who runs the project, Jim Rusconi, to New Orleans to receive the award at their annual convention in April. The site is being translated into several languages including French, Spanish, and Portuguese, and the site's content has expanded to include units on organic chemistry. Portions of the site are being used in many high schools and some universities, including one in Brazil. The site receives several thousand hits a week. See:

```
http://personal.tmlp.com/jimr57/
```

Career Explorations in Architecture

During the current year we have continued our long-term involvement with the Cornell Summer Session for Design Professions. This summer career exploration program brings from 80 to 100 high school juniors and seniors to Cornell for six weeks. The program also serves as an intensive orientation experience for incoming Cornell freshmen in cooperation with the College's Office of Minority Educational Affairs.

The Center does not run the summer session, but over the past seven years the Cornell site has provided lectures by Donald Greenberg and additional evening technical sessions, broken into small groups to permit one-on-one interactions and questions. These sessions include demonstrations of modeling, physically based rendering, architectural sketching, 3D scanning, and digital photography. Dr. Greenberg also leads discussions about careers in graphics and animation, opportunities in college and graduate school, and recommendations for course choices.

Beginning with Children

The Cornell site has continued a cooperative relationship with the Beginning with Children School in Williamsburg, Brooklyn. This school is a public school designated by the New York City Board of Education as a model elementary demonstration school. The sixth-grade science classes visit Cornell and our lab each year, where hands-on sessions provide students an opportunity to experience new technologies firsthand.

C.1 Pre-College Programs for Underrepresented Groups

The Artemis Project

The Artemis Project is a five-week summer leadership program for rising ninth-grade girls, designed and led by female undergraduates at the Brown site. The Artemis Project was not run this summer but we plans to run a variation of the program this spring.

```
http://www.cs.brown.edu/stc/outrea/greenhouse/artemis/home.html
```

Cornell Summer Session for Design Professions

See Pre-College Programs, Section A.3.

SAM I AM

See Pre-College Programs, Section A.3.

Computer and Computational Sciences Program at Caltech

The Caltech site participated in the 7th Annual Computer and Computational Sciences Program, which is organized by the Center for Advanced Computing Research at Caltech. The program gives minority high school students first-hand exposure to cutting-edge research in science and mathematics, which is enhanced by advanced applications of computers. Computer Graphics and Computer Animation technology was presented and discussed.

3.D Opening the Lab Doors—Center Lab Tours, Talks, and Demonstrations

As a nationally funded organization, the Center takes pride in its open-door policy for all interested groups, from academics to industry to local schools. Tours and demonstrations of work in the Center's research labs (and of the interlinking televideo system) continue to expose large numbers of visitors to the state of the art in computer graphics. Each site hosts several hundred visitors a year, with UNC hosting over 700 each year.

The UNC site focuses its outreach efforts on tours, devoting at least one day a month to tours and demonstrations (the equivalent of running a yearly full-time three-week outreach program). Virtually everyone working in the lab, from the site PI to undergraduates, contributes to this demanding and unusually strong commitment to the public.

D.1 Internet Access for the Sciencenter in Ithaca

The Center installed and has continued to support a Web browsing kiosk and a Web server for the Sciencenter in Ithaca. This community-based science museum has garnered national attention for innovative exhibits, community outreach, and extraordinary volunteer commitments.

3.E Plans

We are continuing to refine and improve the education and outreach programs discussed above. The SAM I AM project, the Center's large-scale effort to impact thousands of minority students, will continue to expand. Results from the Exploratories project are being submitted to several conferences and journals. Center outreach efforts are increasingly focused on projects that will ensure results of lasting value to the computer graphics community and the general public.

Figure 10: Corey Toler, a participant in the Cornell Summer Session for Design Professionals and the Center's Undergraduate Research Access program, just completed her Masters at The Program in Computer Graphics at Cornell. Here she works with sixth-graders in the Center's Beginning with Children Program, showing them her software on the responsive workbench.

4. Outreach and Knowledge Transfer

The computer graphics industry continues to hire a significant number of Center students, many for key positions. This is a highly effective form of technology transfer and our students are among the most sought after in the industry. Many tools and techniques developed in Center laboratories have emerged in commercially available products, including products influenced by Center research in physically based modeling, computer-aided design, radiosity, virtual reality techniques, geometric modeling and 3D user interface widgets. Center students working in industry frequently return to their schools to recruit new employees.

