One challenge to the computer-aided designer is to portray physical realities using only visual, logical, or numerical representations. Recently there has been a lot of speculation about meeting this challenge with a new dimension of tools which couples physical interaction to animated output: cyberspace. However, so long as certain inherent limitations remain in the physical part of cyberspace prototypes, there is more to be gained in improving our graphics independently. One aspect of graphics for portraying physicality which we can address right now is texture.

From the full experience of architecture, we know that texture is just one of a variety of phenomena which go beyond the form, color and motion that certain cyberspace adherents seem willing to accept as reality. As we move through a building, we are aware of the presence of mass, variations in temperature, aural resonance, etc. Respect for these phenomena has already suffered in our increasingly visual culture - we hear how the published photograph contributes to an aesthetic of architecture that is only skin-deep, for example - but it is particularly at risk in the world of computers. CAD appears as a threat to many designers precisely because working on a screen makes it harder to touch one’s work. The irony of cyberspace systems is that they may not correct but rather only exacerbate this detachment. Their breakthrough technology for physical interaction incorporates gestural, but not tactile, input; their feedback mechanism provides visual, but not tactile, output; and as the saying goes, if you don’t have a word for it, it’s hard to talk about it. Conventional computer graphics has no tactile capability either, but it does have higher visual resolution and lower pretensions to realism.

There are several reasonable positions to take in response to this situation. The most popular is to firmly uphold the value of the hand-made model. Another, perhaps more enterprising, is to develop better cyberspace technologies which incorporate physical feedback - at least of force, but perhaps someday of relief, vibration, or temperature, too. A third, more expedient in the short term, is to improve the computer-aided design systems’ capacity for visually representing physical phenomena. In this area, there are two primary focal points: the appearance of materials and the articulation of mass and motion properties. We shall examine the former. There is certainly room for better rendering of materials. The current norm, the shaded surface model, tends to make everything look like it is made out of weightless, featureless, polystyrene. This needn’t be the case on more sophisticated rendering systems, which are becoming commonplace. Unfortunately, while the underlying technology of these systems is well-established; the theory of their use is not. Here we address one aspect of use: visual rendering of material texture. We make a case for the importance of texture in architectural design, examines current practices of textural representation, present theoretical aspects of texture parameterization, suggest some future directions, and close with some comments on simulation and interpretation.

Textural Composition.

A textural element in a design may rely primarily on its visual qualities, which are the only ones we are able to portray in textural rendering systems, but it is just as likely to play upon other properties, such as psychological interpretations of enclosing mass, social significances of particular materials, or purely physical sensations such as radiation or conduction of heat. That each of these aspects may be at least as important as the visual
contributes to the argument on the poverty of virtual reality.

Texture has an important relationship to scale. A design element creates different textural experiences when perceived at different distances. For example, a building design might act as a textural element of an urban or landscape fabric. More generally, texture contributes to the making of human scale in traditional designs. Its absence in many modern urban forms has been a great source of public outrage.

Architecture is rife with examples of the defining and characterizing role of texture. The contrasting colors, reflectivities, and thermal properties of water, ceramics, and stone contribute to the appeal of Mediterranean architecture, for example. The rustication of the base of an urban Palazzo expresses the weight and permanence of the structure, distinguishes the street level from the inhabited storeys, and provides detail at the scale of the passers-by. The casual textures used by Frank Gehry express the impermanence, low budgets, and gentle climate of certain building conditions in Los Angeles. Juxtaposed textures of wood, gravel, stones, and plants are the vocabulary of formal compositions by H.H. Richardson. Subtle contrasts of concrete, brushed metal, and wood enrich the work of Louis Kahn, one piece of which we chose as a subject for our rendering studies.

Textural Representations.

Imagine a facade composed of metal panels. As a first approximation, we might model and render it as a uniformly colored rectangle. For more accurate rendering to support closer consideration of design issues like the effects of different column reveals, we might redefine the model as a collection of smaller rectangles - the panels themselves. If we want to study the subtle but important effects of different ways of handling the panel joints, though, this requires a three-dimensional model of surface relief and a rendering procedure that shows the shadow lines under individual panels. We might further recognize that individual panels are not in fact uniform, but display variations of color and shininess across their surfaces.

