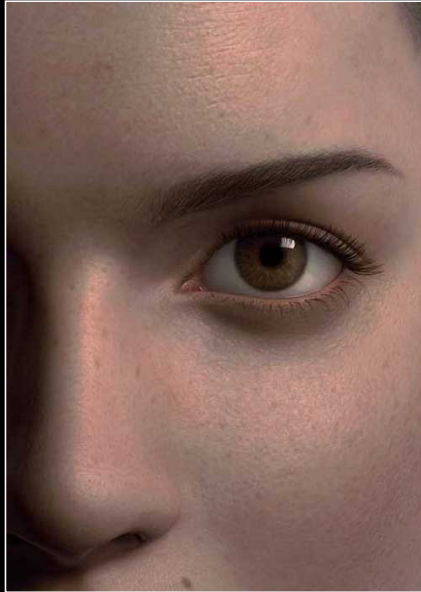# Part I:
Non-photorealistic Rendering

Adam Finkelstein

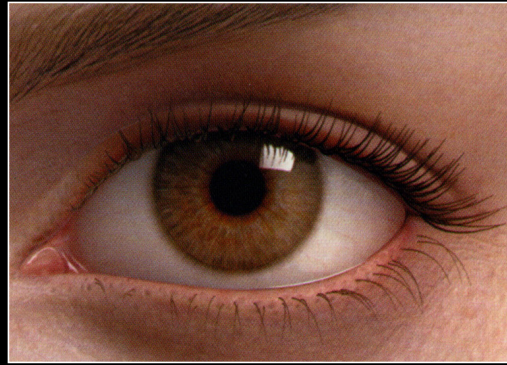Line Drawings from 3D Models
SIGGRAPH 2005 Course Notes

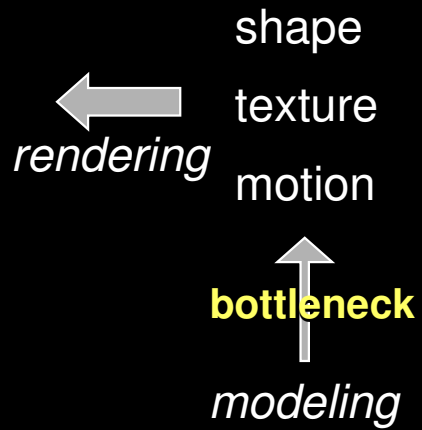# Computer graphics today

Don't try this at home!

"Final Fantasy"
Square 2001

Computer graphics boasts an amazing success story with regard to realistic rendering.

Unfortunately, to make pictures like these you need to have a huge modeling budget.
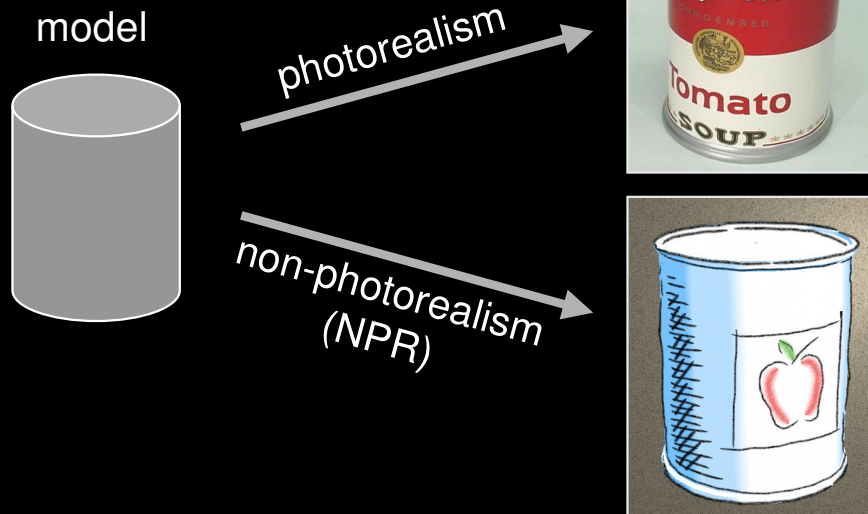
What is 3D content?