4.A Industry and Government Research Relationships

The Center has maintained research relationships with many U.S. hardware and software companies. Current relationships include Adobe Systems, Advanced Network & Services (Advanced), Alias|Wavefront, Autodesk, the Department of Energy (DOE), HP, IBM, Intel, ITD, IVEX, Microsoft, the National Tele-Immersion Initiative, PCA International, Sun Microsystems, and TACO. Center labs have received equipment grants from HP, IBM, Intel, Kodak, Lucent, SGI, Sun, and Tanner Research.

The Center is continuing to pursue a close relationship with IBM through the new Brown University NSF MRI-funded Technology Center for Advanced Scientific Computing and Visualization. The new visualization facility features a Cave visualization environment driven by an IBM supercomputer with scalable graphics hardware designed especially for immersive environments. Advanced, which played a leading role in the growth of the Internet in the early 1990's, has identified telecollaboration as a principal driving application area because of its critical high-bandwidth and low latency demands. In recognition of the leadership role that the Center has taken in different areas of telecollaboration, Advanced has been funding multiple Center research projects in tele-immersions as well at the University of Pennsylvania and the Naval Postgraduate School (NPS). For example, this year the Brown University site developed the SoFT (Software Framework for Tele-Immersion) system jointly with NPS. The Center's tele-immersion work is also sponsored by Intel and DARPA.

Center researchers are working in advisory or consulting capacities with a number of companies, including the Center for Complex Systems and Visualization, Bremen, Germany; the Fraunhofer Center for Research in Computer Graphics, Providence, RI; Lightscape Technologies Inc., San Jose, CA; Mixed Realities, Yokohama, Japan; Raycer Graphics, Palo Alto, CA; and Wholly Light Graphics, Jerusalem, Israel. Center PIs also hold positions on the technical advisory boards of Raycer Graphics and Microsoft Research. A former Center Director is Chairman of the Board of Turbine Entertainment Software, Westwood, MA, and on the Board of Directors and Technical Advisory Board of Synomics Ltd., Cambridge, UK, as well as the Fraunhofer Center for Research in Computer Graphics (CRCG). He is also on the Board of Trustees of AT Cross, Providence, RI, and is a Trustee of the Rhode Island School of Design (RISD).

Center members are part of a MURI grant to develop the mathematical infrastructure for robust virtual engineering. The primary goal of this interdisciplinary grant is to develop mathematical and computational methods to integrate diverse approaches to modeling and simulating systems of rigid, flexible, fluid, and heterogeneous interacting objects. This MURI program proposal includes collaborative relationships with AFOSR and among the university researchers and DoD personnel. DARPA is continuing to fund aspects of the Office of the Future project.

Center PIs have recently served on several government boards, including the NSF CISE Advisory Committee, the advisory committee on Data and Visualization Corridors for the DOE ASCII Program, and the National Research Council CSTB Information Technology literacy committee.

4.B Academic Outreach and Education

A Workshop on Rendering, Perception, and Measurement was held at the Cornell site from April 8-10, 1999. The event was attended by approximately 125 people, including 20 speakers and 45 graduate students. Five people attended from government agencies and labs, 16 from industry, and the balance from academia. Nine countries were represented, with 19 attendees in all from outside the U.S. The workshop was co-sponsored by NSF's Division of Advanced Computational Infrastructure and Research, ACM-SIGGRAPH, and by the Center. This joint sponsorship enabled generous subsidy of the event for students and international attendees. The format of the workshop provided six primary sessions on topics central to current research in rendering and the closely related fields of perception and measurement. Many additional opportunities were provided for small group interaction over the three days of the workshop, including breakout sessions on image-based rendering, perception, global illumination, and measurement. The workshop also included a tour of the Program of Computer Graphics at Cornell. Slides from all the talks at the workshop are available online at http://www.graphics.cornell.edu/workshop (or through the Center's resource pages).

As usual, Center personnel were contributors to many conferences during the year. Highlights include SIGGRAPH 99 participation in 15 papers, four courses, two Electronic Schoolhouse venues, five panels, a technical sketch, the Web3D Roundup, five images in the technical slides set, participation in the Millenium Motel, and work in the Computer Applications Laboratory. Don Greenberg gave the keynote talk at the Eurographics Rendering Workshop in Seville, Spain in June 1999. Recent Cornell Ph.D. Stephen Marschner also presented a paper at the workshop, "Image-Based BRDF Acquisition Including Human Skin," co-authored with Center personnel Steven Westin, Eric Lafortune, Ken Torrance, and Don Greenberg. Ken Torrance gave an invited talk on "A Framework for Realistic Image Synthesis" at the IEEE Computer Society Conference on Computer Vision and Pattern Recognition in Fort Collins, Colorado, in June 1999. Andy van Dam presented the keynote talk at the IFIP International Working Conference on Building University Electronic Educational Environments held at the University of California at Irvine. Van Dam was also co-chair of the First Joint European Commission/National Science Foundation Advanced Research Workshop. He ran a workshop at that venue and was co-author of the final report: "Human-Centered Computing, Online Communities and Virtual Environments."

