Visual Glue

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Abstract

A key function of graphics systems is to present information about the 3-D structure of modeled environments. For real-time simulations, conveying a sense of contact between touching surfaces and relative position and motion between proximate objects is particularly critical. Neither stereo nor occlusion cues are completely effective for such fine judgments. Conventional wisdom often argues that shadows play a critical role. Less often, it is argued that interreflection also contributes to the sense that two surfaces are touching. This paper explores the actual utility of shadows and interreflection in signaling contact and suggests how this information can be exploited in interactive rendering systems to glue objects to surfaces.

1 Introduction

Every opaque body is surrounded and its whole surface enveloped in shadow and light.

– Leonardo da Vinci [1]

Leonardo wrote at length about the relationships between light sources, objects, and shadows. He also described the phenomenon we now call interreflection. Subsequent work on the part of many researchers has yielded an effectively complete understanding of the physics of light transport as it relates to shadows and indirect illumination. More recently, methods have been developed for computationally simulating light transport with sufficient fidelity to produce physically correct images of synthetic scenes [2].

While the physics of shadows and interreflections are now well understood, we know much less about their perceptual effects. One reason for this is the difficulty of constructing controlled experiments involving shadows and indirect illumination. Gilchrist, in discussing how to analyze how the vision system might decouple illumination, albedo, and luminance, muses about “some sort of magical filter that could filter out all light that had been reflected off a surface . . . more than once” [3]. The graphics community now has the tools to provide exactly these sorts of manipulations. These tools make it feasible to learn directly about the effects of shadows and interreflections on perception.

There has been extensive work on geometric cues for spatial perception (e.g., [4, 5]), but much less work has been done on illumination cues. Research on the perception of shadows deals almost exclusively with how detached shadows act as a 3–D position cue, locating the shadow-generating object within a larger three-dimensional environment [6–9], or with shadows as a cue for object shape [10–12]. Within the perception community, the little work that has been done on indirect lighting has dealt with the perception of albedo [3, 13]. Computational analyses of the information about surface shape conveyed by interreflections have been done [14–17], but these results do not directly address the determination of spatial organization.

Visual contact cues are important for simulations of larger-scale environments because they aid in achieving visual realism and in the perception of the 3–D position of objects. They may be even more important when simulating direct user manipulation of objects in a virtual reality (VR) context. As a user reaches to touch or grab an object, his or her hand positions itself appropriately in anticipation of contact with the object. Since this occurs prior to the first contact, it necessarily must be cued by visual rather than haptic stimuli. While stereo undoubably plays a role in signaling imminent contact [18], shadows and interreflections also likely make a significant contribution to this perception.

Naturalness in VR interfaces supporting direct manipulation of objects depends on the appropriate triggering of anticipatory actions and contact when and where expected. Both require carefully constructed visual displays. The depth cues available from high-quality stereo displays are sufficient to provide an approximate sense of object location and confirmation of the position of visible body parts. The techniques conventionally used to generate real-time graphical displays do not, however, provide visual cues to depth and position with a precision sufficient to accurately determine distance and time to contact. In teleoperations using predictor displays, visual icons and snap-to-fit methods are sometimes used in the manipulation of simulated objects [19]. While compensating at least in part for a lack of perceptual precision in such systems, this leads to an unnatural interface requiring substantial training and experience to use well.

Current real-time graphics displays seldom include dynamic shadows and to date provide no support for interreflection. Our conjecture is that both are in fact important in signaling absolute proximity. When the user's hand moves toward an object and grabs it, the shadow cast by the hand appears on nearby objects, and eventually on the object to be touched. When the hand is almost touching the object, the shadow and hand will begin to overlap and at the instant of contact the hand and shadow will lock [8, 9]. As objects move close to each other and finally touch, the interreflection of light between the objects becomes noticeable. Though less studied than the effects of shadows, there is suggestive evidence that interreflection may be an important 3–D geometric cue [14, 20].

In this paper, we address a specific aspect of visually determining spatial structure: how do shadows and interreflection provide a sense of contact between touching surfaces. Rendered images involving objects in contact with an extended surface often have a "cookie cutter" appearance in which the object looks as if it is one image pasted onto another. This effect is common in interactive applications and can even occur in some realistic rendering algorithms such as radiosity, where it is often due to artifacts called light leaks and shadow leaks. Current solutions to this problem rely on explicitly adding fairly accurate shadows, either through interactive shadow techniques [21] or discontinuity meshing for radiosity [22]. These approaches tend to be computationally expensive.

We show that interreflections as well as shadows can be used to significantly reduce the problem of floating objects by gluing them to the surface they lie on. We also show that a wide range of

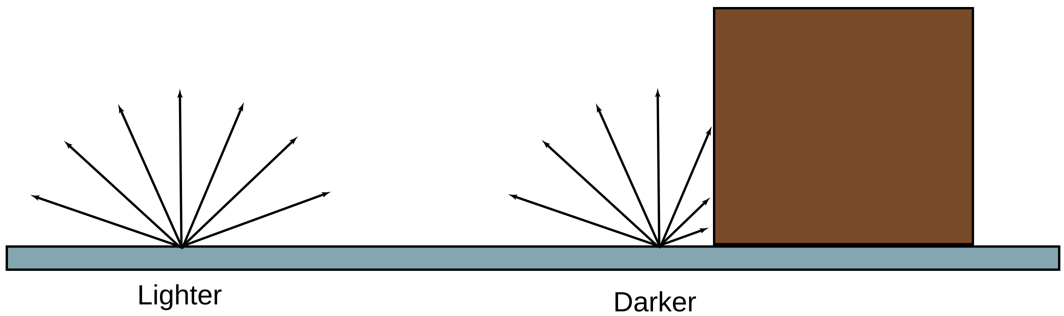


Figure 1: With uniform illumination, points near dark objects see less of the hemisphere and are darker than points further away.

manipulation of the cues still results in effective perception of spatial organization. We use this knowledge to make an interactive program that includes both shadows and interreflection on a low-end workstation. This program serves as a proof-of-concept that coarse approximations of complex illumination effects are sufficient for establishing contact and conveying spatial relationships.

