The Symbiotic Relationship Between Computer Graphics and Colour Imaging

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Abstract

Our goal is to develop physically based lighting models and perceptually based rendering procedures for computer graphics that will allow synthetic images to be generated that are visually and measurably indistinct from real-world images. The research implies the symbiotic relationship which could exist between computer graphics and digital imaging. This presentation describes how work at Cornell's Program of Computer Graphics is attempting to achieve this goal.

Introduction

From its infancy in the 1960's computer graphics images have improved at fantastic rates. The original renderings of simple environments with direct lighting only have been transformed into pictures of complex scenes with shadows, shading, and global interreflections.

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For several decades now, high quality simulations have been used for a large number of tasks such as pilot training and military applications, automotive design, and architectural walkthroughs.[1] Today, certainly virtual reality games and the entertainment industry use the convincing imagery with great success.

But are these images correct? Would they accurately represent the scene if the environment actually existed? In general, the answer is no; yet the results are appealing because the resulting images are believable.

If we could generate simulations that were guaranteed to be correct, that the algorithms and resulting pictures were accurate representations, then the simulations could be used in a *predictive* manner. This would be a major paradigm shift for the computer graphics industry, but would have much broader applicability than just picture making.

A look at how accurate simulations are used in other areas might clarify this point. The entire electronics industry is now based on simulations for chip design; these are automatically used for testing and modifications prior to fabrication. In color science, we utilize the response matching function for our color transformations without recreating the matching experiments. Why can't we use computer graphics algorithms for the testing and development of printing technologies, digital photography, or display devices? Why can't these accurate but artificial scenes be used for algorithmic development in image processing, robotics and machine vision? If we knew the simulated images were correct, we could easily control and isolate the variables, obtain any resolution desired, and avoid the pitfalls of experimental measurements. We could also reduce design cycle time.

The reason this has not been done in the past is that there has been very little work done in correlating real scenes to the results of computer graphics simulations. However, now with more accurate image acquisition and measurement devices, and the economic availability of large amounts of computer processing power, these goals are achievable.

Let me specifically describe some of the current research being conducted at Cornell University's Program of Computer Graphics. We are part of a five university consortium which has been fortunate to have received funding from the National Science Foundation for the establishment of a Science and Technology Center for Computer Graphics and Scientific Visualization. This long term sponsorship has allowed us to embark on an eleven year mission to help improve the foundations of computer graphics for the next generation of computing. Cornell's role has been to develop graphics algorithms which are physically and perceptually indistinct from real world scenes. In general terms, our methodology is as follows.

The process starts with the physical definition of the light sources and the reflection/absorption characteristics of all of the surfaces in the simulated scene. Of course, all of the exact geometry must also be known. The light source descriptions include the spatial and spectral characteristics of each emitting source, including its geometry, goniometric diagram, and the spectral distribution of the illuminant on a wavelength basis.

A comprehensive model of how light scatters when it strikes a surface has now been developed.[2,3] The model includes surface and subsurface scattering, and can be extended to polarized light. The resulting bi-directional reflectance distribution function (BRDF) is a function of the wavelength, surface roughness properties, and the incoming and outgoing directions. The BRDF correctly predicts the diffuse, directional diffuse, and specular components of the reflected light. (Figure 1)

To validate the reflection model, we have created a Light Measurement Laboratory to quantitatively measure the light source characteristics, as well as provide experimental BRDF's in absolute and relative radiometric units. Through this simulation/measurement process we have been able to verify the model's accuracy. Accurately repre-