A symposium entitled "The Computer, The Academy, and The World" was held in Providence, RI on the occasion of former Center Director Andy van Dam's 60th birthday. Former students and others involved in Andy's career gave two days of talks on areas related to Andy's research, such as hypertext (for example Steve DeRose's talk, "The World-wide Web and the Past and Future of Hypertext") and the use of computers in education (for example, Raj Reddy's talk, "Technologies for Learning"). Many Center personnel and all but one PI attended the event. Center themes were well represented in Henry Fuch's talk about "The Office of the Future."

UNC hosted a professor, W. Brent Seales, and a graduate student, Michael S. Brown, from the University of Kentucky. Both have contributed greatly to the telecollaboration work going on at UNC, and have co-authored several papers with UNC colleagues.

4.C International Activities

Don Greenberg gave the keynote talk at the Eurographics Rendering Workshop described above. Cornell has also provided the University of Bristol in the UK reflectance measurements of paint samples for the purpose of studying in detail the perceptual equivalence of a real and a very accurately modeled virtual scene. These measurements are also being made available with the Cornell archive of date from the Light Measurement Lab at http://www.graphics.cornell.edu/research/measure (or through the Center's resource page). The Cornell site hosted two postdocs from the Catholic University of Leuven, Belgium (Eric Lafortune and Philip Dutre). The Caltech site has an international collaboration with a Ph.D. student, Gilles Debunne, and his advisor, Marie-Paul Cani, both of the Joseph Fourier University in Grenoble, France. The Center has also continued its multi-site collaboration with the Fraunhofer CRCG on the tele-immersion project.

4.D Resource Distribution

In keeping with our philosophy of sharing knowledge, we have made software and educational resources available over the Internet. These range from programming environments for scientific visualization to VR libraries to the exact dimensions and material properties of the “Cornell Box.” Space precludes a full listing but all the Center’s on-line software can be accessed from:

http://www.cs.brown.edu/stc/outrea/community.html#software

The Center has also created special “resource” Web pages to more effectively guide researchers and educators to the Center many resources

http://www.cs.brown.edu/stc/resources/home.html

5. Shared Experimental Facilities

The Center structure allows sharing of unique facilities and resources among the sites and with the graphics community. These shared facilities have often provided a basis for collaborative work between Center sites.

Televideo Infrastructure

The Center has upgraded its televideo infrastructure with new televideo codecs at each site and a new Master Control Unit (MCU) at UNC. The new equipment is easier for non-experts to use, is more reliable than the previous equipment, and allows new capabilities, such as people at two locations speaking at the same time. The new equipment has aided the telecollaborative research initiative as well as provided a basis for a new phase of the televideo lecture series, with invited guest lecturers speaking over the televideo.

Advanced Manufacturing Lab

Utah's advanced manufacturing lab (AML) has been involved in several collaborative projects. In the Sketch-N-Make project (see **Telecollaboration - Sketch-N-Make**), the lab was used as a test facility for validating the sketching approach. In the Camera Cluster project, the AML is being used as a rapid prototyping facility. Similarly, the AML is used to rapidly prototype concepts for the face-to-face display. Without access to this facility, these projects might not have been even attempted.