If there are many levels of abstraction available, traditional representations of texture have tended toward the higher ones. In drawing, our vocabulary of mark-making includes stippling, hatching, filling, and smudging, which rarely lead to literal renditions of texture, but nevertheless provide a sufficient vocabulary to differentiate any number of materials in a composition (Figure 1). Incidentally, the tactile qualities which these techniques have (mostly in response to the tooth of the paper) are even less likely to correspond directly to the materials being portrayed. Even in manual modal building, where everything is tactile, and there are opportunities for more direct representation: wood for wood, plaster for stone, wire mesh for steel grid, and so on, representations normally remain schematic and indirect. This is partly so that inaccuracies of direct representation do not dominate the interpretation.

Computer-based renderings are less sophisticated, because the medium is newer, and they are more direct, because the medium is better able to manipulate microstructure. Early systems were pretty much incapable of rendering texture, except to suggest it through specular effects, or perhaps to add it to whole polygons using pixel patterns in display space, but today's renderers can apply almost any pattern or image to a surface of a model, like a decal.

What distinguishes proper texture rendering methods is the ability to consider variations of microstructure within a polygon's boundaries. Any of the properties capable of depiction in a renderer, such as reflectivity, specularity, transparency, and properties of received light, can be modulated over an individual surface facet. An essential characteristic of these methods is the creation of a texture bitmap, which is then projected onto designated surfaces. The bitmap may be stored in a library or, if synthesized, computed whenever needed.

In mapping to model surfaces may be designated interactively, or by some aspect of data structure, such as layer, attribute, or
One way to acquire texture bitmaps is to sample them. Scanning photographs of physical materials sidesteps the problem of procedurally defining complex textures, but it has other limitations. One is memory: highly detailed images are too large to handle quickly and in great number. Another is control: sampled textures create tiling and shading problems, for example, and they are difficult to use coherently on different scales of surfaces in the same image. (Figure 2 shows a parody of this condition). One technique which aids in the manipulation of sampled textures is the spongy brush (Figure 3).

Figure 1. Material differentiation from a few kinds of pencil marks.

Synthesizing textures alleviates these problems. Generative procedures can create increments of texture, plus repetition rules to handle conditions of tiling and scaling. Libraries may store small sets of parameters instead of large bitmaps, although they may include small bitmaps to allow visual identification of textures for browsing. (This is an interesting instance of the store-versus-compute issue). The essential problem in the case of procedural textures has been to simulate natural appearances. The emerging solution depends on two developments of the 1980s: fractal geometry and high-resolution raster graphics. Functions which employ recursion and noise to modulate a given surface property, such as color or transparency, combined with displays having sufficient resolution to show some depth to such recursions have enabled computers to render natural phenomena. The next stage of the solution is to identify useful parameters, structured not for the convenience of the programmers who created the fractal algorithms, but for the needs and habits of designers.

Texture Space.

Design Variables: A texture space is simply the product of the ranges of a set of texture parameters. To a designer, this appears as a realm of visible textures bounded by the limits of design variables which modulate the color, reflectivity, and other appearances of a surface with respect to the geometry of the object.
In architecture, design of texture is normally dependent upon the choice of materials. In selecting wood boards, for instance, the grain is by and large selected through the choice of wood type. Minor modifications may be made through stains and other surface treatments, but significant changes in grain are accomplished by choosing a different material, for instance substituting oak for pine, or brick for concrete block. Materials, then, provide a convenient means for designing subspaces or unique points in texture space.