2 Illumination Patterns

In this section we discuss the various types of shadows and compare with the illumination patterns caused by interreflection between nearby objects.

Shadows come in two distinct types. *Self shadows*, sometimes called *intrinsic shadows*, occur on those parts of the surface of a shadowing object that face away from an illumination source. *Cast shadows*, also called *extrinsic shadows*, occur on surfaces oriented towards an illumination source but occluded from that source by a shadow-generating object. Cast shadows can be *attached* or *detached*, depending on whether or not they are touching the self shadow of the generating object. Cast shadows can signal that the generating object is in contact with the surface on which the shadow is cast. Extended illumination sources cause shadows with penumbra (called *soft shadows* in the computer graphics literature). The "softness" will be evident for any portion of the boundary of a cast shadow not in contact with the generating object. The photometric details of these shadows have been studied extensively in the case of diffuse luminaires illuminating diffuse reflectors [22].

Corresponding terminology has not developed for interreflection effects. For interreflections involving light diffusely reflecting from one object surface onto another extended surface, contact is signaled by the lightening associated with the interreflection being adjacent to the directly illuminated surface. The boundaries of interreflection patterns associated with diffuse surfaces are always "soft," whatever the nature of the illumination. Unlike shadows, however, the shape of the interreflection pattern is not a function of the direction of illumination.

For objects in contact with an extended surface, diffuse illumination produces a luminance pattern on the extended surface that is a hybrid of that associated with shadows and with interreflections. Near the contacting object, light from some directions will be blocked, as in Figure 1. This will produce a darkening of the nearby surface, similar to a conventional shadow due to a compact illumination source, but the shape of the pattern will be similar to the shape of the brightening due to interreflection. The effect is most apparent for dark objects, where it is not masked by secondary illumination. We will refer to this effect as *diffuse shadows*[1]. We note that neither the graphics nor the psychology literature has terminology related to diffuse shadows, which emphasizes the lack of attention they have received from either research community. Similar effects in concavities were noted by Langer [23]. The method for shading presented by Zhukov et. al. [24] effectively determines regions where diffuse shadows are stronger and makes these areas darker.

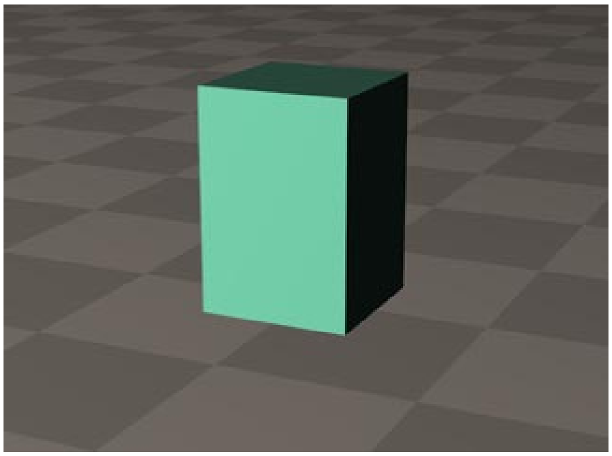
3 Surfaces in Contact

In this section we show that shadows and interreflection provide powerful perceptual cues for physical contact between objects and surfaces. As a result, effective rendering of shadowing and indirect lighting can provide benefits even in applications such as virtual reality, where realism in and of itself is not the primary goal.

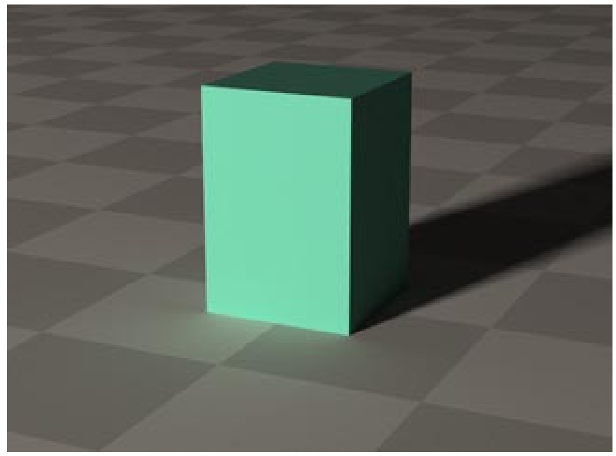
Illumination generates powerful perceptual cues indicating that two objects are in physical contact. Figure 2a shows a block sitting on a flat surface, rendered with a mix of direct and diffuse illumination but without any consideration of shadows or interreflections. Figure 2b shows the same configuration, rendered with the addition of a soft shadow and interreflections. There is now a strong sense of contact not apparent in the previous figure. Figure 2c shows a rendering with a shadow but no interreflections. Note that the sense of the front of the object being in contact is diminished compared to Figure 2b. Figure 2d shows the same configuration, this time rendered with interreflections but not a shadow. Note that the interreflections are not at all prominent, but they have a large influence on the perception of contact when compared to Figure 2a. Also note that in Figure 2d that the interreflections "glues" the front of the object just as well as the shadow glues the side of the object in Figure 2c. Figures 3a-3d show the same effects for an object positioned just above an extended surface. Figures 2b, 2d and 3b, 3d are effective in portraying whether the object is in contact. This contradicts the idea that indirect lighting is an esoteric effect largely of interest only when photorealistic realism is required. In fact, indirect lighting clearly complements shadowing in establishing a sense of contact. When used on its own as a contact cue, indirect lighting is of comparable effectiveness to shadows, despite being less visually prominent.