Computer graphics people often mean just shape when they talk about modeling.

I mean everything. To create a model for which the rendered image is going to look photoreal is VERY expensive.

Fortunately there is an alternative. There is a branch of computer graphics that has been looking for more than a dozen years at how can we exploit principles of abstraction known to artists for many centuries to avoid having to worry about a myriad of perhaps unnecessary details.

Photorealism in painting

Art omitted from notes to avoid copyright issues.

Bouguereau, *The Little Shepherdess*, 1891

The distinction between photorealism and non-photorealism has been known by artists long before computer graphics came around. If you squint your eyes you could imagine that this painting by Bouguereau was a photo.

Non-photorealism in painting

Art omitted from notes to avoid
copyright issues.

van Gogh 1889   Gris 1912   Kandinsky 1923

In contrast, these images exhibit a range of abstraction that clearly departs from realism.

Realistic modeling and rendering

[Deussen 99]

To make a similar and obvious comparison in computer graphics, here is a rendering of a realistic outdoor scene due to Deussen and others. The model is very complex -- the number of polygons would not fit in the memory of most computers today.

Non-photorealistic rendering

[Deussen 2000]

Here is a different rendering of an outdoor scene by Deussen and others. Obviously, there is a lot less complexity there, and yet depending on the application it may be just as appropriate for conveying a particular sense of a place.

Role of computer graphics (CG)

- CG concerns tools for generating various *forms* of imagery.

- Humans use imagery to *communicate* visual information.

- An appropriate *form* of imagery depends on nature of the *communication.*

Consider the role played by computer graphics for the content creator. Perhaps stated most broadly, CG is concerned with the development of tools for generating various forms of imagery be it photorealistic, NPR, or what have you.

People, as content creators, are interested in these tools for the production of imagery to communicate visual information. But the important point is: The appropriate form of imagery for a given task depends upon the nature or purpose of this communication.

9

Photorealism vs. NPR

Photorealism
- Documentation
- Simulation

Non-photorealism
- Explanation
- Illustration
- Storytelling

Many applications uniquely suited to PR or NPR

One can imagine various tasks for which photorealism is uniquely suited and NPR is not

…and conversely, there are certainly applications for which the opposite is true.

CG has traditionally focused upon the production of photorealistic imagery. Let's consider some of its applications.
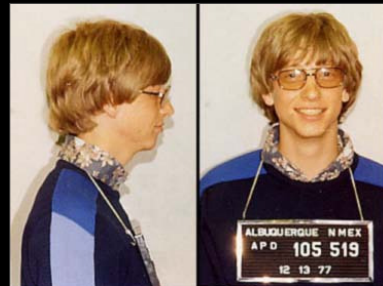
Photorealism: Applications

Photorealism

- Documentation
- Simulation

Non-photorealism

- Explanation
- Illustration
- Storytelling

[The Bill]

Photorealism is certainly well-suited for the job of documentation, where the task is to record imagery in all its detail for posterity. Crime scene photography is a perfect example. Should new evidence or theory prompt a reinvestigation, crime scene photos may be probed for new clues. NPR, such as a sketch of the scene, could certainly record the relative positions of the purse, garment and fence in the image above, but any details missed by the artist at the time would be permanently lost once the items are taken into evidence.

Photorealism: Applications

Photorealism
- Documentation
- Simulation

Non-photorealism
- Explanation
- Illustration
- Storytelling

[ILM]

Likewise, photorealistic computer graphics are uniquely suited to the situation where one seeks live-action imagery (e.g. movies of television) but where its difficult to stage the actual scene.

Here the task is to simulate the desired effect -- huge explosions, tidal waves washing over manhattan, and Yoda dropping his cane and grabbing his light saber -- requiring photorealistic computer graphics imagery for convincing effect.

