Thank you for using the
University at Albany's
Interlibrary Loan Service

Questions?

Call 442-3613 from 10:00 ~ 4:30 (weekdays)

or

Send email to libill@albany.edu

Non-Photorealistic Rendering and Terrain Representation

In recent years, a branch of computer graphics termed non-photorealistic rendering (NPR) has defined its own niche in the computer graphics community. While photorealistic rendering attempts to render virtual objects into images that cannot be distinguished from a photograph, NPR looks at techniques designed to achieve other ends. Its goals can be as diverse as imitating an artistic style, mimicking a look comparable to images created with specific reproduction techniques, or adding highlights and details to images. In doing so, NPR has overlapped the study of cartography concerned with representing terrain in two ways. First, NPR has formulated several techniques that are similar or identical to antecedent terrain rendering techniques including inclined contours and hachures. Second, NPR efforts to highlight or add information in renderings often focus on the use of innovative and meaningful combinations of visual variables such as orientation and color. Such efforts are similar to recent terrain rendering research focused on methods to symbolize disparate areas of slope and aspect on shaded terrain representations. We compare these fields of study in an effort to increase awareness and foster collaboration between researchers with similar interests.

Patrick J. Kennelly
Department of Earth and
Environmental Sciences
CW Post Campus of
Long Island University
Patrick.Kennelly@liu.edu

A. Jon Kimerling
Department of Geosciences
Oregon State University
kimerlia@geo.orst.edu

Keywords: Non-photorealistic rendering, terrain rendering, computer graphics

INTRODUCTION

T he discipline of cartography is not an island, entire of itself. Many areas of inquiry that border on or overlap cartography, such as data classification using statistics, are well documented. Others are not as well delineated, especially with the boom in computer technology in recent years. An example is non-photorealistic rendering (NPR) in computer graphics. In this paper, we map out disjoint but similar research efforts ongoing in NPR and terrain rendering in cartography, highlighting areas of overlapping interests.

Since the earliest graphic output from computers, one goal that researchers in computer graphics strive towards either explicitly or implicitly is photorealism. A computer graphic image is said to be photorealistic if it is virtually indistinguishable from a photograph of the same object. Such a goal may be subjectively evaluated by the user with visual inspection, or objectively evaluated with such tools as light meters.

Although photorealistic images can be made in a number of ways, a typical methodology would be to represent a real world object as a virtual computer object, and then create an image of the virtual object based on characteristics such as shape, color and texture inherited from the real world object. This process is referred to as rendering (Rogers, 1997). In practice, rendering in computer graphics often refers to using information

"In this paper, we map out disjoint but similar research efforts ongoing in NPR and terrain rendering in cartography, highlighting areas of overlapping interests."

from a three dimensional (3-D) computer model to create a two dimensional (2-D) image.

Non-photorealistic rendering is a more exclusive term than its name may imply. Any rendering whose purpose is other than photorealism is not necessarily included in this subject area. Instead, NPR researchers have defined a number of alternative goals for their rendering. These include: scientific curiosity, similarity to handmade graphics, communication of specific information, hypothesis of a language of pictures, and a better understanding of the mechanism of meaning transfer (Strothotte and Schlechtweg, 2002). These diverse goals can be thought of as a categorization of non-photorealistic computer graphics research within the last 15+ years. Some early works focused on NPR techniques restricted to image space; a 2-D image is manipulated to create a different 2-D image. A seminal work that discussed NPR techniques applied to 3-D objects and displayed in 2-D image space is Saito and Takahashi's 1990 article entitled *Comprehensible Rendering of 3-D Shapes*. This work was important in its discussion of geometric buffers to define the object in 3-D space, and comprehensible rendering—techniques with a focus on the effect the rendering has on the viewer. This article also included digital terrain (and building) data that were rendered with shading, contours, oblique profile lines, and height data (elevation layer tinting). This is one of the few uses of terrain data reported in the NPR literature.

In the 1990's, a sense of identity began to develop among NPR researchers. Computer graphics research published in journals, such as the *Institute of Electrical and Electronics Engineers' Computer Graphics and Applications* (IEEE CG&A), explicitly defined goals other than photorealism. The Association for Computing Machinery's (ACM) Special Interest Group for Computer Graphics (SIGGRAPH) conference began sessions on research in non-photorealistic rendering later in the decade.

The beginning of the 21st century brought a flurry of activity that helped to shape the field of NPR. Now a biennial event, the first International Symposium on Non-Photorealistic Animation and Rendering was held in 2000 in Annecy, France. Two important books were also published during this time, Gooch and Gooch's *Non-Photorealistic Rendering* (2001) and Strothotte and Schlechtweg's *Non-Photorealistic Computer Graphics* (2002). These entities helped to shape NPR's identity and categorize its research in a broad range of topics. Topics are diverse and include recreating artistic styles (from watercolor paintings to sumi-e art), the rendering of mechanical drawings, medical imaging, and cartoon animation.

Strothotte and Schlechtweg (2002) assign NPR literature to a number of "points of view." Most of these have direct counterparts in the field of cartography. As examples, "the freedom not to have to reproduce the appearance of objects precisely as they are" would include cartographic generalization, and "the possible deformations of images" would include map projections. Our primary interest is in NPR techniques that are similar to methods used for terrain rendering. These include specific drawing styles and the effect a rendering has on a viewer-comprehensible rendering.

In a general sense, many current software applications for computer graphics may be considered photorealistic-neutral. The user may render a virtual office building with textures of glass and steel, but could also render the same building with a paisley pattern. The focus in computer graphics, as with cartography, is often the purpose of the rendering and the perceived user. For example, a land use/land cover map with hill shading may look less like realistic terrain than a layer tinted map, but may better communicate important patterns to the user.

"Non-photorealistic rendering is a more exclusive term than its name may imply. Any rendering whose purpose is other than photorealism is not necessarily included in this subject area."

"Topics are diverse and include recreating artistic styles (from watercolor paintings to sumi-e art), the rendering of mechanical drawings, medical imaging, and cartoon animation."

"Our primary interest is in NPR techniques that are similar to methods used for terrain rendering. These include specific drawing styles and the effect a rendering has on a viewer-comprehensible rendering."

In this article, we explore the connections between techniques of terrain rendering and NPR. We hope to raise awareness with both cartographic and NPR researchers about the shared areas of research. We also hope that this knowledge may lead to cross fertilization of ideas and collaboration among those doing research in these two fields. Additionally, in reviewing historical and recent stylized techniques for terrain representation, we illustrate that multiple techniques of depiction has always been an important consideration for terrain representation in particular and cartography in general.

DRAWING STYLES IN TERRAIN RENDERING AND NPR

Hatching lines

To introduce drawing styles in NPR, we look first at hatching lines. Hatching lines can be drawn in 3-D object space to show the curvature of the surface. 3-D objects in computer graphics are described with different criteria than those we use for terrain. Beginning with a datum such as mean sea level, cartographers can define the orientation of any surface element using slope and aspect. Most computer graphics objects, however, have no such datum. Thus they are often described by a series of geometric buffers (g-buffers).

Figure 1 compares geometric components used in NPR (and more generally in computer graphics) and those used in terrain representation. **Figure 1a** includes a 3-D virtual model to be represented as a 2-D image on some viewing plane. The rendering will be based on a number of g-buffers, including an identifier of the object within the virtual scene (id-buffer), the distance from the object to the viewing plane (z-buffer), and the surface normal vector (n-buffer) (terminology from Strothotte and Schlechtweg, 2002).

Figure 1b includes a 2.5-D virtual model to be represented as a 2-D planimetrically correct map (planimetric view). Elevation is measured from a datum plane parallel to the planimetric map, unlike the z-buffer, which is measured from the viewing plane. We also use slope and aspect as a surrogate for the n-buffer to uniquely define the orientation of a surface element in object space.

If the viewing plane in **Figure 1a** were to be moved, all z-buffers would need to be recalculated to re-render the image, a common practice in NPR. This is not an issue for planimetrically correct maps, as the viewing plane is always set parallel to the datum plane, and elevation values are invariant with a fixed datum. Those working with terrain rendering have often chosen to work within this planimetric construct that simplifies rendering, but at the same time limits the variability of resulting displays.

The more flexible and less globally consistent nature of NPR rendering is exemplified in Saito and Takahashi's (1990) torus with hatching lines and shading (**Figure 2**). The torus has no datum, so a (u,v,z) coordinate system needs to be defined for this particular object. If the torus were lying flat on a table, **Figure 2a** would correspond to a series of radial planes perpendicular to the table and intersecting at the torus' central axis, and **Figure 2b** would represent traces resulting from intersecting the torus with a series of planes parallel to the table. **Figure 2c** combines shades of gray with these hatching lines over part of the image, using the two hatching line patterns independently or in combination to create a crosshatched pattern.