Strong shadow cues disappear under diffuse illumination. Figure 4a shows a block illuminated by lighting that is approximately uniform, without any account being taken of the interactions between the lighting, object, and surface. Figure 4b shows the same arrangement of light source and scene geometry, this time rendered with accurate light transport. While the effect is subtle, it clearly signals contact between object and surface. The information provided about spatial proximity is even more apparent in Figure 4c, in which the block is lifted slightly off of the surface. Comparing Figures 4a and 4b emphasize that a lighting effect whose presence may not be obvious in isolation can still be an important visual cue for spatial organization.

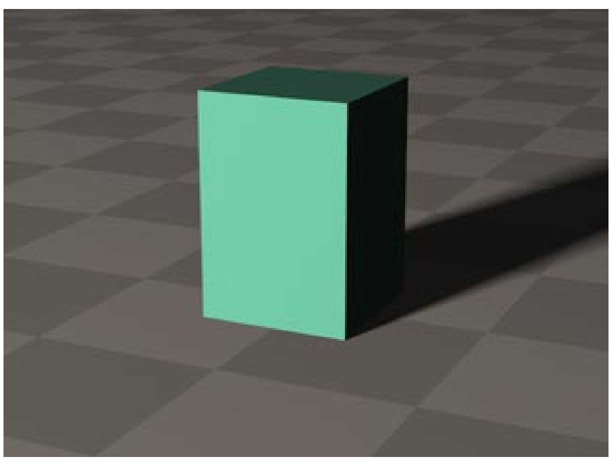
[1]The convention in both vision and graphics is to consider lighting to be broken into effects such as shadows and indirect light. In reality there is a continuum of effects that depends on the configuration of incoming light over the hemisphere (field-radiance), and the standard effects are merely extremes in this continuum. However, it is convenient to have a specific term (diffuse shadows) for the object interactions that occur for nearly uniform field-radiance.



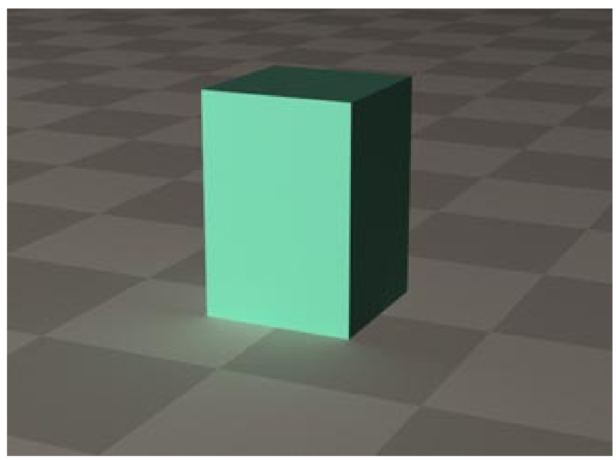
a. No shadows or interreflections.



b. Shadows and interreflections added to **a**.

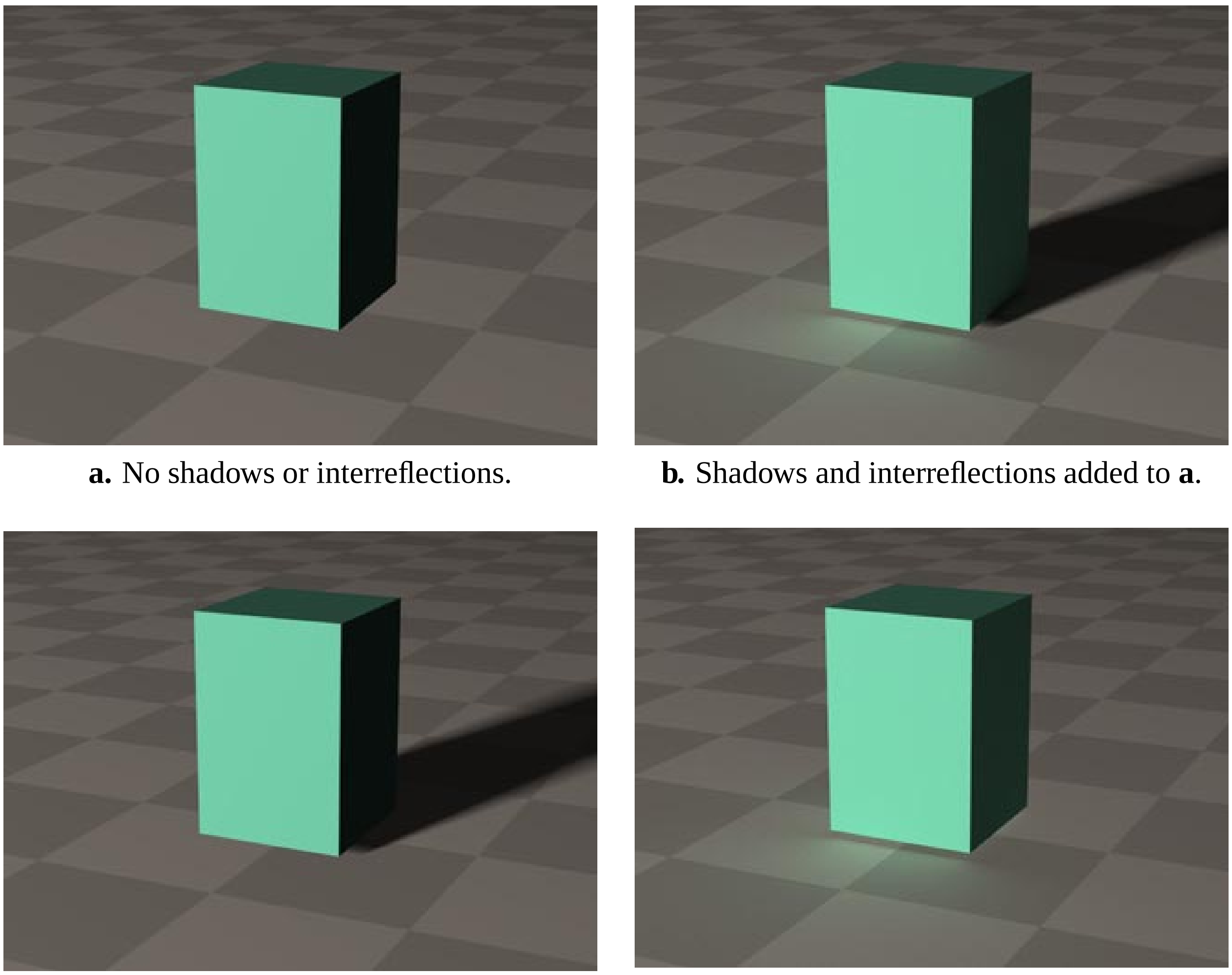


c. Shadows added to a.



d. Only interreflections added to **a**.