Even though we know that these effects are not real, cartoonish NPR could not be employed in there circumstances because it would destroy the illusion necessary for the audience to suspend disbelief and enjoy the story.

NPR: Applications

Photorealism
- Documentation
- Simulation

Non-photorealism
- Explanation
- Illustration
- Storytelling

Many untapped opportunities for NPR…

Depending upon the task at hand NPR may be the appropriate means for communication. Because computer graphics has traditionally focused on tools for photorealistic rendering, there remain many untapped opportunities for new forms of content for authors. One might even argue that there should be more applications under the NPR heading because photorealism is fairly narrowly defined. Nonetheless, there remain compelling reasons why computer graphics has focused on realism, not the least of which are limited tools for stylization and abstraction.
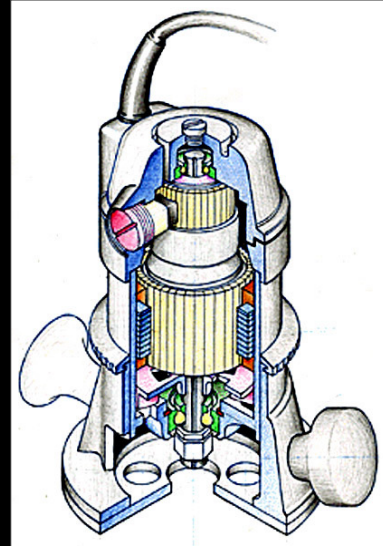
NPR: Applications

Photorealism
- Documentation
- Simulation

Non-photorealism
- Explanation
- Illustration
- Storytelling

[Birkey]

Of course, there are also various applications uniquely suited to NPR, for example when imagery is used for explanation such as this technical illustration of a mechanical tool. Since the intended viewer probably has the real tool in front of him, a photographic image is redundant; instead, the artist can better explain the form and function of the item by disambiguating different components in contrasting colors and suppressing physically accurate shading that obscures this clarity. Silhouette and feature lines are also frequently used to further enhance the objects description.
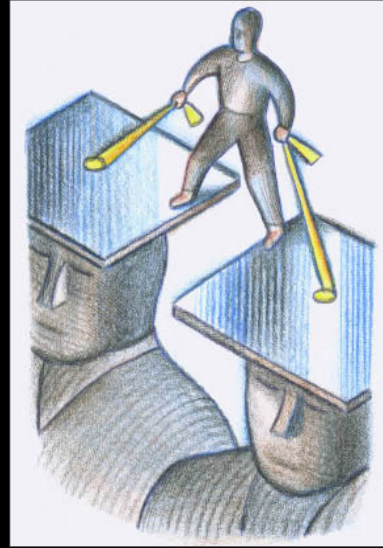
NPR: Applications

Photorealism
- Documentation
- Simulation

Non-photorealism
- Explanation
- **Illustration**
- Storytelling

[Sutter]

Stylization is often also used to illustrate abstract concepts using very succinct imagery. In this example the artist communicates an abstract idea to accompany an op-ed piece originally in the new york times concerning the role of higher education in our society.

If, instead, we imagine replacing this with a comparable photoreal image the abstract concept would be lost amid the details. Rather we'd be distracted by the absurd image of a tiny man standing astride the mortar boards of two giant college graduates.

NPR: Applications

Photorealism
- Documentation
- Simulation

Non-photorealism
- Explanation
- Illustration
- Storytelling

Art removed from notes to avoid copyright infringement.

[Dr. Seuss]

Finally, storytelling is example where stylized and abstract imagery can help to communicate scenes which exist only in the author's imagination. Nere NPR is particularly adept for the fantastical nature of the Dr. Seuss's stories. The effect would be wholly different with comparable photoreal imagery. But there's also another reason. Children, the intended audience in this case generally respond best to brightly colored illustrations, and somehow find them more engaging than photos. So if you look down the row of shelves devoted to children's books at your local book store you'll see that the great preponderance of kid's books use hand-crafted imagery rather than photos.