Figure 2 reveals that hatching lines would fit into a cartographic classification system as a hybrid between short, discontinuous hachures (note

". . . we illustrate that multiple techniques of depiction has always been an important consideration for terrain representation in particular and cartography in general."

"3-D objects in computer graphics are described with different criteria than those we use for terrain."

"Those working with terrain rendering have often chosen to work within this planimetric construct that simplifies rendering, but at the same time limits the variability of resulting displays."

a) Selected elements of the framework used in rendering computer graphics.

b) Selected elements of the framework used in terrain representation.
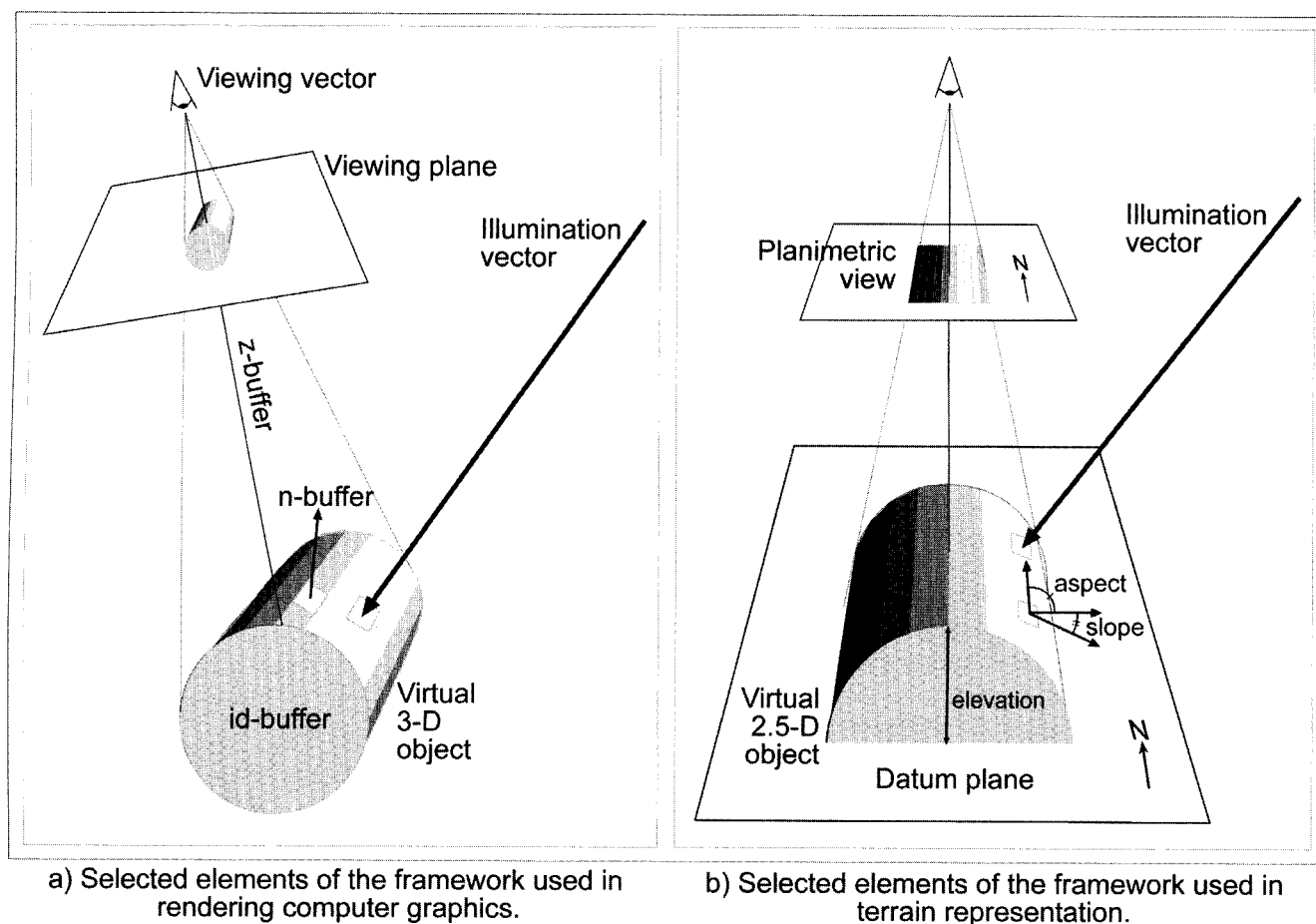
Figure 1. Selected elements of the frameworks used for rendering computer graphics and terrain. a) The geometric buffers used for rendering, including the z-buffer, n-buffer, and id-buffer. Also shown are the relationships among the viewing vector and plane, the 3-D virtual object, and the illumination vector. b) The metrics used for representing terrain, including elevation, slope and aspect. Also shown are the relationships among the planimetrically correct map, the datum plane, and the illumination vector. (see page 84 for color version)
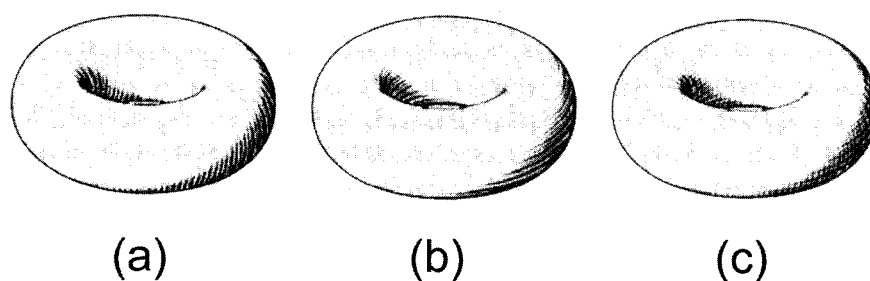

(a)   **(b)**   **(c)**

Figure 2. A torus rendered with hatching and shading. Methods include a) hatching lines similar to cartographic hachures, b) hatching lines similar to cartographic isarithmic lines, and c) cross hatching (a combination of the first two) (Reprinted from Saito and Takahashi (1990) with permission from ACM SIGGRAPH)

difference in spelling) and long, continuous isarithmic lines or contours. Both cartographic techniques are based not on a (u,v,z) coordinate system specific to a particular object, but on a global datum that locally approximates a flat surface. In this construct, discontinuous hachure strokes are oriented in the direction of steepest slope and continuous contour lines are oriented parallel to the datum with no change in slope. Thus if the torus in

Figure 2 were lying flat on the table as datum, the hatching lines of Saito and Takahashi (1990) in **Figure 2a and 2b** would approximate cartographic hachure strokes and contours respectively.
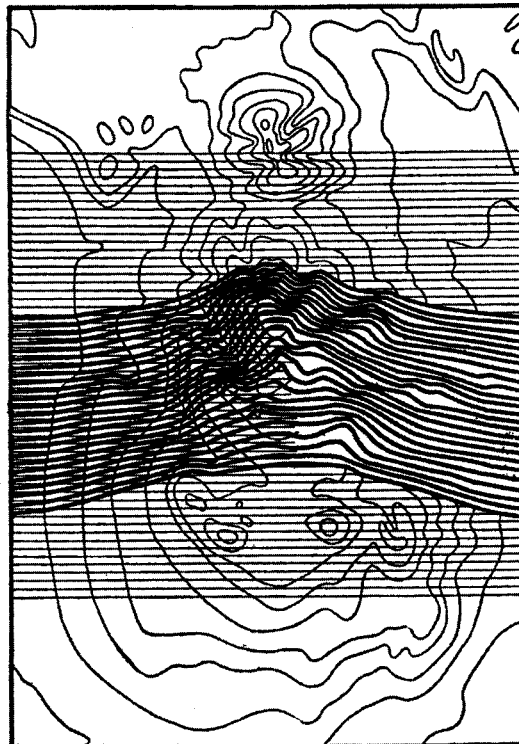
In the field of NPR, Deussen (1998) and Deussen *et al.* (1999) devised a method for generating continuous hatching lines of uniform thickness by intersecting a 3-D virtual object with parallel planes. The technique extracted traces on boundaries defined by a number of parallel, evenly spaced clipping planes. **Figure 3a** shows a 3-D virtual statue rendered with such a technique. No datum is, or need be associated with such a 3-D object, but the parallel planes used in rendering can be said to be tilted up and dipping towards the top of the page. This rendering technique is nearly identical to the inclined contour method devised by Tanaka (1932) 66 years earlier.