In computer-aided rendering, control of textural properties is more independent. In fact, the relation of texture to material is often reversed: one must designate materials by means of textures. A designer may choose to render a wooden material with the grain suppressed and tightened, and may easily change the color from a maple-like off-white to an dark ebony tone. A terrazzo floor may instantly have the aggregate reduced in size and changed from grey to pink. At first glance this seems a great freedom. As with other freedoms, however, this comes with new responsibilities, and can also become a burden. Setting the geometric arrangement of the grain in a board is typically not an option, but rather an imperative. The problem this creates is that we need to move around in texture space in different directions than the systems provide, but we lack our own scales for describing textures. How should we specify the grain of a pine board? We might talk about "bands" in the board, which arise from slicing the rings of the tree. We then must have a way to specify the bands, possibly "bands per inch," with a "dark edge" at one side of the band. Next we must specify the direction of the bands with respect to the board. We might wish to specify what percentage of the band the dark edge comprises. We then might need to specify a certain degree of randomness, of irregularity in the bands and edges. Colors must be specified, not only for the bands, but also the dark edges. As we look at wood and realize how many factors can vary, we realize how many variables might have to be set. The demands of precise specification can become a burden and a distraction. As an example of how problems arise, consider the task of selecting wood color in the Alias rendering system. In the specification of wood, one must choose three colors, one for the bands,
one for edges, and one for colored "flecks" in the wood. For each of these selections, a set of color mixing interfaces appears, allowing the user to mix one of 16-odd million colors. Upon setting the three colors, the user may then see two samples of the wood as he has defined it, a "sphere" of the wood, and a flat sample. It is relatively easy to arrive at color settings that look something like some kind of wood by this method. A rule of thumb is to use some shade of beige for the bands, a darker shade for the flecks, and a brown for the edges. But it is much more difficult to match a preconceived appearance, for instance that of cherry wood with a particular shellac.

**Design Vectors.**

The combination of n independent design variables yields an n-dimensional space of possible design solutions. Setting a new value for a parameter defines a different point in this solution space. In design, this amounts to a trial and error approach. Varying a parameter continuously, however, defines a path in the space. In this case, the designer observes a continuum of variations from which to identify a desirable solution. This may facilitate discovery. Of course, there are an infinite number of design vectors in a space. Choosing a useful one is a matter of designating the appropriate independent variable. Consider, by analogy, the issue of color, since RGB color space is three-dimensional and therefore easier to visualize. When color raster graphics first became viable in the early 1980’s, systems achieved color variations by setting different red, green, and blue levels in their frame buffers. But designers, accustomed to working with color wheels and levels of saturation and brightness, were frustrated by the RGB controls that these systems provided for color manipulation. Interaction was improved as systems began to provide HSV controls too. (The translation from HSV to RGB is just a bit of algebra). Hue is an example of a design vector which enables designers to make useful moves between desired points in color space in terms of one component rather than three.

Similarly, we may expect more useful parameterizations of texture spaces to emerge. But texture space is more complex: first, it has far more variables, and second, there really isn’t any scale of texture notations that is familiar to designers. We have to invent one.

One approach is to reduce the number of parameters. Consider one case: Whereas the Alias system offered a single infinitely variable texture called "wood," as participants stumbled upon recognizable wood textures, the parameter settings were saved and renamed "pine," "cherry" and "ebony." In generating later renderings, the student would choose the closest wood (light, red, dark) and tune the appearance for the particular application. This process of tuning was particularly effective because it was much less time consuming than creating a new wood texture "from scratch." This suggests the need for a two-tiered parameterization of textures, a mapping of a low-level texture space of many dimensions to a high-level material space of few dimensions. For example, a high-level parameterization of wood might include the species of the wood, the finish, and a parameterization of a vector between a point with wavy grain with knots and a point with straight regular grain. This level is analogous to the specifications made with conventional materials. A low level parameterization would allow tuning of the myriad of parameterized details which combine to form the high level descriptions.

Vectors through texture space encourage exploration of the range of textural possibilities between two texture settings. In considering a coarse grain marble and a fine grain granite, for instance, a visual effect may be desired somewhere between the two. Problems of this sort are easier to express as a vector between two points in a texture space than by the variation of the settings of thirty variables on stone texture that it took to create either. By considering a single vector through texture space, we may then consider a point half or two thirds of the way from one point to the other, or on an appropriately powered system, watch a continuous transformation of one into the other. These and other excursions in texture space could be a fascinating enhancement of virtual reality.
Texture Coordinates and Model Space.

A few parameters in texture space worth particular examination are the ones which control the scale and orientation of the mapping of the texture bitmap onto model surfaces. These are not unfamiliar variables in the design process - a builder laying out a stone floor is using them, for example - but controlling them on the computer gives them different qualities.