> Now that "perfect" design is possible with the click of a mouse, the industrialized world has become nostalgic for "imperfect" design.
> As computer-aided everything takes over our lives we begin to realize, little by little, what is missing from the high-tech world. We realize that a crooked line sometimes has more soul than a perfectly straight one….
>
> -- David Byrne *When Bad Art is Good*
> Utne, March-April 2003

David Byrne wrote this comment in an article for Utne. In the article he was mostly talking about 2D design and illustration, but I believe his point translates to renderings from 3D as well. This may explain the recent emergence of NPR as a research area within computer graphics.

Let me quickly run through a few of the benefits of NPR…

Non-photorealism

Less detail

Art omitted from notes to avoid copyright issues.

Picasso

I have already made the point that NPR can use abstraction to reduce the level of detail necessary. Picasso was a master of elision of detail as you can see in this drawing.

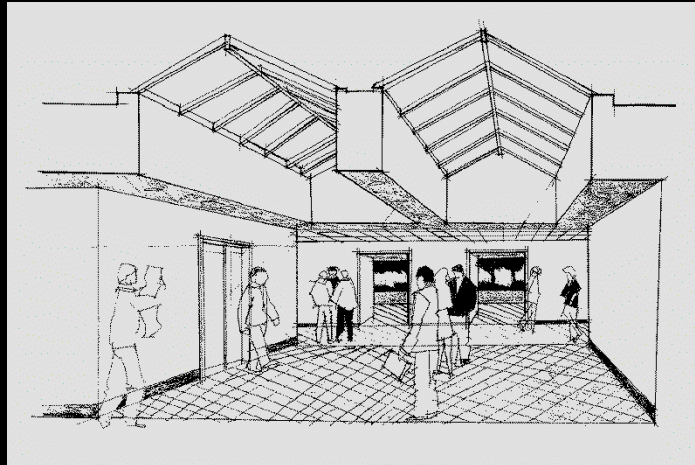Non-photorealism

Quick

Design studies
(Hewlett-Packard)
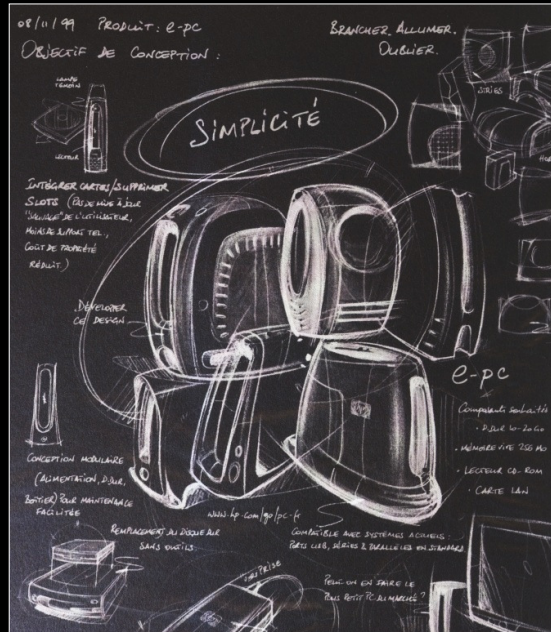
Obviously, drawings can be made very quickly, and can convey through their very nature that this is a just a quick design to give an impression of shape or feeling -- that the design is unfinished.

Non-photorealism

Extra semantic information

Mitchell Bldg
Stanford

Architects often use renderings such as these to convey a sense of space and how people fit into it. In contrast, with a photorealistic rendering the client might start to call into question the color of the walls or the pattern of the carpet, which was not at all the design focus of the architect.

Non-photorealism

Guide viewer's eye

"The New Chair"
[Curtis 98]

We can also use non-photorealism to guide the viewer's eye twards important features in a scene and away from unimportant fixtures. So, for example here, by using elision of detail, our attention is really drawn towards items like the chair and the human figure in its energetic style,

The fact that it's NPR, makes the fact that it's not realistic not bothersome. We don't worry that the computer is floating in mid-air! We're not stressed out that the human figure doesn't look exactly like a person. So the rendering style makes possible today story elements that are not feasible with PR.