Tanaka's first method of rendering landforms was the orthographic relief method, although it is commonly called the inclined contour method (Tanaka, 1932). Instead of using planes parallel or perpendicular to the datum to create contours or profiles respectively, Tanaka intersected the topography with evenly spaced parallel planes at an oblique orientation to the datum. Although these traces have no intuitive meaning, each trace is in its proper planimetric location. Assuming north to the top of the page, parallel planes dipping directly to the south will result in a trace that appears as a hybrid between a contour and a profile. The resulting shading effect gives the appearance of illumination from the south, with

"This rendering technique is nearly identical to the inclined contour method devised by Tanaka 66 years earlier."
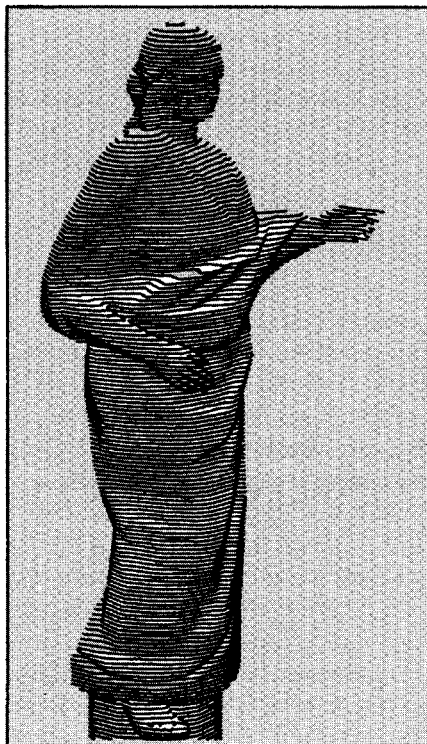
a) NPR rendering by Deussen (1998)   b) Terrain rendering by Tanaka (1932)   c) Terrain rendering using the GIS method of Peuker et al. (1974)
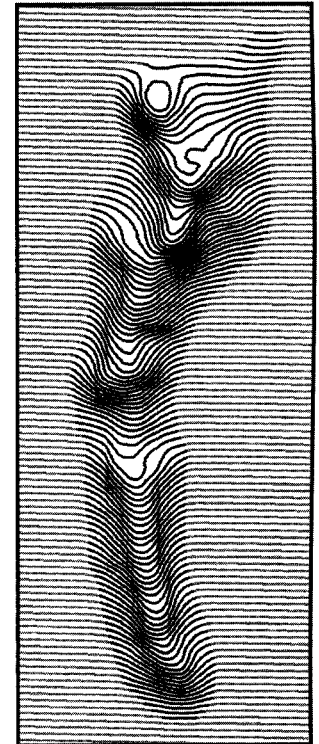
Figure 3. Three examples rendered from traces resulting from the intersection of a series of parallel planes and a virtual object. The first shows lines resulting from the intersecting a geometric model of a statue and a series of evenly spaced parallel planes. (From Deussen (1998) with permission from Springer-Verlag Publishers).The second illustrates Tanaka's inclined contour method (from Tanaka (1932) with permission from The Geographical Journal). The third is a map created from a generalized digital elevation model of the Newfoundland mountains of northwestern Utah. Planes dipping to the north are used with Tanaka's inclined contour method as computer automated by Peucker et al. (1974).

the unfortunate consequence of perceptually inverting the topography for most users (**Figure 3b**).

In **Figure 3b**, Tanaka began with a contour map, then drew parallel lines oriented east-west. The constant spacing of the lines determined the steepness of the oblique, intersecting plane. Contours were then redrawn on the oblique plane. Beginning with the lowest topographic contour, inclined contour traces move to subsequent contour levels each time a higher landform contour intersects a higher contour on the oblique plane. The resulting spacing of lines results in oblique illumination of the terrain.

"The simplest methodology takes the terrain surface, adds it to a dipping plane surface, and then contours the new surface in the traditional manner."

Early geographic information system (GIS) technology automated the inclined contour technique (Peucker *et al.*, 1974). The simplest methodology takes the terrain surface, adds it to a dipping plane surface, and then contours the new surface in the traditional manner. **Figure 3c** is an inclined contour map of the Newfoundland Mountains of northwestern Utah, rendered using a generalized digital elevation model and parallel planes dipping to the north, which is to the top of the page. The rendering is similar to Deussen's NPR image in **Figure 3a**.

Inclined planes used to create the rendering can have any orientation, but planes that do not slope down to the south will not result in traces resembling pseudo-profiles for a map with north to the top of the page. Robinson and Thrower (1957) used planes dipping to the south, and refined Tanaka's technique by adding lines to the shaded side of terrain to give the impression of northwest illumination (**Figure 4a**).

More recently, Visvalingam and Whelan (1998) and Visvalingam and Dowson (1998) devised the profile-stroke (P-stroke) method. This sketch-based method is a filtered subset of profile plots of concave and convex surfaces presented as an oblique view of the terrain (**Figure 4b**). These simplified sketches mimic landscape drawings and were inspired by the inclined contour renderings of Robinson and Thrower (1957). This work is the only research in cartographic visualization widely cited within the NPR literature.

"These simplified sketches mimic landscape drawings and were inspired by the inclined contour renderings of Robinson and Thrower."

Stroke-Based Illustrations

One research focus in NPR is creating images based on individual line segments that simulate the style associated with pen-and-ink illustrations. This stroke-based illustration method, which resulted from NPR research on artistic form, compiling rules and computer automation of the process, depicts both tone and texture simultaneously (Gooch and Gooch, 2001). In some cases, these methods were based solely in image space; the user would begin with an image, use brush tools to define the orientation of strokes throughout the image, and apply stroke textures provided by the application (Salisbury *et al.*, 1994, Salisbury *et al.*, 1996, and Salisbury *et al.*, 1997). **Figure 5a** shows detail of a pen and ink rendering of a raccoon's face created from an image.

"Similar to the procedure of NPR researchers, early mapmakers defined rules and automated the resulting steps in creating hachures."

Similar to the procedure of NPR researchers, early mapmakers defined rules and automated the resulting steps in creating hachures. Swiss Major J.G. Lehmann in 1799 was the first to quantitatively represent the terrain with hachures. He used black lines oriented in the aspect direction with the thickness of the line proportional to the slope (Robinson *et al.*, 1995). Imhof (1982) and Slocum *et al.* (2005) include a list of all rules for hachuring. An example of a slope hachure map created by Lehmann (1843) and reproduced in Imhof (1982) is shown in **Figure 5b**.

Quantitative rendering with hachures began with a contour framework, with the spacing and orientation of contours determining orientation and thickness of hachures. Strictly applied, however, hachures render
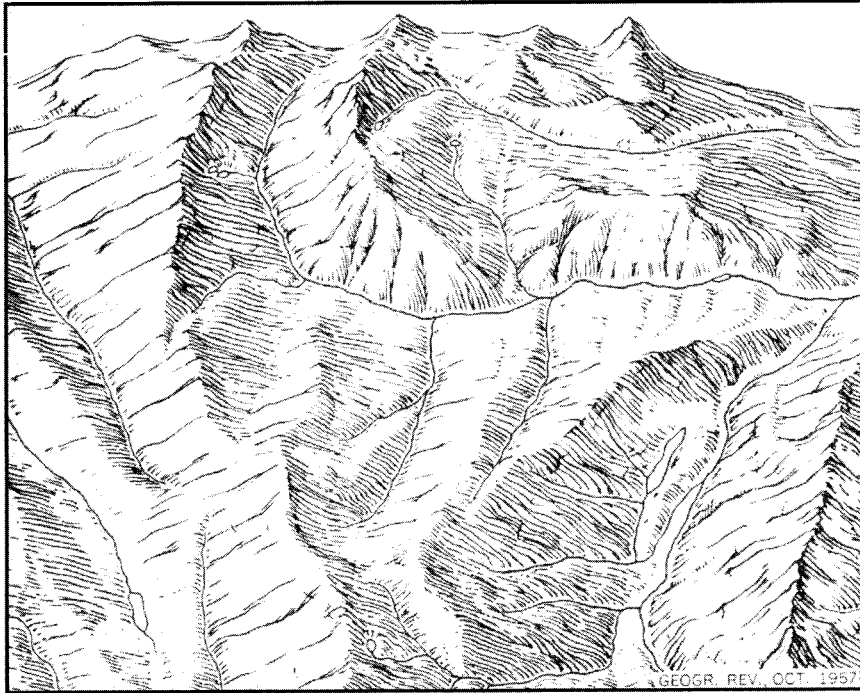
a) Hand rendering by Robinson and Thrower (1957)
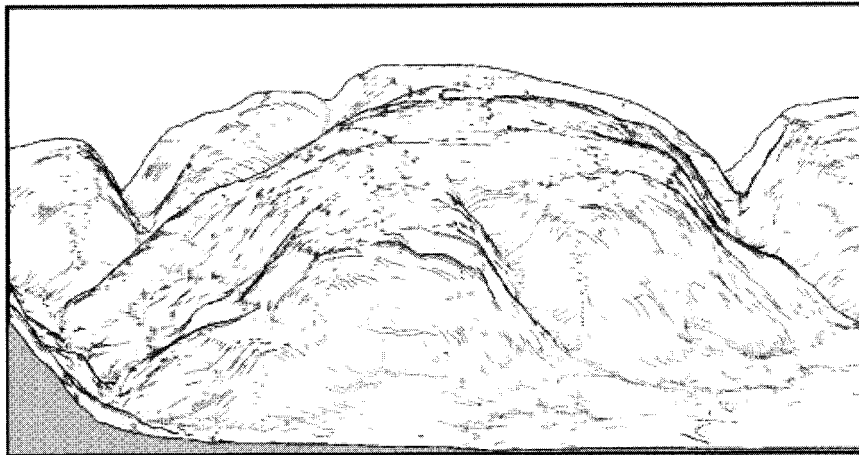
b) Computer rendering by Visvalingam and Whelan (1998)