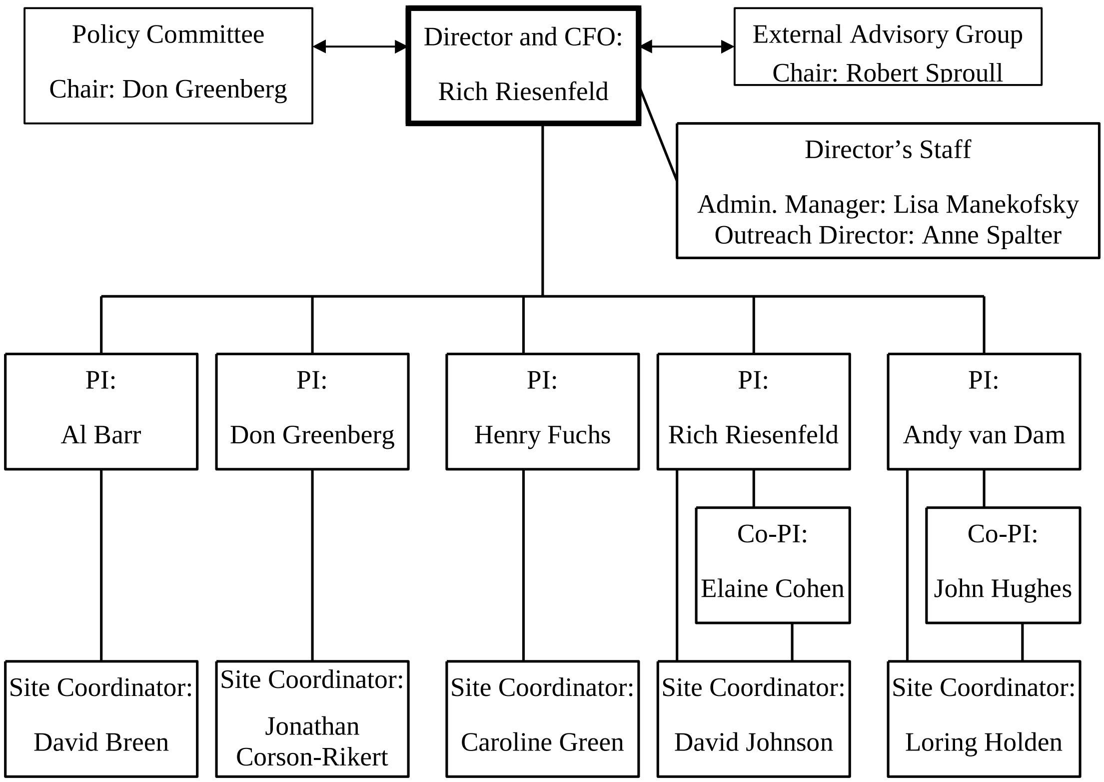
The Cornell Light Measurement Lab

We have measured a set of materials and made the light source spectra, filter and lens transmission spectra, and full bidirectional reflectance distribution functions (BRDF's) available to the research community. They represent a valuable resource for developing and validating reflectance models and rendering techniques. The data and some rendered images can be found at

http://www.graphics.cornell.edu/online/measurements/

6. Administration and Management

6.A Organization Chart



There have been no changes in the Center's organizational structure during this reporting period. We do not plan any changes for the request award year.

6.B Director's Narrative

Reflecting back over the past year, I feel a true sense of pride and accomplishment at the progress of the Center. Just to cite some representative successes:

- Center papers made up almost one third of the SIGGRAPH 99 proceedings, plus Center personnel were involved in numerous panels, sketches, and demonstrations.
- Center personnel gave keynote speeches and invited papers at several national and international conferences and workshops.
- Our collaborative research projects are fruitful, resulting in a number of conference papers and stimulating new research projects. These continue to serve as the focus for the Director's Reserve funding, and have produced highly encouraging results.
- The televideo link among the Center sites has been upgraded with new capabilities and continues to be an increasingly vital component of our collaborations.

As the numerous external reviews in our history have underscored, the STC is home for excellent science and researchers. Regardless, good science is not to be taken for granted even if it has come to be expected of us. As Director I must be especially vigilant in asking the question of what has the Center done collectively that might not have happened without it. What has the Center, per se, facilitated? Surely good science would have been accomplished by our researchers even without the presence of the Center. However, I am especially pleased to see the focus of the Center has remained principally on long term, fundamental issues. In this respect I believe that the STC has been important in encouraging research in hard problems that require sustained concentration and support.

We have been encouraged, even pressured at times, to increase our collaborative activities across sites. For many understandable reasons this did not come about naturally or quickly. Even with some external urging, it took time for this aspect of the Center to develop more fully. However, during the past year, I feel that we have achieved this goal to a remarkably comfortable degree. We have achieved a realistic level of understanding about each other, so that we undertake ambitious goals that have good likelihood of success. Our expectations are high, but tempered with realism. In short, we have learned to work with each other in a productive and complementary fashion. The level of regular intersite, meaningful collaboration is at a high. I feel we have grown individually and collectively to get to this position.

As we see the world shrink with increasing digital communications capacity, I feel validated in thinking that our STC is an important early experiment in the collaborative form that research will increasing take on in the future. Now that we have struggled through so many basic difficulties and finally arrived at a stage of development where we collaborate with comfort and pleasure over vast distances to reinforce our strengths and visions, I feel encouraged to think that our experience has value beyond the internal scope of our Center. In fact, our recent cultural and financial NSF audit further indicated that our family history has lessons to benefit others interested in related experiments. During the past year we have arrived at the point where we can unhypocritically offer our experiences to others who may be just embarking on similar journeys.