Non-photorealism

Emotionally rich

"Curse of Monkey Island"
LucasArts

We can also create images with greater emotional impact using non-photorealism. For example, this screenshot of a crypt scene, taken from the Lucas Arts' game "the Curse of Monkey Island," contains a quality of both spookiness and humor that would be hard to capture in a photoreal scene.

Let me take just a few moments to give a brief overview of the history of NPR.

NPR: Simulating various media
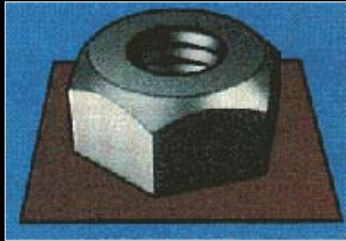
Technical Illustration [Saito 90]
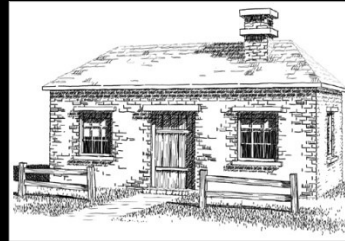
Pen & Ink [Winkenbach 94]

Watercolor [Curtis 97]

Paint [Hertzmann 98]

In the 1990s, this field emerged as an alternative to photorealism. Research efforts largely focused on ways to simulate various media such as technical illustration, pen-and-ink watercolor and paint. The goal was to make an image that was believably created by hand in one of these traditional media. These systems were mostly-automatic: the program attempted to mimic what an artist/illustrator might do.

NPR: Dynamic imagery
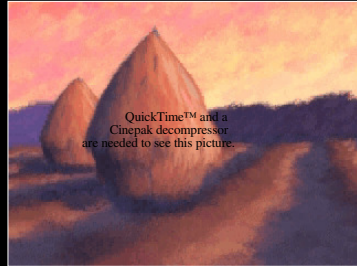
Painterly rendering for
3D models [Meier 96]

Painterly rendering for
video [Litwinowicz 97]

In the latter part of the decade, a few people began to investigate dynamic NPR. Here the challenge is dealing with frame to frame coherence. One of the reasons why this research is exciting is that it creates imagery that would be tedious or perhaps impossible to create by hand. These pieces were created offline.

NPR: Interactive Rendering
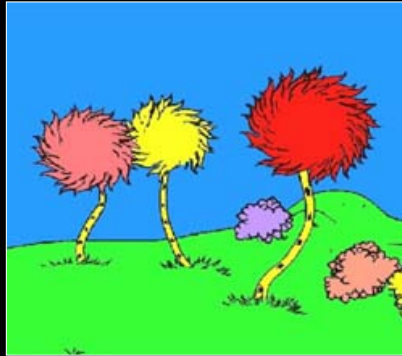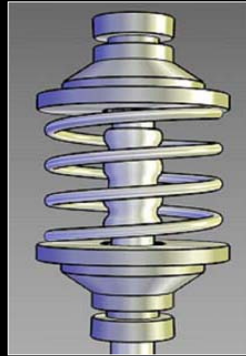
[Kowalski 99]   [Gooch 98]   [Praun 01]

However, more recent advances in algorithms and graphics hardware have made it possible to create these kinds of animations in real-time. Here, the computer is creating imagery that could *not* be created by hand, because it's impossible to actually draw images like these at, say 10 frames per second while a viewer navigates some environment. To me this is the most exciting aspect of NPR, as it opens the door for new applications (such as interactive illustrations) that were not possible to do before computer graphics.