Figure 4. Two examples of stroke based renderings of terrain. The top is a planimetrically correct map of the Camp Hale area of Colorado based on Tanaka's inclined contour method. Additional strokes have been added on the more shaded side of the terrain to enhance the 3-D appearance (From Thrower and Robinson (1957) with permission from the Geographic Review). The bottom is an oblique view of a terrain rendered with the profile stroke (P-stroke) method. (From Visvalingam and Whelan (1998) with permission from Eurographics UK).

landforms as if illuminated from a vertical source. To simulate oblique illumination, cartographers used aspect, slope and illumination direction to adjust variations in thickness of black hachures on a white background. This permitted illuminated and non-illuminated surfaces to be more easily distinguished. An example of a portion of such a shadow hachure map of Üetliberg (near Zürich) from Imhof (1982) is presented in **Figure 5c**.

a) NPR rendering using a pen-and-ink method
(Salisbury et al., 1997)

b) Terrain rendering using slope hachuring
(Lehmann, 1843)

Figure 5. Examples of a pen-and-ink rendering and two hachure maps. The top is a pen-and-ink rendering of an image of a raccoon (From Salisbury et al., 1997).The middle is a planimetrically correct slope hachure map of a steep mountain region drawn by Lehmann and originally published in 1843 (Reproduced in Imhof (1982), Chapter 1, Figure 13, p. 10). (Reprinted with permission from Walter de Gruyter). The bottom is a planimetrically correct shadow hachure map of Üetliberg near Zurich (From Imhof (1982), Chapter 10, Figure 150, p. 223. Reprinted with permission from Walter de Gruyter).

c) Terrain rendering using shadow hachuring
(Imhof, 1982)

All images from **Figure 5** show fine detail, with tone and texture working together to create a shading effect. Hachure maps, however, are usually created from an object space model of the topography. In the case of **Figures 5b** and **5c**, the model is an elevation contour map of the area. NPR research has also identified methods to create pen-and-ink illustrations directly from object space (Winkenbach and Salesin, 1994 and Winkenbach and Salesin, 1996). Objects are represented by parametric surfaces, and strokes are drawn in directions related to the 3-D geometry of the object. **Figure 6a** is an example of a wooden bucket rendered from object space.

Yoeli (1985) was the first to computer automate rule-based hachuring. An example of his results is presented as **Figure 6b**. He began with a contour framework and applied Imhof's (1982) rules for shadow hachuring. Lines tend to have a wavy appearance as individual straight hachure lines vary slightly in aspect direction between sequential contours.

Portions of the two renderings in **Figure 6** have a similar appearance but reflect important differences between techniques. The wavy strokes in Winkenbach and Salesin's (1996) illustration are not the result of minor variations in orientation. Instead, they are customized strokes to mimic the texture of wood. Additionally, longer strokes of varying thickness were used in the same direction to represent gaps between the individual

"Yoeli was the first to computer automate rule-based hachuring."
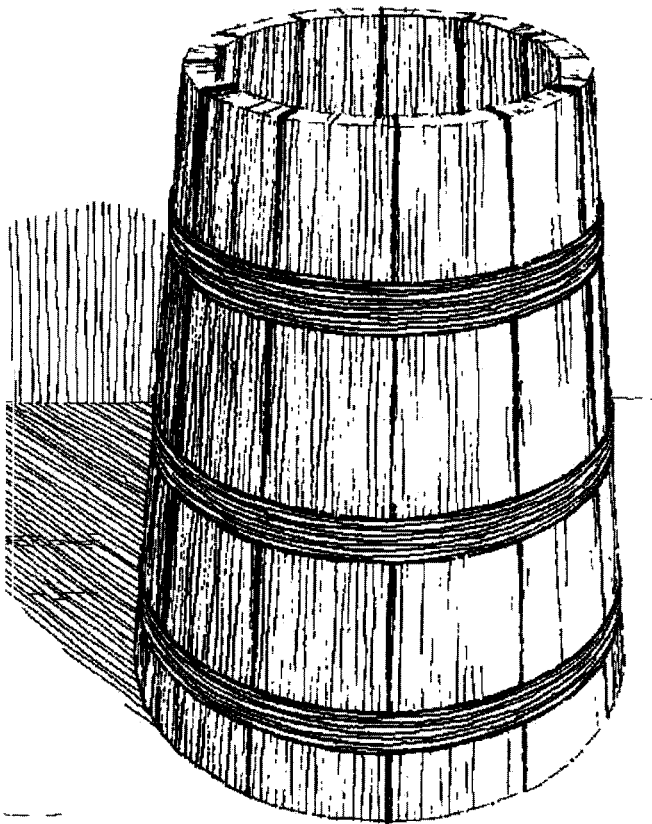
a) Pen-and-ink rendering
of a 3D parametric surface
(Winkenbach & Salesin, 1996)

b) GIS rendering of a terrain
(Yoeli, 1985)

Figure 6. Computer automated renderings from virtual 2.5-D and 3-D objects using hachure mapping and pen-and-ink drawing methods. The left is a pen-and-ink rendering of a wooden bucket (From Winkenbach and Salesin (1996) with permission from ACM). The right is a planimetrically correct shadow hachure map created from a framework of isarithmic lines (From Yoeli (1985) with permission from the Cartographic Journal).

boards. Finally, straps were drawn with strokes that were based on the geometry of the virtual object, but at an orientation orthogonal to that of the wood texture and gaps. This NPR rendering began with a smooth 3-D object, used enhancement techniques to apply textures, and thus depicted textures associated with naturally occurring terrain perturbations.

Buchin *et al.* (2004) extended the use of hachure lines into 3-D. They used slope lines to render landscape illustrations with oblique illumination techniques by calculating stroke density. They also used a textured based approach, moving away from the uniform lines used by Yoeli (1985) in his hachure maps. They applied these line drawings on oblique views of terrains.

ADDING HIGHLIGHTS AND DETAILS FROM OBJECT SPACE

"Two issues associated with such losses listed by Strothotte and Schlechtweg are (1) lack of contrast between adjacent objects of the same color, and (2) a clear indication of surface shape or curvature."

Comprehensible rendering recognizes that shading can result in lost information in the transition from 3-D object space to 2-D image space. Two issues associated with such losses listed by Strothotte and Schlechtweg (2002) are (1) lack of contrast between adjacent objects of the same color, and (2) a clear indication of surface shape or curvature. We will discuss current NPR and terrain rendering research that addresses these issues.

Silhouette, Crease and Boundary Lines

Objects rendered with NPR can be complex 3-D models with significant changes in orientation at edges between adjacent faces. The resulting feature edges are of particular concern in the rendering process. Feature edges include silhouettes and creases. A silhouette is defined from the viewing vector (Gooch and Gooch, 2001). At a silhouette point, the surface normal vector would be perpendicular to the viewing vector. In other words, it acts as an edge between the portion of the 3-D model facing towards and away from the viewer. A crease is an edge defined by an abrupt change in the orientation of the surface normal (Gooch and Gooch, 2001). The user can define a threshold angle; if the angular difference between two surface normal vectors exceeds the threshold, then a line representing a crease is included in the rendering. Creases are defined by the 3-D object and thus view invariant, while silhouettes vary with the orientation of the viewer.