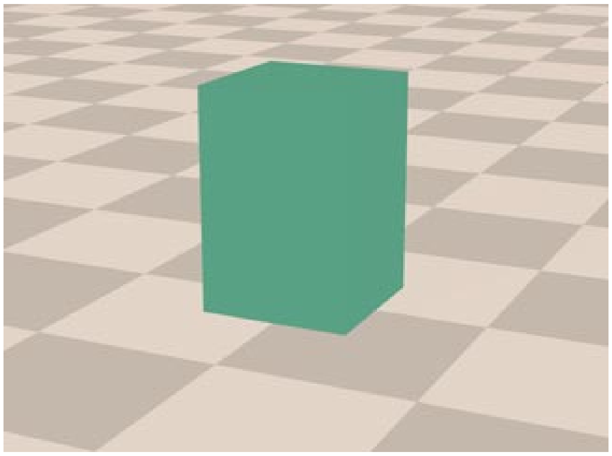
Figure 2: Objects in contact with extended surface.



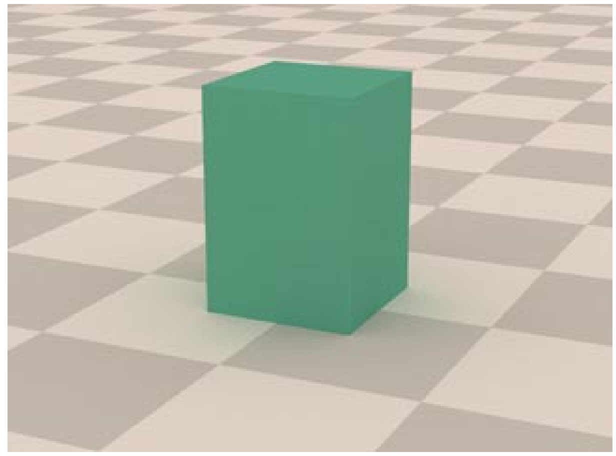
a. No shadows or interreflections. **b.** Shadows and interreflections added to **a**.

c. Shadows added to a. **d.** Only interreflections added to **a**.

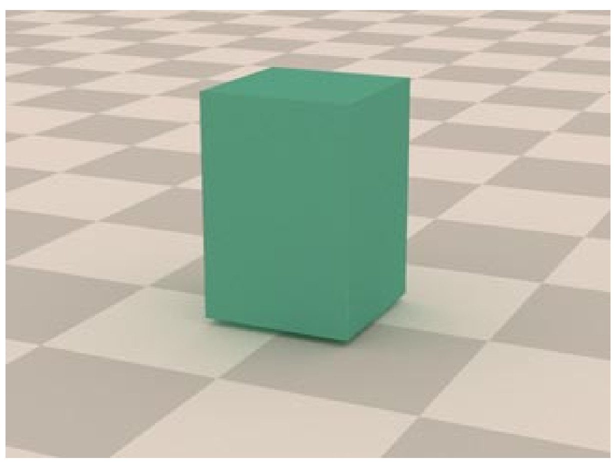
Figure 3: Objects just above extended surface.



a. No interaction between lighting, block, and surface.

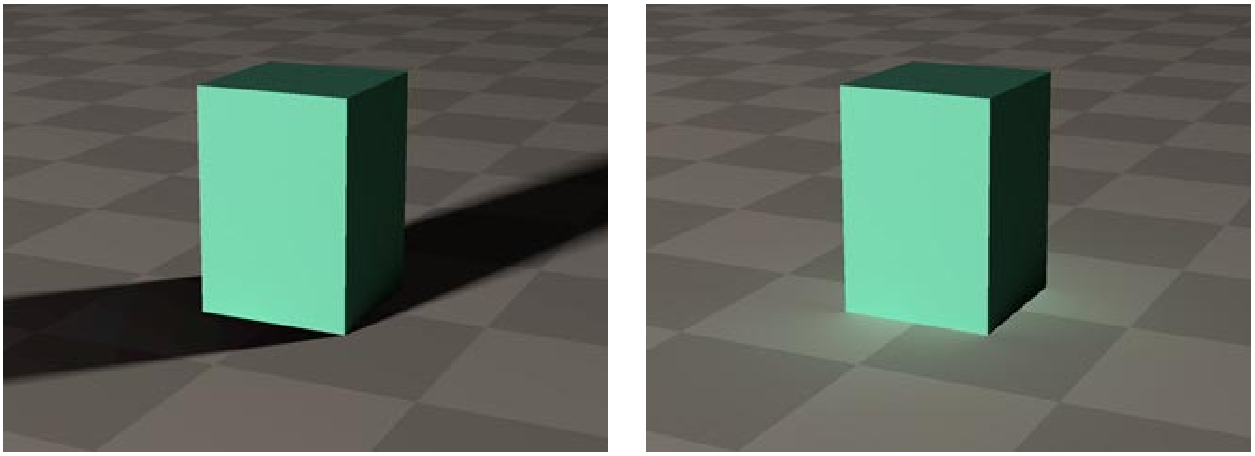


b. “Diffuse shadows” added.



c. Same as **b** but with raised block.