Elements of stylized rendering

Toon shading
Stylized strokes
Paper Effect
Detail Marks
Hatching
Outlines
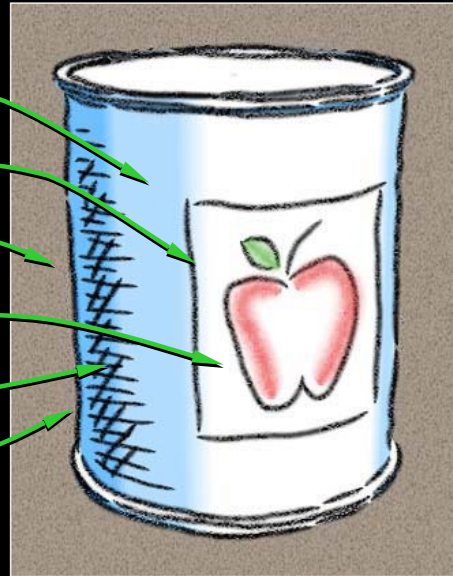
A single illustration can incorporate many different technical elements that combine to form a cohesive image. So there are many different tools that have emerged from the NPR community to be able to make such illustrations with computers. For example, we have cartoon shading, stylized strokes, effects for interaction of media with paper, the ability to draw specific marks onto surfaces, hatching, and automatic outlining tools.

Line drawings

Elements of line outlines…
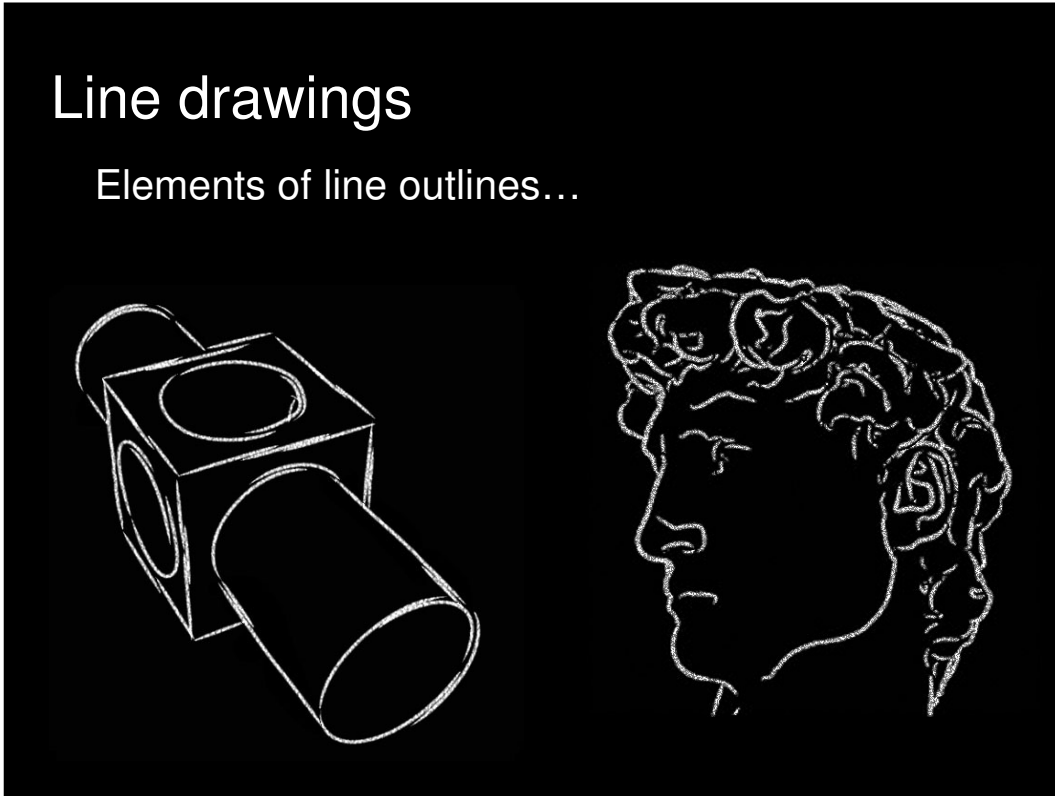
In this course we focus on line drawings, in part because they tend to be the simplest form of rendering from 3D models and are often used as a component of more sophisticated rendering schemes. And within line drawings, most of our emphasis will be on outlines such as those shown here. There are three kinds of lines that contribute to the outlines.
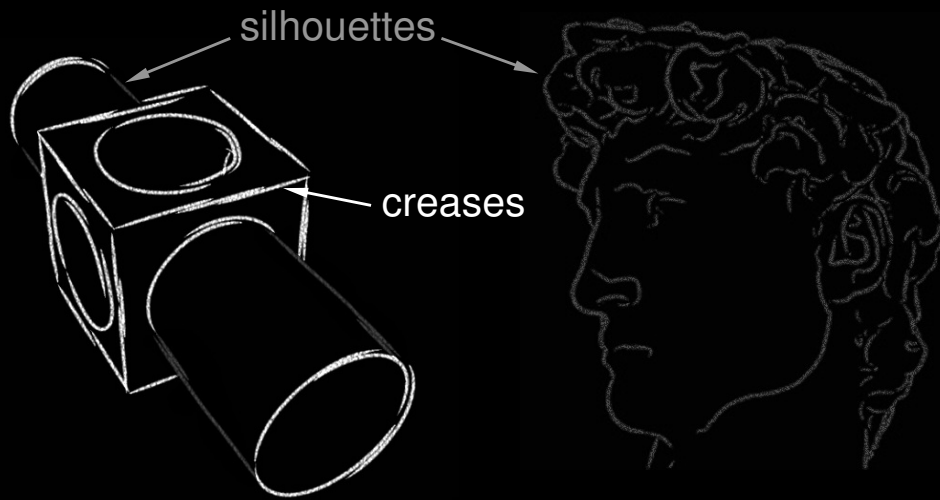
Line drawings