"Creases are defined by the 3-D object and thus view invariant, while silhouettes vary with the orientation of the viewer."

Gooch *et al.* (1999) used black silhouette lines and white crease lines with shaded facets to render technical illustrations (**Figure 7a**). Using an illumination source for shading on the visible portion of the 3-D model, white creases tend to highlight the shading. Black silhouette lines also highlight shading, indicating areas where a portion of the 3-D model is hidden from view.

"Creases in terrain appear to be unexplored, but may be trivial compared with the related but more geographically meaningful topographic features such as stream valleys and drainage divides."

Cartographers creating planimetrically correct maps have had no strong motivation to explore silhouettes or creases in terrain rendering. They generally use 2.5-Dimensional (2.5-D) data models to represent topography, in which any (x,y) location has one and only one z value (Weibel and Heller, 1991). This format ensures the absence of silhouette lines on planimetrically correct maps. Creases in terrain appear to be unexplored, but may be trivial compared with the related but more geographically meaningful topographic features such as stream valleys and drainage divides.

Tanaka's (1950) cartographic technique for planimetrically correct representation of terrain caused some discussion of representing edges. Tanaka's relief contour or illuminated contour method was a procedure for drawing black and white contours of variable thickness to represent
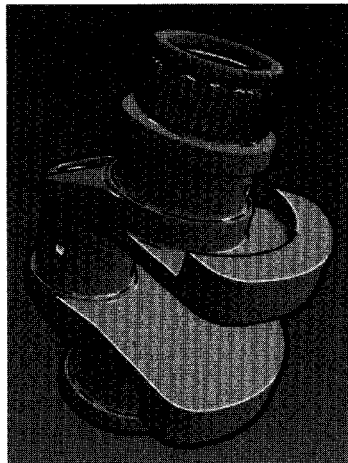
a) Silhouette and crease
lines (Gooch et al., 1999)

b) Illuminated contours
(after Imhof, 1982)
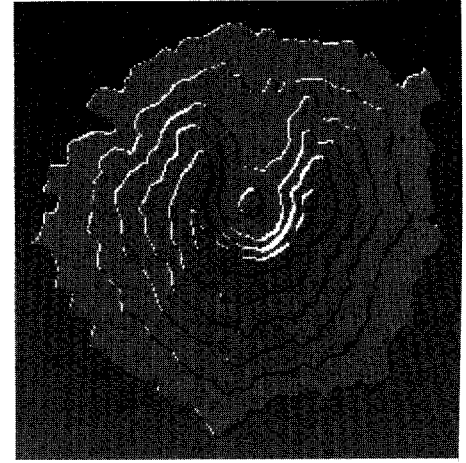
c) Illuminated contours (after
Kennelly and Kimerling, 2001)

Figure 7. A comparison of illuminated contours with crease and silhouette lines. The right shows silhouette lines in black and crease lines in white designed to communicate the shape and structure of a complex mechanical model (Reprinted from A.A. Gooch and B. Gooch, 1999 with permission from ACM SIG-GRAPH). The middle is a hand-rendered illuminated contour map (Modified from the cover of Imhof (1982)). The left is a computer automated illuminated contour map of Mt. St. Helens in Washington state (modified from Kennelly and Kimerling (2001) with permission from Cartography and Geographic Information Science). (see page 85 for color version)

non-illuminated and illuminated areas. Black contours approximated a shadow cast by a flat, stepped surface and white contours approximated similar features cast in negative from a light source 180° from the true direction of illumination. In essence, the topography was being approximately rendered as if it were a stack of cardboard layers cut from contour outlines.

Imhof (1982) discusses Tanaka's (1950) technique, and includes an example of such a map on the cover of his book (modified as **Figure 7b**). He criticized the technique saying that it gives an unnatural impression of steps. Kennellly and Kimerling (2001) attempted to mitigate this effect by using surface normal orientation instead of the aspect direction used by Tanaka to vary line thickness. The resulting illuminated contours are thinner in areas of gentle slope, and thicker in areas of steeper slope (**Figure 7c**). Regardless, illuminated contour techniques can be thought of as rendering topography by representing contours as a vertical step between otherwise flat areas. In NPR terminology, this method creates creases where none naturally exist.

To see the relationship between illuminated contours and silhouette lines, we would have to move away from the planimetrically correct map. Imagine a virtual model based on the contour cutout model. If the viewer (as represented by the viewing vector) were to look at the model from the same direction as the illumination vector, all silhouette lines would correspond with black contours. The remaining crease lines would correspond with white contours.

Halftones in Object Space

Computer graphics have always expressed a strong interest in the method by which images are displayed and reproduced. Computer graphics research has delved extensively into the arena of digital halftoning or dithering (for example Ulichney, 1987). For grayscale images, this involves using black and white pixels for display on a computer monitor. Cartography has shown similar interest in halftoning (for example Robinson *et al.*, 1995,

"In essence, the topography was being approximately rendered as if it were a stack of cardboard layers cut from contour outlines."

"To see the relationship between illuminated contours and silhouette lines, we would have to move away from the planimetrically correct map."

"It seems fair to say the primary interest of cartographers has been similar to computer graphic researchers seeking photorealistic results; both want to create continuous tones of gray for more realistic displays."

pp. 367-370). It seems fair to say the primary interest of cartographers has been similar to computer graphic researchers seeking photorealistic results; both want to create continuous tones of gray for more realistic displays. This is accomplished primarily by using patterns of black and white pixels that are as difficult to detect as possible. The result is an image or map with smoothly varying shades of gray, and completely lacking in texture from the black and white pixels used to create the shade of gray.

NPR researchers have taken the dithering process from a procedure traditionally done in 2-D image space to a process that takes information from 3-D object space and use this information for orienting halftones in the rendering. Veryovka and Buchanan (1999) used such comprehensible rendering to orient halftones on an image of three objects of variable shape and orientation. **Figure 8a** shows the results of using the surface normal vector to define halftone orientation. A close-up of the sphere reveals that elongate black pixel patterns follow the orientation of the 3-D object.

Kennelly (2002) used halftones oriented in the aspect direction to create a similar effect (**Figure 8b**). These orientations are determined using aspect information from the 2.5-D digital elevation model and classified into 12 categories. The resulting display allows 16 shades of gray based on classifying hill shade values. The resulting map adds surface orientation information to the hill shading as a halftone-based texture.

Obvious differences are evident between **Figure 8a** and **8b**. One difference is Veryovka and Buchanan (1999) assigned a different texture to each object (cylinder, sphere and box) for better visual separation. They also developed an error diffusion algorithm to vary texture contrasts and tones throughout the image. The result of the error diffusion step is that their image looks smoothed; the GIS rendering looks stark by comparison. Finally, the GIS rendering orients all halftones in the aspect direction. The NPR rendering varies orientation with a surface normal defined by a g-buffer, but this does not uniquely define the orientation of the halftone pattern. For example, halftones are oriented around the curved side of the cylinder (direction of maximum curvature), but they could just as easily been oriented in a parallel manner from the cylinder's base to its top (direction of no curvature).

"Veryovka and Buchanan (1999) used such comprehensible rendering to orient halftones on an image of three objects of variable shape and orientation."

Color for Detailed Rendering

Colors can also be applied to images based on information from 3-D object space. NPR research has specifically looked at the use of color to enhance shading. Gooch *et al.* (1998) vary colors by modifying the classic diffuse and specular shading models, the latter shown on sample hemispheres at the top of the left side of **Figure 9**. They combined two color properties into their scheme as illustrated at center left. First, they assigned a color to an object, and then modulate it through a scaled range of grayness based on shading. Next, they used warm to cool color variations, such as pure blue to yellow. The changes in temperature created the illusion that cool colors recede and warm colors advance. Additionally, Gooch *et al.* (1999) note this change in color temperature is associated with a shift in luminosity. The bottom left of **Figure 9** shows a mechanical drawing using three object colors based on id-buffer. Each color is a linear blend of two tonal variations, with a Phong shading model used to create specular shading.

"The changes in temperature created the illusion that cool colors recede and warm colors advance."