Outreach continues to be a vigorous program that takes on quite different forms at each site. We continue to use the network whenever we can to augment our outreach program's effectiveness. In our concluding phase, I have been shifting emphasis toward activities that will have more lasting value and contribute to the impact of the Center on the community at large. I am especially interested in promoting educational resource materials and developing our website as a hub that will be frequently visited by educators in computer graphics. In this spirit, we are collecting a growing set of applets that succinctly demonstrate significant graphics principles. In general, we are shifting toward efforts that will leave a legacy upon which educators can draw.

The lecture series is also taking a somewhat different form this year. We are going outside of the Center for approximately half of our lectures. This will bring in new faces, new perspectives, and contribute to the focus improving the connection between the Center and the outside community. While we have made a significant scientific impact, we are now intent on making a larger cultural, professional, educational, and social impact on our field. Given the dynamic and intense nature of our field and its enormous scope and size, it is a remaining challenge to accomplish this.

On the one hand, the Center is enjoying a high level of effectiveness in its operations due to its development and learning experiences. That is gratifying. On the other hand, as we prepare diminishing budgets for year 10 we are directly faced with the chilling fact that support for the STC is in it concluding years. We are entering the final phase. At this point we must also engage ourselves in a coldly objective fashion to self-evaluate what has worked. We now must ask what activity and relationships we want to use as a core for our next funding incarnation.

6.C Center Advisors - the External Advisory Group

• Dr. Norman Badler, Professor, CIS and Director

University of Pennsylvania Center for Human Modeling and Simulation

• Dr. Ingrid Carlbom, Head of Image Synthesis and Recognition Research Department

Bell Laboratories, Lucent Technologies

• Dr. Donald Gaubatz, Consultant/Investor

Multimedia/ATM Networking, Microprocessor Report Editorial Board

• Dr. Roscoe Giles, Associate Professor

Boston University Department of Electrical and Computer Engineering

Director, Center for Computational Science, Boston University

• Dr. Evelyn Hu, Professor

University of California Department of Electrical and Computer Engineering

Director, NSF STC for Quantized Electronic Structures (QUEST)

• Dr. Robert Sproull, VP & Fellow

Sun Microsystems Laboratories

• Dr. James J. Thomas, Chief Scientist

Information Sciences Department, Pacific Northwest National Laboratory

• Dr. Michael Wozny, Professor

Department of Electrical & Computer Systems Engineering, Rensselaer Polytechnic Institute

7. Budget

The budgetary information follows this page.

8. Appendices

8.A Publications

A.1 Publications benefiting from Center support:

[bree99a] David Breen, Sean Mauch and Ross Whitaker, “3D scan conversion of CSG models into distance volumes,” Proceedings of the 1998 Symposium on Volume Visualization, ACM SIGGRAPH, October 1998, pp. 7-14.

[bree99b] David Breen and Sean Mauch, “Generating shaded offset surfaces with distance, closest-point and color volumes,” Proceedings of the International Workshop on Volume Graphics, March 1999, pp. 307-320.

[chen99] Min Chen, “Perturbation Methods for Image Synthesis” M.S.thesis, Caltech, May 1999,

[cohe99] J.M. Cohen, L. Markosian, R.C. Zeleznik, J.H. Hughes, and R. Barzel, "An Interface for Sketching 3D Curves," Proceedings of 1999 Symposium on Interactive 3D Graphics, ACM SIGGRAPH, pp. 17-22.

[desb99a] Mathieu Desbrun, Mark Meyer, Peter Schroeder, and Alan Barr, “Implicit fairing of irregular meshes using diffusion and curvature flow,” Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 317-324.

[desb99b] Mathieu Desbrun, Peter Schroeder and Alan Barr, “Interactive animation of structured deformable objects," Proceedings of Graphics Interface '99, June 1999, pp. 1-8.

[gooc99] Bruce Gooch, Peter-Pike J. Sloan, Amy Gooch, Peter Shirley, and Richard Riesenfeld, “Interactive Technical Illustraion,” Proceedings of 1999 Symposium on Interactive 3D Graphics, ACM SIGGRAPH, pp. 31-38.

[goul99] D.L. Gould, R.M. Simpson, and A. van Dam, "Granularity in the Design of Interactive Illustrations," Proceedings of SigCSE '99, ACM SigCSE, pp. 306-310.