Elements of outlines…

silhouettes
(a.k.a. contours)
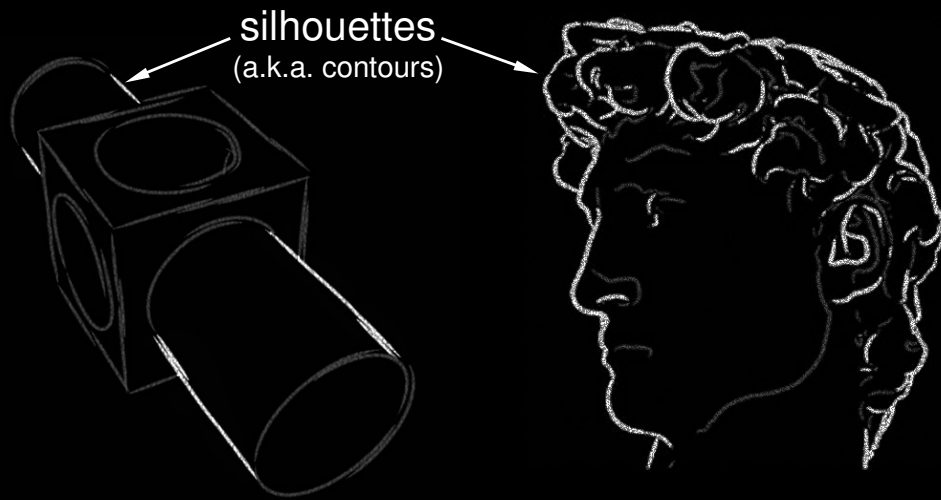
First are the silhouettes (equivalently called "contours" by some researchers) They separate front-facing from back-facing regions of the surface, as a function of view point…

Line drawings

Elements of outlines…

silhouettes

creases

Creases are path which are defined statically on the mesh surface generally representing sharp features, such as the those present on this mechanic part on the left. Other features behave similarly, such as marks drawn directly onto the surface denoting for example the boundary between two different surface textures.