Figure 4: Diffuse shadows also act as a cue for contact.



a. Two shadows. **b.** Two interreflections.

Figure 5: Wrap-around glue.

To confirm the subjective sense that both shadows and interrfections act as strong contact cues, a controlled psychological experiment was run [25]. Subjects viewed rendered images of the block and ground plane with no shadows or interrfections, just a shadow, just an interreflection, a shadow and interrfections, two shadows (Figure 5a), two interreflections (Figure 5b), and two shadows and two interreflections. Two sets of images were produced, one with the block in contact with the ground plane and one with the block just above the ground plane. The subjects were quite accurate in their determination of contact when either shadows or interreflections were present. Maximum accuracy came when both shadows and interreflections were present in the image, however the accuracy was only slightly better than either shadows or interreflections. When neither shadows nor interreflections were present, responses were at chance rates, indicating that no other information was available in the images signaling contact.

Applications involving real-time interaction with complex virtual environments need to present users with a clear sense of spatial organization and contact. Based on what we have just shown, shadows and indirect illumination are likely to play an important role in achieving this objective. This is a disquieting observation, since accurate rendering of interreflection is extremely costly. Shadows, while computationally less complex, still require substantial resources to render. This is particularly true when soft shadowing is done. As a result, it is important to probe more deeply into the role shadows and interreflection play in signaling contact between one object and another.

4 How accurate do we need to be?

Limitations of displays and computational power necessarily require that graphical renderings at best only approximate what would be seen in a physical environment. Thus, one of the goals of graphics research is to discover computable and displayable approximations to light transport that generate appropriate visual cues. It is particularly important to understand shadows and interreflections within this context, since both require substantial computational effort to render accurately and even then, limitations on dynamic range preclude faithful displays.

The first question to address is whether there is really a synergistic interaction between shadows and interreflections, as is suggested by Figures 2b and 3b. As shown in Figure 5, the answer may be something of a surprise. Figure 5a shows a rendering comparable to Figure 2b except that the interreflection has been replaced by a second shadow added to the extended surface. Figure 5b is similar, except that this time the shadow has been replaced by a second interreflection. Comparing these images with Figures 2b and 3b shows that two shadows, two interreflections, or correct shadows and interreflection are all approximately the same in their ability to signal contact. This leads to the conclusion that it matters more that cues to contact be present along the entire visible perimeter of the object-object contact boundary than whether the cues are associated with shadows, interreflections, or both. The interchangeability of shadows and interreflection also suggests that visual prominence, which is large for shadows and small for interreflections, may not be related to strength as a contact cue.

The next question to ask deals with the fidelity required of shadow or interreflection cues in order to signal contact. The answer to this too may be surprising.

The accuracy with which shadows need to be rendered in order to convey a sense of position in a larger spatial environment is highly variable, depending on the specific circumstances. Sometimes, soft shadows are important [8], other times they are not [9, 26]. When common motion of object and shadow is present, the actual appearance of the shadow seems almost irrelevant, with patterns that would never be confused for a shadow on their own sufficing perfectly well [9]. This is an effect that is commonly used in video games and animation to convey a sense of height. Height, however, is not the same as contact. In Figure 6 we show that although crude shadows are good at presenting coarse height information, they are not effective at giving contact cues. For contact, arcade-style shadows are not accurate enough.

There are other areas, such as film, where very crude shadows may not be acceptable. Film requires more accurate shadows when it uses composited special-effects images that must touch the background, which may have as much to do with visual realism as it does with enhancing the sense of contact. This may also hold for maintaining immersion in virtual environments.

In the case of contact, we know that the physically realizable patterns of light are themselves highly variable, ranging from shadows to interreflections to diffuse shadows. The vision system could conceivably deal with this variability in at least two ways. One possibility is that the vision system is able to detect and interpret each type of cue on its own. A second possibility is that the vision system uses approximations sensitive to any of the contact cues. The tools of photorealistic rendering can be modified in ways that let us test which of these hypotheses is more likely. As with 3–D localization, the key is to discover whether or not approximate imagery can still convey the same sense of spatial organization.

In Figure 7, we have manipulated the shadow and interreflection patterns first presented in Figure 2c. Figure 7a is rendered with no shadows or interreflections. In Figure 7b, photorealistic shadows and interreflections have been added. In Figure 7c, the contrast of the indirect illumination effects has been increased, while the contrast of the shadow has been halved. Figure 7d was produced by subjecting the interreflection to a significant hue shift while reversing the contrast of the shadow. Even when the intensity and hue of shadows and indirect lighting are grossly distorted,