[gree99] Donald P. Greenberg, “A Framework for Realistic Image Synthesis,” Communications of the ACM, Volume 42, No. 8, August, 1999, pp. 44-53.

[hart99] David Hart, Philip Dutré, and Donald P. Greenberg, “Direct Illumination with Lazy Visibility Evaluation,” Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 147-154.

[john99a] David E. Johnson, Thompson V. Thompson II, Matthew Kaplan, Donald Nelson, and Elaine Cohen, “Painting Textures with a Haptic Interface,” Proceedings of IEEE Virtual Reality'99, March, 1999, pp. 282-285.

[john99b] David E. Johnson, Elaine Cohen, “Bound Coherence for Minimum Distance Computations,” Proceedings of IEEE International Conference on Robotics and Automation, Detroit, MI. May 10-15, 1999. pp. 1843-1848.

[kowa99] Michael A. Kowalski, Lee Markosian, J.D. Northrup, Lubomir Bourdev, Ronen Barzel, Loring Holden, and John F. Hughes, “Art-Based Rendering of Fur, Grass, and Tree,” Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 433-438.

[lavi99] J. LaViola and R. Zeleznik, “Flex and Pinch: A Case Study of Whole Hand Input Design for Virtual Environment Interaction,” To appear in IASTED International Conference on Computer Graphics and Imaging, 1999.

[mark99] L. Markosian, J.M. Cohen, T. Crulli, T., and J.F. Hughes, "Skin: A Constructive Approach to Modeling Free-Form Shapes," Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 393-400.

[mars99] Stephen R. Marschner, Stephen H. Westin, Eric P. F. Lafortune, Kenneth E. Torrance, and Donald P. Greenberg, “Image-based BRDF Measurement Including Human Skin,” in D. Lischinski, G.W. Larson (eds.), Rendering Techniques ’99, Proceedings of the Eurographics Workshop in Granada, Spain, June 21-23, 1999, pp. 130-144.

[meen99] Gopi Meenakshisundaram**. “**A Fast and Efficient Projection Based Approach for Surface Reconstruction,” Technical Report TR99-023, Department of Computer Science, University of North Carolina at Chapel Hill.

[meye99] Mark Meyer and Alan Barr, “ALCOVE: Design and implementation of an object-centric virtual environment," Proceedings of the IEEE Virtual Reality ’99, pp. 46-52.

[mill99] T.S. Miller and R.C. Zeleznik, "The Design of 3D Haptic Widgets," Proceedings of 1999 Symposium on Interactive 3D Graphics. ACM SIGGRAPH, pp. 97-102.

[nels99a] Donald Nelson and Elaine Cohen, “Interactive Mechanical Design Variation for Haptics and CAD,” Accepted at EUROGRAPHICS 99, September, 1999.

[nels99b] Donald S. Nelson, David E. Johnson, and Elaine Cohen, “Haptic Rendering of Surface-to-Surface Sculpted Model Interaction,” to appear in Proceedings 8th Annual Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems, November, 1999.

[patt98] Sumanta N. Pattanaik, Mark D. Fairchild, James A. Ferwerda, and Donald P. Greenberg, “Multiscale Model of Adaptation, Spatial Vision and Color Appearance,” Proceedings of the Sixth Color Imaging Conference, Society for Imaging Science and Technology, November 1998, pp. 2-7.

[pree99] A.J. Preetham, Peter Shirley, and Brian Smits, “A Practical Analytic Model for Daylight,” Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 91-100.

[rama99] Mahesh Ramasubramanian, Sumanta N. Pattanaik, and Donald P. Greenberg, “A Perceptually Based Physical Error Metric for Realistic Image Synthesis,” Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 73-82.

[rask99a] Ramesh Raskar, Michael S. Brown, Ruigang Yang, Wei-Chao Chen, Greg Welch, Herman Towles, Brent Seales, and Henry Fuchs, **“**Multi-Projector Displays Using Camera-Based Registration**,"** To appear in Proceedings of IEEE Visualization 99, October 24-29, 1999

[rask99b] Ramesh Raskar and Michael Cohen, “Image Precision Silhouette Edges,” Proceedings of Symposium on Interactive 3D Graphics, April 1999, pp. 135-140.

[rask99c] Ramesh Raskar, Greg Welch, and Wei-Chao Chen, **"**Table-Top Spatially-Augmented Reality: Bringing Physical Models to Life with Projected Imagery**,"** To appear in Proceedings of Second International Workshop on Augmented Reality (IWAR'98), October 20-21, 1999.

