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COURSE NOTES

21 RADIOSITY

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I. INTRODUCTION

Course Chair: Dr. Donald P. Greenberg

During the past twenty years, computer graphics techniques for simulating the reflection of light have progressed so that today images of photorealistic quality can be produced quite efficiently. (Figures I-1, I-2, I-3, I-4) Early algorithms considered direct lighting only, but global illumination phenomena with indirect lighting, surface interreflections, and shadows can now be modeled using ray tracing, radiosity and Monte Carlo simulations. *This tutorial describes the radiosity method and how it has evolved in computer graphics during the last six years.*

Today almost all computer manufacturers offer workstation platforms with graphics software and hardware to render objects directly illuminated by light sources. Object surface characteristics can be diffuse and specular, and polygons can be rendered with flat shading, linearly-interpolated shading [GOUR71] or with highlighting [PHON75]. Although the speed and number of surfaces which can be processed is impressive, the resulting displays are still easily recognized as computer simulations. The primary reason is that with the exception of the constant ambient term, the computer renderings described do not consider the effect of the intra-environment surroundings. In real scenes, the lighting and reflections are far more complicated and subtle. Every surface receives light *directly* from light sources, or *indirectly* from reflections off of neighboring surfaces. The indirect lighting is frequently called the ``global illumination". This phenomena is very difficult to model accurately, but for realistic image generation, these global effects must be modeled in great detail.

In essence, realistic simulations depend on the local reflection model at each surface, a model which defines the outgoing intensities in any direction as a function of the incoming energy, the global illumination, from all directions. Details of local reflection models and global illumination are discussed in Section II.

During the past few years, two tractable, but restrictive methods have become popular, ray tracing and radiosity. Both methods provide limited global illumination effects, but produce very realistic images. In ray tracing, which is particularly appropriate for specular environments, the discretization and sampling step occurs at the image plane, and the results are *view-dependent*. In the radiosity approach, which is excellent for diffuse scenes, the environment is discretized, and the results are *view-independent* .

The standard radiosity procedure for image generation is based on methods from thermal engineering, and is applicable to environments composed of ideal diffuse emitters and reflectors. Surface intensities are determined by accounting for the energy directly received from the light sources and indirectly reflected from other surfaces. To accomplish this, form factors are computed which describe the geometrical relationship between any two surfaces based on the shape, area, and orientation of each surface, the distance between them, and the portion of each surface visible to the other. By taking into account occluding surfaces, complex environments can be accurately modeled.

The introduction of the radiosity method has led to a complete decoupling of the light reflection simulation from the final image rendering. That is, once the solution is obtained, the illumination of each surface can be treated as part of the model and subsequently used for multiple views. Since only the rendering process has to be repeated for each image, and this part of the standard graphics pipeline is now executed in hardware on many graphics workstations, dynamic sequences can be displayed. Furthermore, the inclusion of all elements of the environment in calculating the global illumination effects yields more accurate solutions than those previously achieved. The phenomena of "color bleeding" from one surface to another, variable shading within shadow envelopes, the effect of area light sources, and penumbra effects along shadow boundaries can all be reproduced.

The most time-consuming portion of the radiosity procedure is the calculation of the form-factors which describe the fraction of energy leaving one surface and arriving at another. One tractable method to account for environments which include occluded surfaces is the hemi-cube approach. By using an ordered sampling at regular discrete intervals, similar to scan-conversion algorithms, computations can be accelerated or even implemented in hardware.

However, sampling problems inherent in the hemicube algorithm limit its usefulness for very detailed environments. A more accurate approach is to use ray-tracing to perform the numerical integration of the form-factor equation. Exact geometries can be used, for the shadow testing, and small elements can be accounted for, reducing the aliasing problems.

Details of the basic radiosity formulation including both of the currently used algorithms for form-factor computation, as well as their limitations, are described in Section III.

For all of the radiosity methods, to reduce the computational expense without sacrificing image quality, a two-level adaptive subdivision approach has been formulated. First, surfaces are divided into patches and a coarse patch solution, where the patches act as light sources and reflectors, is obtained. Then the environment can be sampled by further subdivision into elements. The elements act as receivers of the light from the coarse patch solution, and provide the sample values for the final rendering process. The advantage is that the element subdivision can be continued adaptively as high radiosity gradients are discovered without recomputing the patch radiosities. Effectively, this means that the picture quality improves by sampling the environment in areas where the changes are the greatest. These techniques for adaptive subdivision are also presented in Section III.

Perhaps even more importantly, the adaptive procedures mentioned previously reveal another important phenomenon; that is, a coarse solution which generates a reasonable approximation of incoming energy combined with a more detailed, finer solution to generate outgoing intensities can produce excellent results for the modeling of global illumination effects. Carried a step further, the incoming energy can be estimated by using only the surfaces providing the largest energy to the entire environment. Thus, rather than solving a complete set of simultaneous equations, an iterative approach which considers the contribution of one surface at a time can be used. This approach monotonically converges to the correct solution, but interim results can now be displayed as the solution is progressively refined. For most environments, computation requirements have been reduced by two orders of magnitude to obtain nearly correct solutions. Details of this method are discussed in Section IV.

Before any new rendering algorithm is accepted by the computer graphics community, the simulation results should be evaluated by comparison to physical experiments. How can one claim to provide photorealistic quality if there is no correlation between the simulation and the physical world? Too many of our currently utilized computer graphics procedures fail this test. To verify the validity of the radiosity approach, some comparisons between simulations and simple physical model environments were performed. Daylighting experiments conducted on real spaces have also been measured and compared to the predictive approaches. These results are detailed in Section V.

Many of the limitations of the radiosity method are now being eliminated. The restriction of complete diffusivity can be removed. Although the approach is currently not tractable since the number of equations becomes so large, different reflection functions have been incorporated into the radiosity solution allowing for specular reflections and ``reflection tracking''. In one approach, the addition of a postprocessing step can incorporate specularity quite efficiently. The standard radiosity solution has also been extended to include the effects of scattering due to a participating media, eliminating the assumption of energy transport through a vacuum. Recently some rudimentary approaches, based on the "shooting" of positive and negative energy have been proposed for dynamic environments eliminating the static scene restriction. These recent extensions to the basic radiosity formulation are presented in Section VI.

A number of restrictions and disadvantages to the radiosity method however still exist. The approach is not the panacea to computer generated photorealism. The computation times are still excessive, the reflection models too restrictive, and numerical inaccuracies revealed as sampling and aliasing artifacts remain problematical. But the general radiosity approach is based on fundamentally correct physical principles and it will be significantly enhanced in the near future. Solutions are not yet attainable in real-time, but with the power of today's workstations, computational times can now be measured in seconds. Clearly, the radiosity method will have a significant influence on our ultimate solutions for realistic image generation.