Color techniques have also been used for terrain rendering. Moellering and Kimerling (1990) devised the MKS-ASPECT™ color scheme using the Hue-Lightness-Saturation (HLS) color space. The HLS color model is represented as a two cones with hexagonal bases fitted together base to base. Lightness varies along the central axis, with all fully saturated
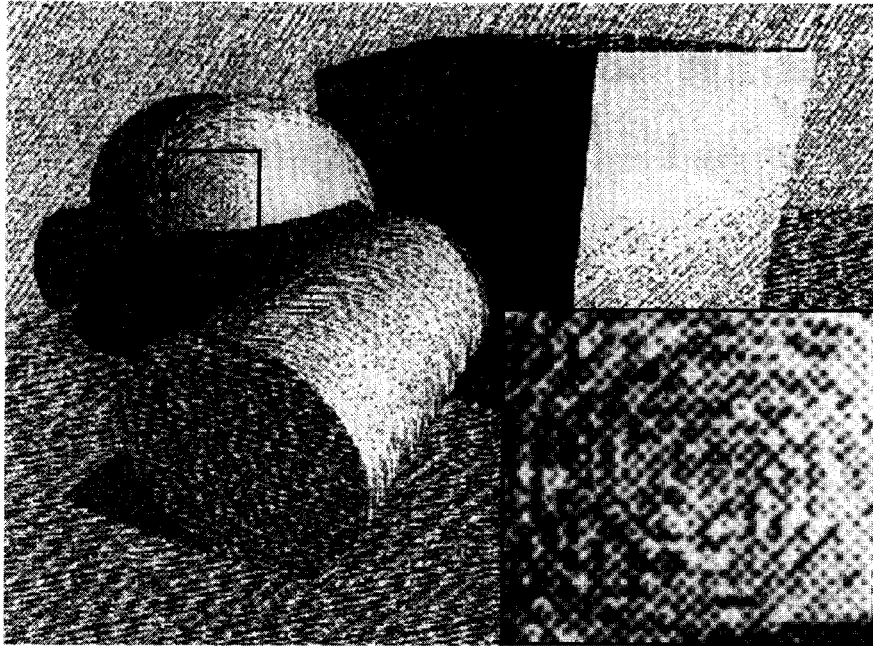
a) Oriented halftones of 3D shapes
(after Veryovka and Buchanan, 1999)
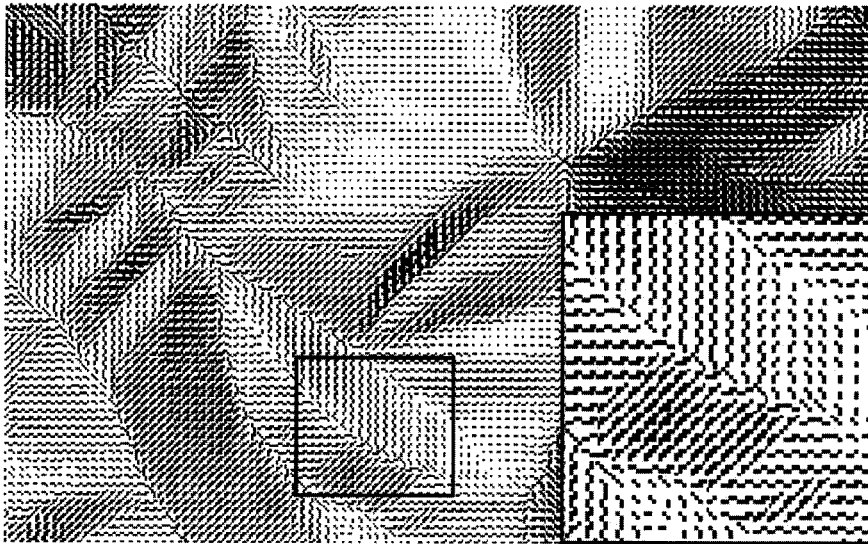
a) Oriented halftones of 2.5D terrain model
(after Kennelly, 2002)

Figure 8. Two examples of images with oriented halftones. The top shows geometric objects whose texture is based in part on halftones whose orientation is controlled with information stored in geometric buffers (g-buffers) (Modified from Veryovka and Buchanan, 1999 with permission from NCC Blackwell Ltd.). The bottom shows a planimetrically correct map of the Sweet Grass Hills of north-central Montana using halftones oriented in the aspect direction. (From Kennelly, 2002, with permission from Cartographic Perspectives).

colors having a lightness of 50%. The 50% lightness slice of the HLS color model forms a hexagon similar in appearance to a color circle of all hues. Selecting colors around the slice, they sought easily discriminated colors. Additionally, the relative luminance of the selected colors as measured on
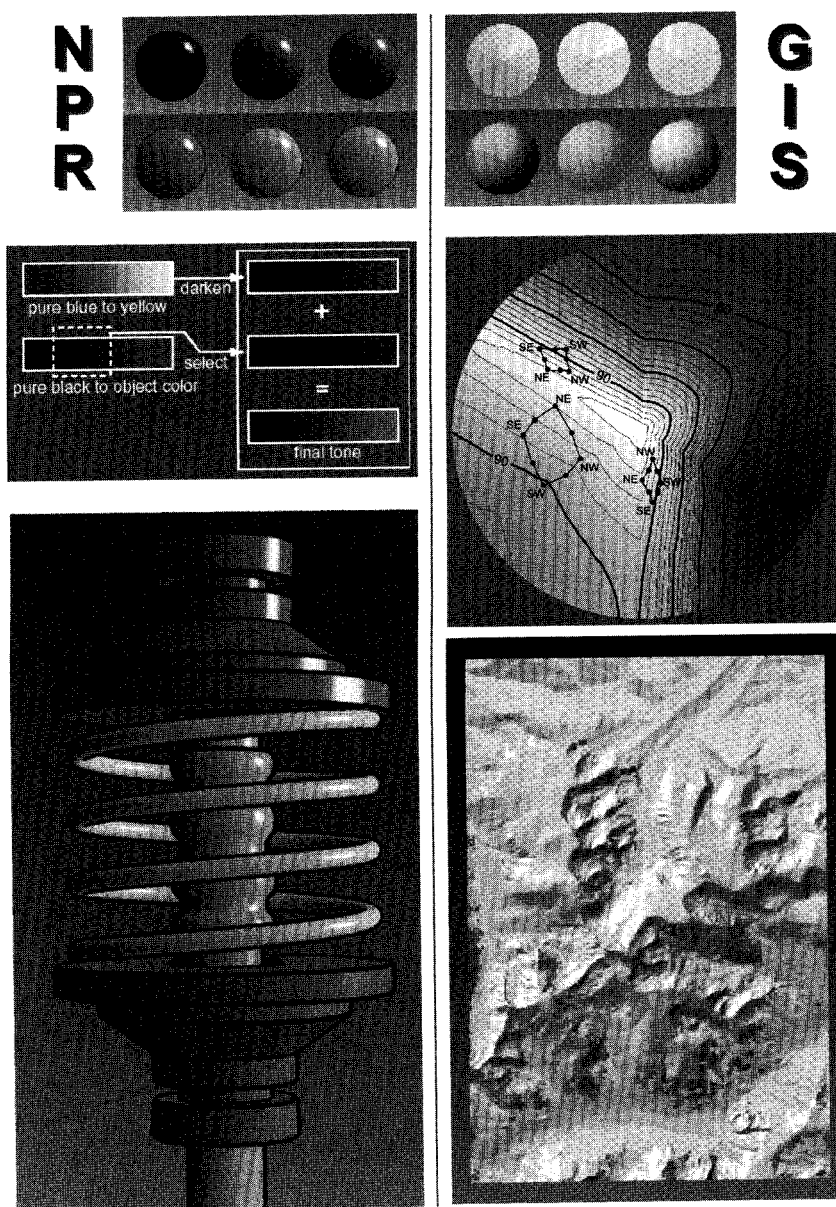
Figure 9. These two coloring schemes add color details and highlights to conventional shading techniques. The NPR technique on the left uses cool to warm undertones to add subtle tonal variations to object colors (From Gooch et al., 1998 with permission from ACM SIGGRAPH). The terrain rendering scheme on the right of a portion of the Absaroka mountains of southwestern Montana uses aspect-variant colors that add luminous highlights and enhance shading of surface elements (Modified from Kennelly and Kimerling (2004) with permission of Cartography and Geographic Information Science). (see page 86 for color version)

the computer screen with a spectrophotometer matched a modified cosine illumination intensity function. The resulting rendering replaced ambiguous shades of gray with unique colors, while approximating traditional hill shading effects.

Brewer and Marlow (1993) devised a scheme based on aspect and slope using the Hue-Value-Chroma (HVC) color model. In the HVC color model, differences in each variable are perceptually equidistant. As with the previous technique, colors were selected around the entire color circle. They did not, however, try to match a theoretical cosine curve, but rather

used this color model to maximize lightness differences among hues. Additionally, they varied chroma, which is similar to saturation, with slope, using more saturated colors for steeper land forms.