One of these is the ability to grossly mismatch the scale of the texture with respect to the scale of the model. (This is of course not exclusive to computer models). Most participants in this study encountered conditions of this sort in their early explorations. A wall, assigned a wood texture, appeared as a smudged brown plane. Upon examination, it was realized that the mismatch was such that the wood grain was effectively microscopic, and the smudged effect arose from Moiré patterns of the repeating wood grain. Smaller errors gave results akin to the effects of constructing model buildings with full-sized materials. A most persistent problem was encountered in generating the wood detail image shown in Figure 4, where it was discovered that wood grain in the Alias system tended to run vertically along the z plane only. Thus a board lying flat on the x-y plane would be rendered with its broadest surface comprised entirely of end grain. The directionality of the texture space was apparently irrespective of the orientation of model elements, which made creation of the detail difficult. Regardless of the orientation of the boards comprising the detail, the grain ran vertically in the renderings. In order to complete the image, therefore, the boards were locked to the light source as a single object, and the detail was rendered. The detail object, including the light source, was then rotated by 90 degrees and rendered again. The image shown is a composite of these two renderings wherein the boards running vertically were cut from the first rendering, and the boards running horizontally were cut from the second.

The issue of texture scale is complicated by the fact that textures are often three-dimensional. In these cases the metaphor of applying a decal loses its accuracy. As an example of a merely two-dimensional texture, consider sand.
Because there is no "grain", there is no directionality; from any orientation you get the same pattern. A three-dimensional texture, such as marble or wood, on the other hand, has directional grain running through it. When we observe the meeting of top and side planes in a marble block, we expect to see the continuity with respect to the grain of the two planes. With wood, we expect to see end grain at the top of a board (Figure 5). Three dimensional texture definitions are necessary to accomplish these effects.

In working with materials in architectural contexts, we rarely deal with a single element, such as a board, brick or stone slab. The mapping of texture coordinates, especially three-dimensional ones, to repeated elements in model coordinates, presents a special problem. Imagine a row of vertical boards (Figure 6). We can neither apply the same mapping of texture coordinates to each lements model coordinates, for then every board would appear identical (as if cheap woodgrain vinyl), nor can we apply one mapping of texture coordinates to the whole group, for then it will look as though it has not been assembled but cut from a single piece of wood (in which case the effect of separate boards is easily lost). A similar condition of a marble stair is illustrated in Figure 7. For a reasonable appearance, one must instead establish a sequence of vectors in texture space to establish a different mapping from texture coordinates to model coordinates for each board in the group. In order to avoid mismatches of texture and model space, several factors must combine. First the scale of the geometric model must be clear to the designer. Second, the scalar relationship of the texture to the geometry must be clear. This may be accomplished by expressing the texture in geometric terms, such as "aggregate per square inch." Third, the coordinate system of the texture must be "attachable" to the object, so that as a board takes on different positions in space, it may maintain its position in texture space, rather than be effectively cut from a different portion of a tree for each position in space it may be placed in.

Figure 7. An assembly which appears to be cut from a single block of material.

Figure 8. An exterior study in which texture is dominant but light is also important.
Format of the Study.

These very specific examinations of texture are taken from a more general study of rendering which was conducted in a seminar at Harvard University Graduate School of Design in the fall of 1990. The intent of the work was to raise issues of interpretation and to identify practical avenues of application of technologies which are beginning to become accessible to mainstream designers. The systems used for the work included the Alias software running on Silicon Graphics computers, Topas and BigD running on an IBM/TARGA system, and Stratusvision running on the Macintosh. Modeling was done with AutoCAD on Sun and IBM computers.

In order to provide a common basis from which to explore alternative expressions in rendering, a single subject was shared by all participants. The Yale Center for British Art was chosen for its subtle interplay of light and textures, its clear palette of materials, its varying scale of textural events, its relative ease of modeling, and its proximity for visits.

It is not possible to show all of the work which emerged from this study, nor is it possible to avoid showing some of it which is as much about lighting as texture (Figures 8-9). Such pieces are shown partly to demonstrate an order-of-magnitude increase over a couple of years ago in the number of ray-traced images that a few people can produce in a short time.

Realism?