[rask99d] Ramesh Raskar, Greg Welch, and Henry Fuchs, “Seamless Projection Overlaps using Image Warping and Intensity Blending**,”** Proceedings of 4th Annual Conference on Visual Systems and Multimedia, November 18-20, 1998.

[rask99e] Ramesh Raskar, Greg Welch, and Henry Fuchs, "Spatially Augmented Reality," Proceedings of First IEEE Workshop on Augmented Reality, November 1, 1998.

[seal99] Brent Seales, Greg Welch, and Chris Jaynes, "Real-Time Depth Warping for 3-D Scene Reconstruction**,"** Proceedings of 1999 IEEE Aerospace Conference, March 6-13 1999.

[star99] Michael M. Stark, Elaine Cohen, Tom Lyche, and Richard F. Riesenfeld, "Computing Exact Shadow Irradiance Using Splines," Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 155-164.

[thom99a] Thomas V. Thompson II, and Elaine Cohen, "Direct Haptic Rendering Of Complex Trimmed NURBS Models," to appear in Proceedings of the 8th Annual Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems, November, 1999.

[yang99] Ruigang Yang, Michael Brown, Brent Seales, and Henry Fuchs, "Geomterically Correct Imagery for Teleconferencing," to appear in proceedings of ACM Multimedia 99, November 1999.

[zele99] R.C. Zeleznik and A.S. Forsberg, "UniCam - 2D Gestural Camera Controls for 3D Environments," Proceedings of 1999 Symposium on Interactive 3D Graphics, ACM SIGGRAPH, pp. 169-173.

A.2 Publications benefiting from shared facilities:

[alia99] Daniel G. Aliaga and Anselmo Lastra, "Automatic Image Placement to Provide a Guaranteed Frame Rate," Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 307-316.

[arvo99] James Arvo, "Computer aided serendipity: The role of autonomous assistants in problem solving," Proceedings of Graphics Interface '99, June 1999, pp. 183-192.

[bast99] Rui Bastos, Kenneth Hoff, Willliam Wynn, and Anselmo Lastra, "Increased Photorealism for Interactive Architectural Walkthroughs," Proceedings, Symposium on Interactive 3D Graphics, 1999, ACM SIGGRAPH, pp. 183-190.

[chan99] Chun-Fa Chang, Gary Bishop, and Anselmo Lastra, "LDI Tree: A Hierarchical Representation for Image-based Rendering," Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 291-297.

[kirb99] R. Michael Kirby, H. Marmanis, and D.H. Laidlaw, "Visualizing Multivalued Data from 2D Incompressible Flows Using Concepts from Painting", Visualization '99 Proceedings, October 1999.

[laid99a] David Laidlaw, "Continuous Bayesian tissue classification," in C. Bajaj (Ed.), Data Visualization Techniques, J. Wiley & Sons, Chichester, UK, 1999, pp. 107-129.

[laid99b] D.H. Laidlaw, K.L. Cook, and Y.M. Goldfeld, "Evaluating Effects of Diffusion Weighting Choice on Accuracy of Diffusion Tensor MRI of Fixed Mouse Spinal Cord," Proceedings of the 7th International Society for MR in Medicine, May, 1999.

[laid99c] D.H. Laidlaw and J.M. Tyszka, "A Demonstration of Errors in Relative Pressure Calculations from MR Velocity Data," Proceedings of the 7th International Society for MR in Medicine, May, 1999.

[nyla99] Lars Nyland, David McAllister, Voicu Popescu, Chris McCue, Anselmo Lastra, Paul Rademacher, Manuel Oliveira, Gary Bishop, Gopi Meenakshisundaram, Matt Cutts, and Henry Fuchs, "The Impact

of Range Data on Computer Graphics," Proceedings of Multi-View Modeling and Analysis Workshop (MVIEW99), pp 3-10.

[oliv99] Manuel M. Oliveira and Gary Bishop, "Image-Based Objects," Proceedings of the 1999 Symposium on Interactive 3D Graphics, ACM SIGGRAPH, pp. 191-198.

[poll99] N. Pollard, "Simple Machines for Scaling Human Movement," Proceedings of the Eurographics Workshop on Computer Animation and Simulation, September, 1999.

[rade99] Paul Rademacher, "View-Dependent Geometry," Computer Graphics Proceedings, Annual Conference Series, 1999, ACM SIGGRAPH, pp. 439-446.