Kennelly and Kimerling (2004) introduced the idea of applying colors with aspect-variant luminosity using the Hue-Saturation-Value (HSV) color model, and then hill shading in a traditional manner. HSV is a popular color model for software that includes color pickers. With such color model, it is easy to see the relationship among colors to be picked or modified. For example, users can begin with a green, and then see other shades of green nearby that can be described by such terms as richer, paler, more yellowish-green, or more blueish-green. HSV, however, is distorted with respect to the luminance of colors. Colors of 100% value (the V of HSV) can have very different luminosity. Kennelly and Kimerling (2004) mapped the luminosity for all colors on the 100% V slice of this color model to use with an aspect variant color scheme.

"HSV, however, is distorted with respect to the luminance of colors."

Examples of such GIS-based shading applied to sample hemispheres are presented for comparison with those of Gooch *et al.* (1999) at the top of the right side of **Figure 9**. Unlike previous aspect based methods designed as alternatives to traditional hill shading, this color scheme is to be used in combination with hill shading.

This aspect-variant color scheme selects eight colors in a diamond pattern in HSV color space, with luminosity increasing from northeast to southwest, and saturation increasing from northwest to southeast. Examples using a variety of green, tan and blue colors are represented in the middle right of **Figure 9** with black dots plotted on top of the HSV color cone. The bottom right of **Figure 9** shows these three object colors applied to different land uses in a terrain model with hill shading of a portion of the Absaroka Mountains, Montana. Areas of snowfields/ice are displayed in blue, exposed rock is in tan, and vegetated areas are in green. Luminosity between northeast and southwest facing surface elements varies with color luminosity, while brightness values between northwest and southeast facing surface elements varies with shading. The resulting display creates or increases contrast between some adjacent surface elements by uniquely assigning color by aspect, increasing brightness value and decreasing saturation to the northwest, and increasing luminosity to the northeast.

"Unlike previous aspect based methods designed as alternatives to traditional hill shading, this color scheme is to be used in combination with hill shading."

The techniques of Gooch *et al.* (1998) and Kennelly and Kimerling (2004) have important differences (See **Figure 9**). Gooch *et al.* (1998) calculated colors from a lighting model, with the goal of rendering tone-scaled object colors with cool-to-warm undertones. The resulting rendering offers subtle color changes consistent with traditional shading models. Colors are symmetric across a plane parallel to the illumination vector. Kennelly and Kimerling (2004) focused on quantifying luminosity in color space, then varying luminosity with aspect and hill shading from two different directions. The resulting map is not intended to match an optically based shading model. It also lacks radial symmetry of color, an intentional attempt by the authors to vary color for each aspect direction.

"The techniques of Gooch et al. and Kennelly and Kimerling have important differences."

DISCUSSION

The ability of mapmakers to create accurate renderings of terrain with a 3-D appearance hundreds of years before the advent of computers resulted primarily from two unique aspects of their early trade. First, data for quantitative models of real world objects were collected and represented in a systematic and intuitive manner. Second, common geographic methods of representing this data resulted in renderings, or could be used as a

framework (such as contours) to create new renderings.

Elevation data are measured from vertical datum, such as mean sea level. Terrain measurements at different points can be related by such intuitive concepts as higher or lower. The general behavior of the terrain as a smooth, continuously varying field also contributes to a simple model. If each point has one and only one elevation value, a 2.5-D model can accurately represent the surface.

Virtual models used in computer graphics differ significantly, as illustrated in **Figure 1**. There is no defined datum for objects, such as the statue, the bucket, or the mechanical part rendered in **Figures 3, 6, and 7** respectively. Whether a point on a bucket is higher or lower than another is only meaningful if a z-coordinate related to a datum were used to define its 3-D shape. If a z-value is used, whether a point on the bucket is higher, lower, or at the same z-value depends on how the coordinate system was defined with respect to the bucket. Additionally, the nature of these discrete objects implores a 3-D instead of a 2.5-D model for accurate representation.

Mapmakers often create images of their virtual models using the methodology shown in **Figure 1b**, which is a simplifying convention often used to create planimetrically correct maps. With such maps, the viewing vector is defined perpendicular to the datum, with the viewing plane or map consequently being parallel to the datum. NPR researchers working with terrain would describe planimetrically correct maps as seen from an orthographic viewpoint directly above the terrain model. In essence, this view fixes some g-buffers necessary for NPR rendering as constants for a particular terrain (See **Figure 1**). The elevation is inversely related to an invariant z-buffer. The orientation of any surface element can be uniquely represented by two intuitive angles: slope and the aspect.

The earliest efforts to graphically render terrain used isarithmic or contour lines. These were drawn based on elevation data only, but their orientation and spacing represent aspect and slope respectively. As long as contour lines are darker than the background, contours themselves shade terrain so that steeper areas appear darker. This rendering of the terrain is similar to shading resulting from a light source shining perpendicular to the datum. It is generally called vertical illumination and judged as inferior to illumination at some intermediate angle between vertical and horizontal, called oblique illumination (Imhof, 1982).

To create better renderings, mapmakers typically began with the contour framework. and used slope and aspect information to create oblique shading effects. This included changing the relative brightness of contours with respect to the background (Tanaka's methods), or changing thickness and spacing of hachures drawn between contours with respect to slope and aspect (as described by Imhof (1982)). All of the maps presented here are obliquely illuminated, with the exception of Lehmann's hachure map (**Figure 5a**).

Researchers in NPR—or computer graphics in general—have no need for the concept of vertical illumination. They can, nonetheless, achieve a similar rendering of poor quality if the illumination vector is oriented in the same direction as the viewing vector. Additionally, NPR researchers have no need for slope or aspect. Without a widespread datum and with 3-D models constantly changing orientation in 3-D space, they are primarily concerned with how a surface normal vector orientation is changing with respect to the illumination vector.

In practice, researchers working with terrain rendering can and do work directly with the surface normal vector and illumination vector for rendering. Still, discussing the most recent cartographic methods for ren-

"Terrain measurements at different points can be related by such intuitive concepts as higher or lower."

"In essence, this view fixes some g-buffers necessary for NPR rendering as constants for a particular terrain."

"Additionally, NPR researchers have no need for slope or aspect."

dering terrain without using terminology such as slope and aspect would be a challenge. For example, all of the color methods cited above vary colors with slope, aspect, or both. Mapmakers representing terrain adopted a useful tradition and terminology hundreds of years before and continue to look for effective techniques within this construct.

Procedures for defining and rendering virtual models in 3-D space is a more inclusive approach, but one that is also more complex in its implementation. Terrain rendering has created many striking representations of oblique views of terrain, from the block diagrams of William Morris Davis to the P-stroke sketches of Visvalingam and Whelan (1998). Additionally, the technical challenges of such displays have been long documented in terrain rendering literature, from the detailed techniques of Lobeck (1924) to more recent discussions of GIS-based perspective displays (for example Weibel and Heller, 1991).

CONCLUSIONS

Mapmakers hundreds of years ago were able to use well defined data structures and innovative display procedures to render terrain. With few exceptions (such as architectural renderings and engineering drawings), terrain maps would remain some of the only non-computer based images quantitatively rendered from models constructed from careful measurements of real world objects. The challenges of measuring and relating terrain data were facilitated by the use of a datum and a 2.5-D data model. The challenges of representing these quantitative models with a systematic procedure lent itself to the use of planimetrically correct maps. The challenge of drawing terrain maps with the appearance of 3-D rendering led to the development of procedures that would match shading from an oblique illumination source.

Many of these techniques met the challenges of creating realistic renderings. Other examples provided oblique shading while at the same time creating very unique and stylized renderings. Two examples of these would be physiographic diagrams and rock drawings. Physiographic diagrams such as those of Erwin Raisz (1931) use standard, easily recognized black and white symbols to represent landforms. These symbols also render the terrain through tonal variations in the individual symbols. Rock drawings are striking and stylized representations of steep and complex rocky areas (Imhof, 1982). These renderings are achieved by artistically combining a number of rendering components, including contours with local variations in interval, skeletal or edge lines, rock hachures (a variety of shadow hachures), color and shading (Imhof, 1982).

Despite the fact that more realistic maps can now be made of the same areas mapped with these techniques, these renderings remain much revered and often cited. Cartographers have always been interested in multiple methodologies for depicting similar data. These less realistic techniques are simply examples of a variety of methods to represent terrain.