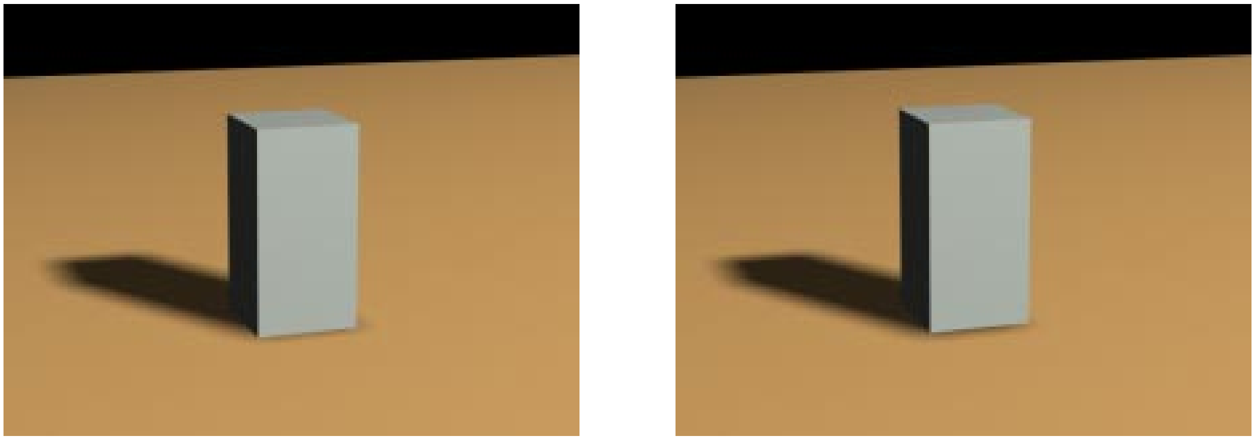
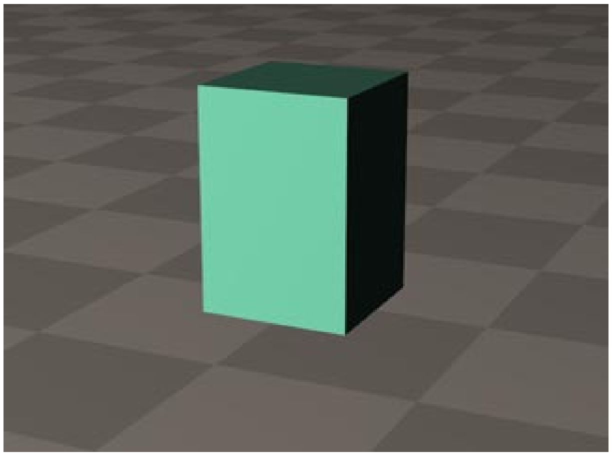
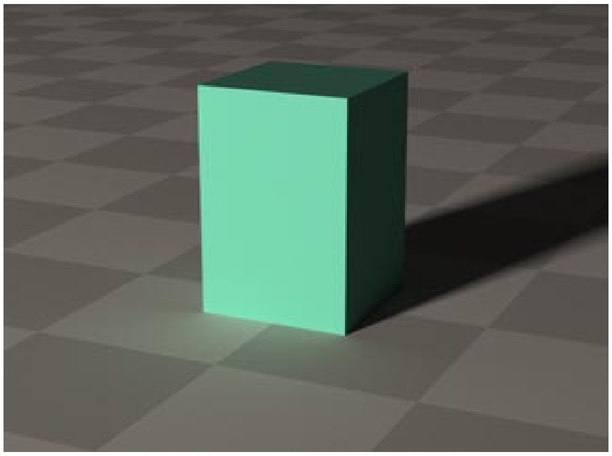


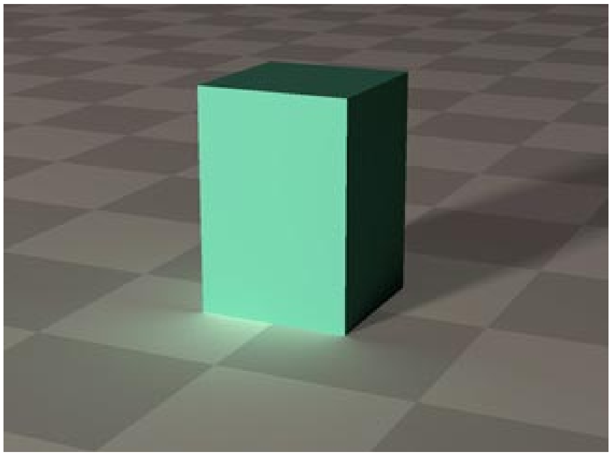
Figure 6: Blurred, arcade-style shadows. Left, in contact. Right, near contact



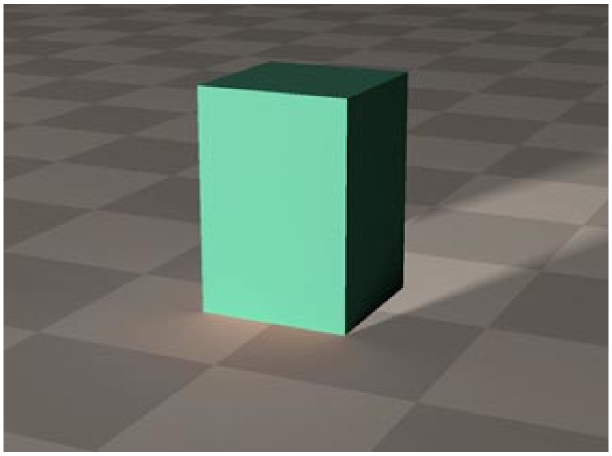
a. No shadows or interreflections.



b. “Correct” shadow and interreflections.



c. Bright interreflections, less dark shadows.



d. Hue shifted interreflections, reverse contrast shadows.

Figure 7: Manipulating shadows and interreflection cues.

the impression that the objects are in contact is not significantly diminished[2]. The experimental study described in Section3 also included the case where the hue of the interreflection was shifted and a reverse contrast shadow was shown, as in Figure 7d. Accuracy was high for the hue and contrast manipulated image, though less so than for photometrically correct shadows and interreflections. Langer's work [23] may help explain the the reason for the lower accuracy. Images of contrast reversal for concavities seem to be interpreted as containing a light source. The contrast reversal makes the cube appear to have light streaming out from under it. This could only happen if it were not in contact.