[smit99] Steve Smithies, Kevin Novins and James Arvo, "A handwriting-based equation editor," Proceedings of Graphics Interface '99, June 1999, pp. 84-91.

8.B Graduates During the Reporting Period

Graduate's Name	MS/PhD	Industry/Academia
Eric Lafortune	PhD	Industry
Mark A. Livingston	PhD	Industry (HP Labs)
Dom Bhuphaibool	MS	Industry (Pulse Entertainment)
Mark Bloomenthal	MS	Academia (U of Utah)
Min Chen	MS	Academia (Caltech)
Jessica Crawford	MS	Academia (UNC-CH)
Caroline Dahllof	MS	Industry (Electric Image)
Dan Gelb	MS	Industry
David Hart	MS	Academia
Michael Kawolski	MS	Industry (ART Media Integration and Communications Research Laboratories))
Adam Lake	MS	Industry (Intel)
Gopi Meenakshisundaram	MS	Academia (UNC-CH)
Jeff Pickering	MS	Industry (Soundsbig.com)
Arcot Preetham	MS	Industry (Evans and Sutherland, UT)
Mahesh Ramasubramanian	MS	Industry
Steven Skolne	MS	Academia (Caltech)
Corey Toler	MS	Other

Jeff White	MS	Industry (go2net)
Audrey Wong	MS	Industry (Pixar)
Eric Wong	MS	Industry
Ellen Scher Zagier	MS	

8.C List of Center Participants (Faculty Level and Equivalent)

Receiving Center Support (Not Necessarily Salary Support):

Alan Barr

David Breen

Elaine Cohen

Thomas Doeppner

Sam Drake

Don Greenberg

Henry Fuchs

Chuck Hansen

John Hughes

Chris Johnson

Rich Riesenfeld

Brent Seales

Peter Schroeder

Peter Shirley,

Brian Smits

Kenneth Torrance

Herman Towles

Andries van Dam

Greg Welch

Affiliated, (Not Receiving Center Support)

James Arvo

Gary Bishop

Fred Brooks

Mathieu Desbrun

David Hanscom

David Laidlaw

Robert McDermott

Nancy Pollard

User of Shared Center Facilities

Nick England

John Hollerbach

Anselmo Lastra

Lars Nyland

John Poulton

8.D Biographical Information for New Investigators

There are no new investigators to report.

8.E Awards and Honors

James Arvo was named an Okawa Fellow and received an NSF Career Award in 1999.

Gopi Meenakshisundaram (UNC) was awarded a Link fellowship.

Peter Schroeder was named a Packard Fellow in Fall 1998.

Andries van Dam was awarded an IEEE James H. Mulligan, Jr. Education Medal.

Best Panel Award, Visualization '98 Proceedings - "Art and Visualization: Oil and Water?" with David Kremers, Felice Frankel, Victoria Interrante, and Thomas F. Banchoff (October 1998).

8.F Summary of External Advisory Group Meetings

On December 10, 1998, the Center held an External Advisory Group (EAG) meeting in Boston.

F.1 Attendees

Members of the EAG

Norman Badler, Ingrid Carlbom, Don Gaubatz, Roscoe Giles, Bob Sproull, Jim Thomas, Michael Wozny (Evelyn Hu was unable to attend due to a prior commitment).

STC PIs, Co-PIs, and Faculty

Al Barr, Elaine Cohen, Henry Fuchs, Don Greenberg, John Hughes, David Laidlaw, Nancy Pollard, Rich Riesenfeld, Andy van Dam

Site Coordinators and other STC Staff

David Breen, Jonathan Corson-Rikert, Caroline Green, Loring Holden, Lisa Manekofsky, Anne Morgan Spalter, Mark Oribello

F.2 Meeting Notes

The meeting began with an overview from Rich Riesenfeld, who had become Center Director a few months earlier as a result of a rotation of Directors (as discussed in last year's annual report). Rich explained his vision for the Center's final three years, which included thinking about the legacy of the Center. Following this were short presentations showing the current state of the work in our core research areas. Anne Spalter then gave a presentation on Center Outreach efforts.

The afternoon was devoted to getting feedback from the EAG. They approved of Rich's plans for the future and probed for more information. The EAG then offered further suggestions regarding thinking about the remaining years of the Center. The participants also discussed contributions the Center can make to the field of computer graphics, contributions that will outlive the STC. The EAG cautioned against waiting too long to begin implementing new efforts. Finally, the Group stated their continued willingness to help the Center participants as we charted a new course for the future.

8.G Continuing and Pending Support

Continuing and Pending Support pages follow this page.