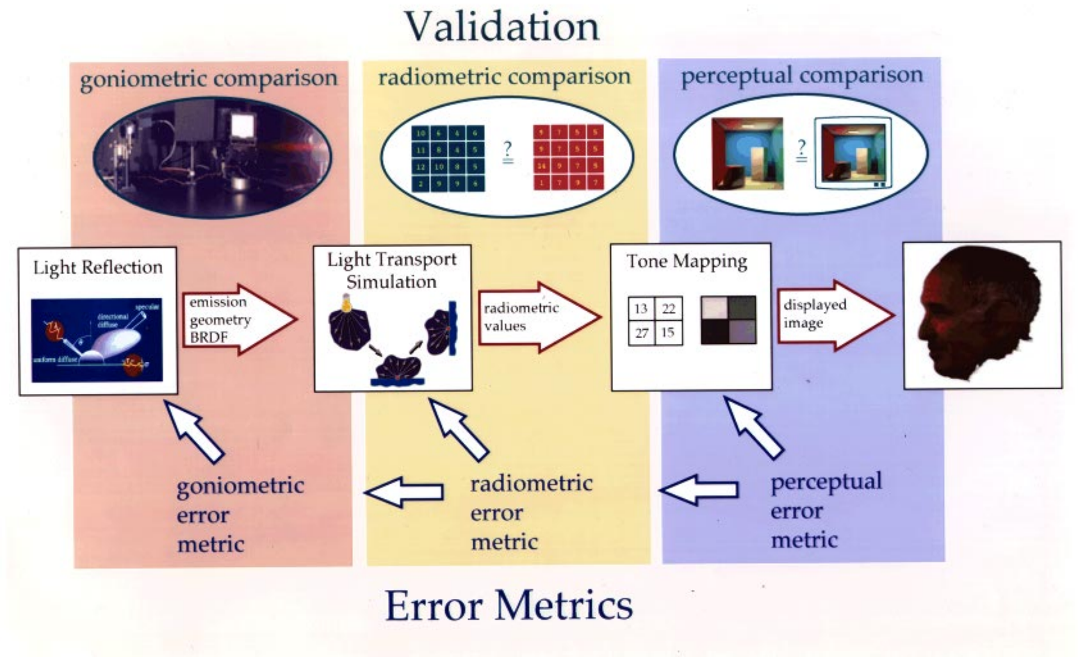

Figure 1.

senting the complex reflection behavior requires many mathematical terms, either as spherical harmonics, wavelets, or a mathematical series. Depending on the level of representation, we can predict the maximum error bounds.

Once the emission, geometry, and reflection functions (BRDF's) are known, we can then simulate the light transport. The general equations have been well known, but until recently neither the processing power nor the accurate reflection model was available to perform accurate simulations.[4]

In real scenes, all surfaces have the capability for interacting with each other. Thus, solving the equations for the incident light distribution on each surface of a complex environment is very computationally expensive. For these reasons, most algorithms make many simplifying assumptions, yet still produce images of startling quality and realism. The two most common methods used are ray-tracing, introduced to the graphics community in 1979[5] and radiosity, first presented five years later.[6] Neither of these commonly used algorithms are exact, each neglecting various and significant mechanisms of light transport. Both methods produce photorealistic images.

The more exact solutions can be obtained by finite element techniques (radiosity) but since the simulations are really boundary element problems with far-field interactions, and fine meshes are required for high visual resolution, the resulting matrices are both large and dense. Thus, we are now using statistical techniques (Monte Carlo), to obtain our solutions.[7] The algorithms are quite simple, and easily parallelized, but require the "shooting" of millions of photons to obtain satisfactory results with known error bounds. Once our simulations are completed, a complete view-dependent description of the radiance of all surfaces is known. Note that at this stage we have not yet created a computer graphics image, but only computed the radiometry of the scene.

To validate the simulation of the light transport, we create an image plane and determine the radiant energy reaching this plane. Assuming we have accurately built and measured a physical test environment, we can then experimentally measure and compare the results of the simulation using a carefully calibrated, high resolution, liquid cooled CCD camera with the same image plane. As shown in Figure 1, this simulation/measurement paradigm allows us to not only tune the global illumination transport algorithm, but provide feedback on the accuracy required for representing the light reflection model from the first phase.

I wish to emphasize the fact that the first two phases of this process represent the *physical simulation* only, the comparisons are radiometric, and a picture has not yet been created.

Producing an image implies that we are moving to the *perceptual* domain. Global illumination algorithms accurately simulate scene luminances, but do not specify how to display them for realistic visual appearance. Display and printing devices and media are limited in dynamic range and color gamut whereas simulations can be unbounded. Ambient lighting conditions significantly effect the human perception of a scene. It is necessary to develop perceptually correct mappings from scene luminances to display luminances so that all important aspects of visual appearances are maintained. If possible, the results in the perceptual domain can also be predictive. By developing models of visual perception, and producing images that accurately predict the visual appearance of scenes under different viewing conditions, the simulations can be used for illumination engineering, ergonomic and safety design. Furthermore, by simulating scenes under adverse conditions, we can perhaps reduce impediments to the aged or visually impaired or improve conditions for navigation or night driving.

We have just begun work in this area, initially with some simplified models of glare and adaptation.[8,9] This year, in our facility, we are installing a perception laboratory to study these effects.

One major goal of this research is to reduce the computational expense of the global illumination algorithms. An inherent cause of the slowness of these algorithms is that an excessive amount of time is spent computing scene features that are measurably unimportant and perceptually below the visible threshold of the average human observer. Algorithms could be substantially accelerated if we can develop perceptually-based error metrics that correctly predict the visibility of scene features. The establishment of these techniques will not only allow proper tone mappings, but provide the feedback loop for modifying the physical computations. (Figure 1)

We believe that by separating the physically based computations from the perceptually based image creation, and by experimentally comparing results at each phase of the process, we can ultimately produce images that are visually and measurably indistinct from real world images.

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