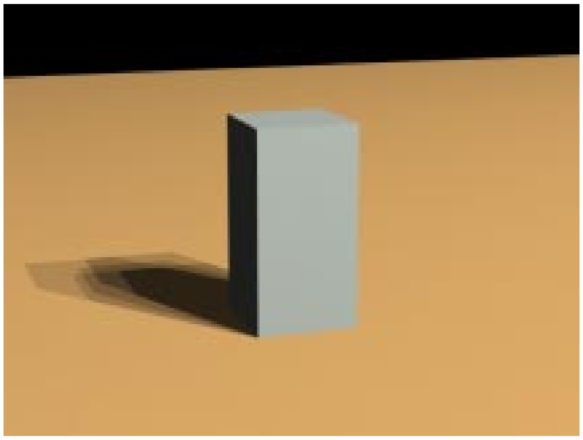
We feel that the significant feature of shadows and interreflections that signals contact is the alignment of the edge of the illumination pattern with the edge (or corner) of the object. We feel that approximate shadow and illumination algorithms that preserve this feature will also be effective in signaling contact. The arcade-style shadows of Figure 6 don't work as well for signaling contact as shadows based on beam-tracing [27]. Beam tracing replaces a soft shadow with shadows from many nearby point sources, which for a small number of point sources has obvious banding. It is, however, still effective in signalling contact [9]. This is not surprising because the shadow edges do align to the corner of the shadowing object. Approximate shadows resulting from blurring hard shadows on the shadowed object (e.g. [28]) do not have this property. Multiple levels of blurring [29] can give the silhouette width variation, but they cannot possess the singularity of real contact points. For this reason we believe beam traced shadow artifacts may not interfere with contact cues even if the artifacts are visually obvious, while blurred hard shadows may interfere with the perception of contact as shown in Figure 8. We suspect that blurred shadows are used in entertainment applications because they are aethetically superior to beam-traced shadows, but we note that the level of blurring is typically quite small, making the problems near where the singularity should appear less obvious.

5 Relevance to interactive rendering

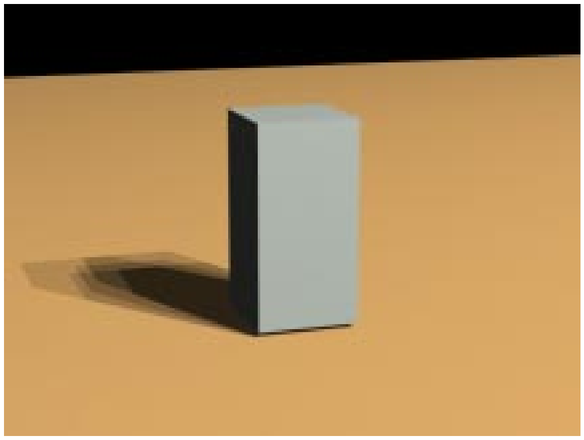
In the previous section we showed that the ability for illumination cues to "glue" an object to another surface does not depend strongly on the details of the illumination cues, provided they are present. For applications where accurate spatial perception is more important than subjective realism, even coarse approximations to indirect illumination, conventional shadows, and diffuse shadows are able to indicate contact in a rendered image. To show the value of this in applications where interactive performance is of critical concern, we have developed an algorithm which is capable of generating perceptually effective contact cues using very crude approximations to shadows and interreflection.[3] This algorithm is simpler and faster than methods for accurately rendering shadows interactively (e.g., [30]) and is orders of magnitude more efficient than current methods for generating physically based indirect lighting effects. Because it uses projected tex-

[2]This insensitivity to hue does *not* carry over into other perceptual effects involving the interaction of indirect illumination and scene geometry [13].

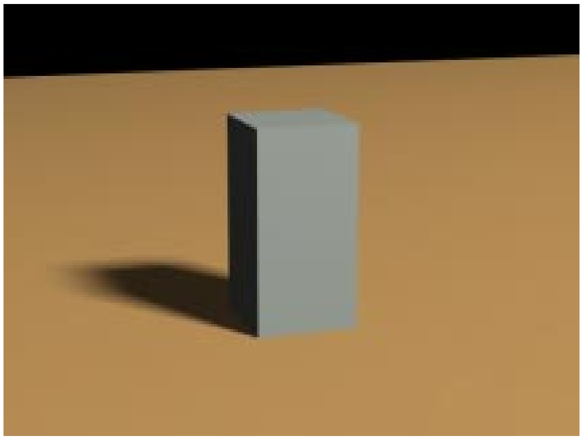
[3]The algorithm modifies the intensities of the area using the multi-pass rendering and blending functionality of OpenGL. A dark projected texture is subtracted from the base intensity, and a separate light projected texture is added to the base intensity. These operations are accomplished using `glBlendFunc(GL_DST_COLOR, GL_ZERO)` and `glBlendFunc(GL_DST_COLOR, GL_ONE)` for shadows and indirect illumination respectively.



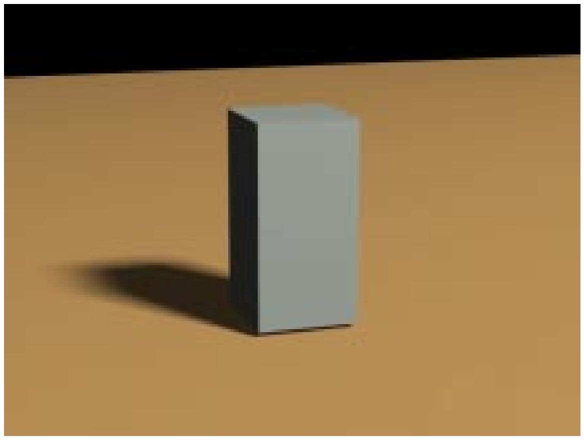
a. Beam traced shadows.



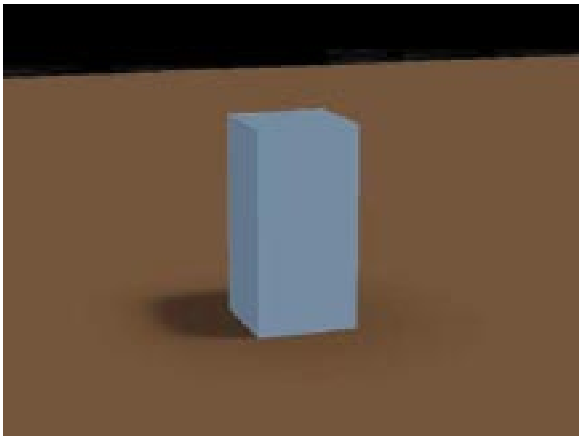
b. Beam traced shadows for raised block.