The question of interpretation versus simulation was the main issue raised by this work. What is the role of artistic license, or of artistic appreciation in a medium so capable of accuracy? What are the non-visual properties being ignored?

Conventional design representations are interpretive. The forms of art as we know it neither resemble external reality, nor do they correspond to designers' inner vision. Rather, they are independent, intermediate objects. To the degree that they are successful at mediating, they convey more than they explicitly contain. Furthermore, they convey

Figure 9. An interior study in which light is dominant but texture is also important.

Figure 10. A realistic rendering without light diffusion or atmospheric effects.
something different to each person. Realism occurs when the observer confuses the
representation with the represented. To

achieve this, the representation may or may not
employ resemblance. In it more likely to
depend upon transparency of the medium,
which in turn relies on well-established artistic
conventions. Interpreting these conventions
requires some degree of appreciation. Some
media require more appreciation than others.
A photograph is intelligible to a wider audience
than a painting. The greater the visual
fidelity, it would seem, the less required of the
viewer.

Computer-based renderings, despite their
sometimes astonishing fidelity, still require
appreciation. Using sophisticated computer-
graphic rendering capabilities capable of
photographic-quality resemblance does not
necessarily make the task of rendering
architectural environments easier. An
immaculate, perfectly shined black surface is
similarly not easy to keep clean. Precisely
because of its immaculate surface, every piece
of dust, every fingerprint is immediately seen,
and demands the attention of the viewer.
Similarly, the perfection possible in
sophisticated rendering immediately calls
attention to any imperfection in a model.
Further, clearly rendered textures demand
comparison to the precise images of materials
we believe they are meant to convey. For the
fine simulation not to be interpreted as a badly
crafted image, both the author and the observer
must appreciate the intent of the
representations employed. For the best
interpretation, they should also appreciate the
capabilities and limitations of the medium.
Consider a counterexample: someone
unaccustomed to seeing accurate portrayal of
shadows and textures without corresponding
treatment of light diffusion and atmosphere
may find a raytraced rendering stark and
sterile (compare Figures 10-11).

Computer-based renderings may benefit from
artistic license. They may do this by lowering
expectations in terms of literal detail, for
example by stippling a photographic-quality
rendering, or they may do so by implying
detail. For example, one might render a
building once with textures and once in the
same colors but without the textures. Patches of texture might then be selectively applied from one image to the other, and blended into the image using a paint system. The resultant image would be of the sort where a plane with a few patches of brick gives the clear impression of a brick wall without the need to render each brick with photographic clarity. In another case, one might abandon resemblance at one level to invoke greater resemblance at another. Figure 13 illustrates this approach. Though the small elements here are not literal representations of the surface module or texture of the building, the image viewed as a whole gives an appropriate collective impression of the facade. In a piece of this sort, false cues serve to counteract the expectation of the perfect correct cues. Indeed, artistic license is often applied to remove spurious information from an image. In another participant's work, for example, it was found that the sometimes "cartoon like" effect which may arise from imperfect matches of color and texture in creating exterior renderings, could be reduced by converting the color rendering to black and white and reducing the number of shades of gray.

Simulation is a special case of realism in which the conventions are well-formed mathematically and fidelity is strived for at all levels. Computer-aided textural rendering is often presumed to be equivalent to simulation, but it shouldn't be. Even if realism is the goal, there are often cases where local inaccuracy will contribute to global accuracy. Like any other medium, it contains rhetorical elements. It makes assumptions, often by means of leaving things out: drawing remains the art of what you don't show. Rendering involves interpretation. If we are to learn from conventional media, we will develop a sophisticated culture of indirect representation. The implication is that the manipulations of texture space are a nascent artistic medium, in which early endeavors will possibly seem banal, but in which expressive conventions will emerge, with the passage of time, and masterpieces will become possible. We must head in that direction.

References.


Illustration Credits.

1. Paul Stevenson 
2. Stephen Buerich 
3. Jerry Woznowicz 
4. Warren Wake 
5. Alex Aisenson 
6. Warren Wake 
7. Alex Aisenson 
8. Alex Aisenson 
9. Ta-Wei Chou 
10. Ta-Wei Chou 
11. public domain photo 
12. Eui-Young Chun

62