Since the advent of computer models, display and rendering, there has been a proliferation of images created from virtual objects. NPR offers an interesting example of such work, because many such renderings are quite stylized. As such, it is easy to recognize methods or procedures that are similar to antecedent terrain rendering techniques. It is also possible to identify NPR techniques that may be interesting to apply to terrain renderings.

Newly developing NPR methodologies give those of us with an interest in the history and practice of terrain rendering two unique and important opportunities. The first is the opportunity to raise awareness with

"Terrain rendering has created many striking representations of oblique views of terrain, from the block diagrams of William Morris Davis to the P-stroke sketches of Visvalingam and Whelan."

"With few exceptions (such as architectural renderings and engineering drawings), terrain maps would remain some of the only non-computer based images quantitatively rendered from models constructed from careful measurements of real world objects."

"Other examples provided oblique shading while at the same time creating very unique and stylized renderings."

NPR researchers of the rich and important heritage of terrain rendering techniques. Second, identifying areas of overlapping interest with respect to current research seems rich in opportunity. Possibilities include 1) increased collaboration with NPR research, 2) applications of NPR techniques within the terrain rendering construct, and 3) advancing methods for cartographic renderings of 3-D objects.

REFERENCES

Brewer, C.A. and Marlow, K.A., 1993. Computer Representation of Aspect and Slope Simultaneously. *Proceedings, Eleventh International Symposium on Computer-Assisted Cartography (Auto-Carto-11)*, Minneapolis, Minnesota. pp. 328-337.

Buchin, K., Sousa, M.C., Döllner, J., Samavati, F. and Walther, M., 2004. Illustrating Terrains using Direction of Slope and Lighting. *4th International Cartographic Association Mountain Cartography Workshop*, Vall de Núria, Catalonia, Spain.

Deussen, O., Hamel, J., Raab, A., Schlechtweg, S. and Strothotte, T., 1999. An Illustration Technique Using Intersections and Skeletons. In *Proceedings of Graphics Interface '99* (Kingston, Canada, June), pp. 175-182. San Francisco: Morgan Kaufmann.

Deussen, O. 1998. Pixel-Oriented Rendering of Line Drawings. In Strothotte, T. (Ed.) *Computational Visualization: Graphics, Abstraction, and Interactivit*, pp. 105-119. Berlin: Springer-Verlag.

Gooch, B. and Gooch, A.A., 2001. *Non-Photorealistic Rendering*. Natick, MA, A. K. Peters Ltd.

Gooch, A.A. and Gooch, B., 1999. Using Non-Photorealistic Rendering to Communicate Shape. In Green, S. (Ed.) *SIGGRAPH '99 Course Notes. Course on Non-Photorealistic Rendering*, Chapter 8. New York: ACM SIGGRAPH.

Gooch, B. and Gooch, A.A., 1999. Interactive Non-Photorealistic Rendering. In Green, S. (Ed.) *SIGGRAPH '99 Course Notes. Course on Non-Photorealistic Rendering, Chapter 10*. New York: ACM SIGGRAPH.

Gooch, A.A., Gooch, B., Shirley, P. and Cohen, E., 1998. A Non-Photorealistic Lighting Model for Automatic Technical Illustration. In Cohen, M. (Ed.) *Proceedings of SIGGRAPH '98* (Orlando, July), Computer Graphics Proceedings, Annual Conference Series, pp. 447-452. New York: ACM SIGGRAPH.

Imhof, E., 1982. *Cartographic Relief Presentation*. Berlin and New York: Walter de Gruyter.

Kennelly, P. and Kimerling, A.J., 2004. Hillshading of Terrain Using Layer Tints with Aspect-Variant Luminosity. *Cartography and Geographic Information Science*, **31**:2: 67-77.

Kennelly, P., 2002. Hillshading with Oriented Halftones. *Cartographic Perspectives* 43: 24-41.

Kennelly, P. and Kimerling, A.J., 2001. Modifications of Tanaka's Illuminated Contour Method. *Cartography and Geographic Information Sciences*. 28: 111-123.

Lobeck, A.K. 1924. *Block Diagrams and Other Graphic Methods Used in Geology and Geography*. London: John Wiley and Sons, Inc.

Moellering, H. and Kimerling, A.J., 1990. A New Digital Slope-Aspect Display Process. *Cartography and Geographic Information Systems*, 17: 151-159.

Peucker, T.K., Tichenor, M. and Rase, W.D., 1974. The Computer Version of Three Relief Representations. In Davis, J.C. and McCullagh, M. (Eds.) *Display and Analysis of Spatial Data*, New York: John Wiley & Sons, pp. 187-197.

Raisz, E. 1931. The physiographic method of representing scenery on maps. Geographical Review 21:2: 297-304.

Robinson, A. H. and Thrower, N.J.W., 1957. A New Method for Terrain Representation. *Geographical Review* 47:4: 507-520.

Robinson, A.H., Morrison, J.L, Muehrcke, P.C., Kimerling, A.J. and Guptill, S.C., 1995. *Elements of Cartography*, 6th ed. New York: John Wiley & Sons.

Rogers, D.F., 1997. *Procedural Elements for Computer Graphics*, 2nd ed. New York: McGraw-Hill.

Saito, T. and Takahashi, T., 1990. Comprehensible Rendering of 3-D Shapes. In *Computer Graphics (SIGGRAPH '90 Proceedings)*. **24**: 197-206.

Salisbury, M.P., Anderson, S.E., Barzel, R., and Salesin, D.H., 1994. Interactive Pen-and-Ink Illustrations. In Glassner, A. (Ed.) *Proceedings of SIGGRAPH '94* (Orlando, July), Computer Graphics Proceedings, Annual Conference Series, pp. 101-108. New York: ACM SIGGRAPH.

Salisbury, M.P., Anderson, C., Lischinski, D., and Salesin, D.H., 1996. Scale-Dependent Reproduction of Pen-and-Ink Illustrations. In Rushmeier, H. (Ed.) *Proceedings of SIGGRAPH '96* (New Orleans, August), Computer Graphics Proceedings, Annual Conference Series, pp. 461-468. New York: ACM SIGGRAPH.

Salisbury, M.P., Wong, M.T., Hughes, J.F. and Salesin, D.H., 1997. Orientable Textures for Image-Based Pen-and-Ink Illustrations. In Whitted, T. (Ed.) *Proceedings of SIGGRAPH '97* (Los Angeles, August), Computer Graphics Proceedings, Annual Conference Series, pp. 401-406. New York: ACM SIGGRAPH.

Slocum, T., McMaster, R., Kessler, F. and Howard, H., 2004. *Thematic Cartography and Geographic Visualization*. 2nd Ed. Upper Saddle River, NJ: Pearson Prentice Hall, Inc.

Strothotte, T. and Schlechtweg, S., 2002. *Non-Photorealistic Computer Graphics: Modeling, Rendering, and Animation*. San Francisco, CA: Morgan Kaufmann.

Tanaka, K., 1932. The Orthographic Relief Method of Representing Hill Features on a Topographic Map. *Geographical Journal* 79:3: 213-219.

Tanaka, K., 1950. The Relief Contour Method of Representing Topography on Maps. *Geographical Review* 40: 444-456.

Visvalingam, M. and Whelan, J.C.,1998. Occluding Contours within Artistic Sketches of Terrain, in *Eurographics-UK '98*, (16th Annual Conference of the Eurographics Association, University of Leeds, 25 - 27 March), pp. 281 – 289.

Visvalingam, M. and Dowson, K., 1998. Algorithms for Sketching Surfaces. *Computers & Graphics* **22** (2&3), pp. 269 – 280.

Veryovka, O. and Buchanan, J.W., 1999. Comprehensive Halftoning of 3-D Scenes. In *Computer Graphics Forum (Proceedings of Eurographics 99)* **18**:3: 13-22.

Weibel, R. and Heller, M., 1991. Digital Terrain Modelling. In Maguire, D.W., Goodchild, M.F. and Rhind, D.W (Eds.) *Geographic Information Systems: Principles and Applications*. New York: John Wiley & Sons, Inc.

Winkenbach, G. and Salesin, D.H., 1996. Rendering Parametric Surfaces with Pen and Ink. In Rushmeier, H. (Ed.) *Proceedings of SIGGRAPH '96* (New Orleans, August), Computer Graphics Proceedings, Annual Conference Series, pp. 469-476. New York: ACM SIGGRAPH.

Yoeli, P. 1985. "Topographic relief depiction by hachures with computer and plotter." *Cartographic Journal* **22**: 111-24.