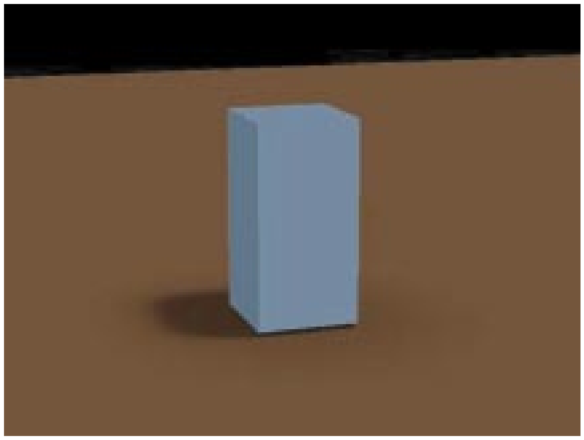
c. Correct shadows.



d. Correct shadows for raised block.

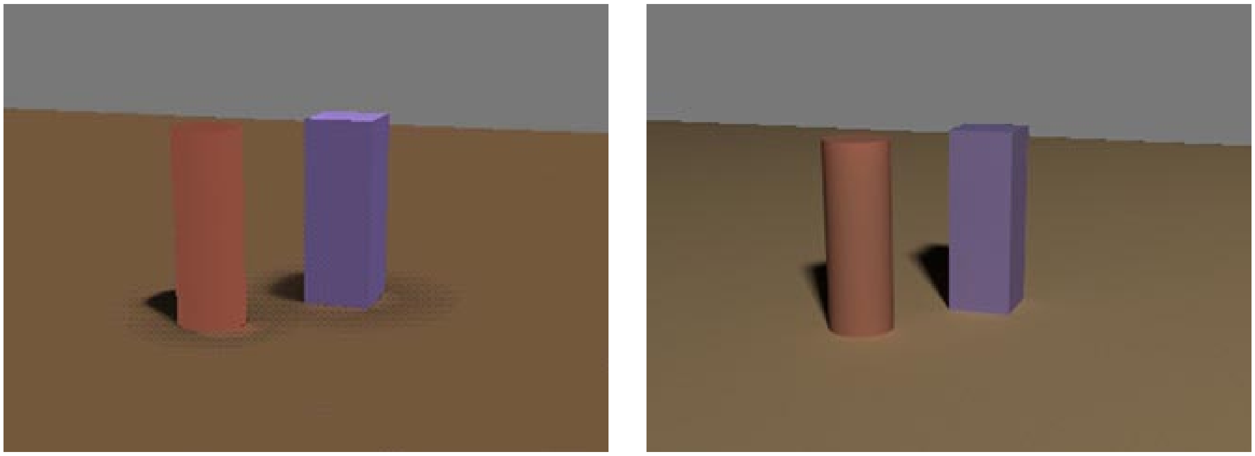


e. OpenGL approximation.



f. OpenGL approximation for raised block.

Figure 8: Shadow approximations signaling contact.



a. Simple approximation to shadows and interreflections.

b. Accurate shadows and interreflections.

Figure 9: Coarse approximations are sufficient to convey a sense of contact.

tures, it also works for irregular ground planes. Unlike obscurance maps [24], this technique is effective in dynamic environments, though with a loss of visual realism.

Figure 9a shows an image generated on a low-end workstation at interactive rates using this technique. Figure 9b shows the same scene rendered with a highly accurate renderer, running on a high-end processor and requiring close to an hour of CPU time. Although the second image is subjectively more realistic, it does not visually imply contact much more effectively than the approximation.

6 Conclusion

Four fundamental points are made above:

- *Both* interreflections and shadows – either alone or in combination – can serve as cues for contact.
- The visual prominence of shadows and interreflections is not an indication of their effectiveness in conveying information about spatial organization.
- The presence of contact cues along the whole of the line of contact is more important than whether the cues involve shadows or indirect illumination.
- Crude approximations to shadows and interreflections are sufficient to establish a sense of contact, even when the subjective sense of realism is seriously compromised.

While the graphics community has known that shadows are useful, indirect illumination has often been considered only important for applications where high subjective realism is valued. This historical down-grading of indirect illumination relative to shadows is probably due to the difference in visual prominence, which we have argued is not directly related to their effectiveness as contact cues. Our results imply that even virtual reality systems where realism is not the primary goal might well benefit from at least approximating indirect lighting, particularly since in such cases simple techniques are likely to be sufficient for conveying an adequate sense of spatial organization. A further use is for visualization applications where demonstrating contact may be important, but shadows obscure too much information. The ability to use indirect lighting cues gives another choice to the designer of such applications.

Haddon and Forsyth, commenting on a computational analysis of the information available about scene geometry in shading patterns due to interreflections, observe that "the best prospect for extracting shape information from shading is to construct programs that observe stylized properties of shading and associate those properties with shape primitives or their properties" [20]. We reach the same conclusion approaching a closely related question from a human vision perspective: stylized patterns of lightness and darkness are sufficient to signal perceptions associated with shadows and interreflections in a way that is almost invariant to the actual radiance values that are present.

There are several important perceptual issues that are not addressed in this paper. We have demonstrated that in static scenes shadow and indirect illumination cues can establish object contact. When moving objects are brought into proximity with other objects, the dynamic cues may have different characteristics than the static cues. Also, non-diffuse effects may raise issues that do not arise in the diffuse case.

Finally, this paper is an example of the symbiotic relationship that is naturally arising between the graphics and psychology communities. Graphics researchers can provide variation to the optical behavior of the world which enable new sorts of programmable stimuli, and psychology researchers can help the graphics community prioritize what is rendered, so that efficient and effective algorithms can be developed.

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