Line drawings

Elements of outlines…

silhouettes

creases

suggestive
contours
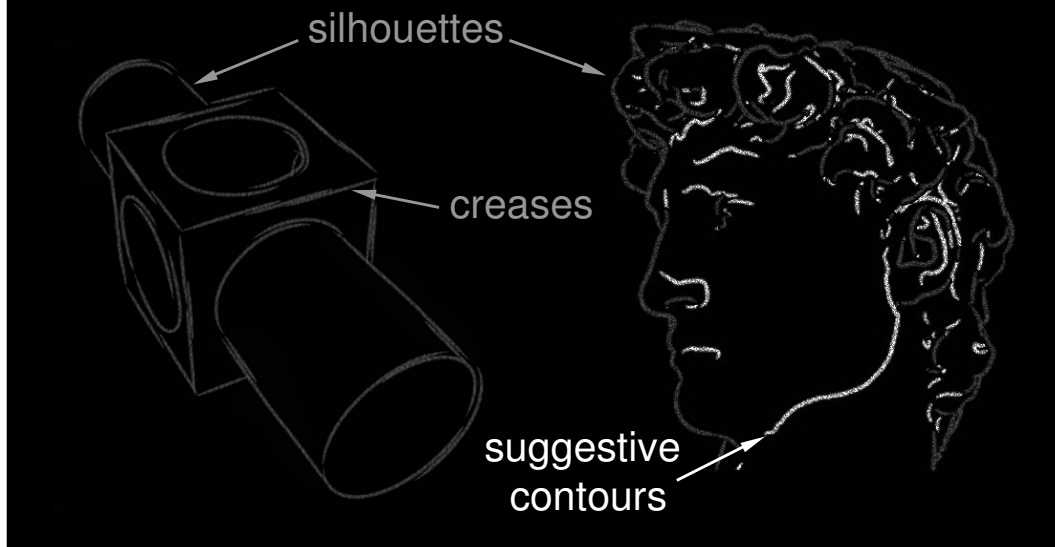
Third, we recently introduced "suggestive contours" which are
dynamic features similar to silhouettes that are view dependent and
help denote the shape. It turns out that suggestive contours may be
thought of as places on the shape that would be silhouettes from
nearby views.

Line drawings

silhouettes

creases

suggestive contours
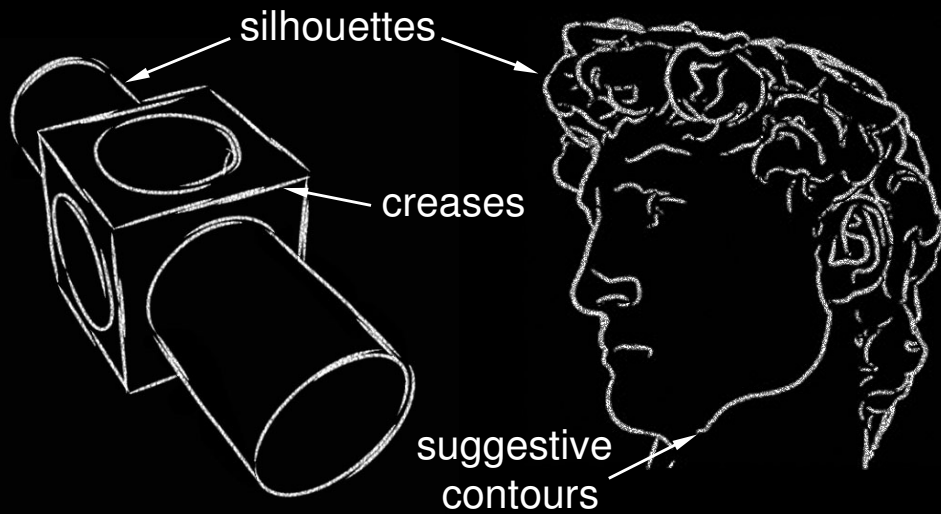
These three elements, though not exhaustive, can produce a wide range of line drawings, and often contribute to more complex illustrations.

Hatching

Stroke-based shading of 3D models

Strokes convey:

- tone
- material
- shape
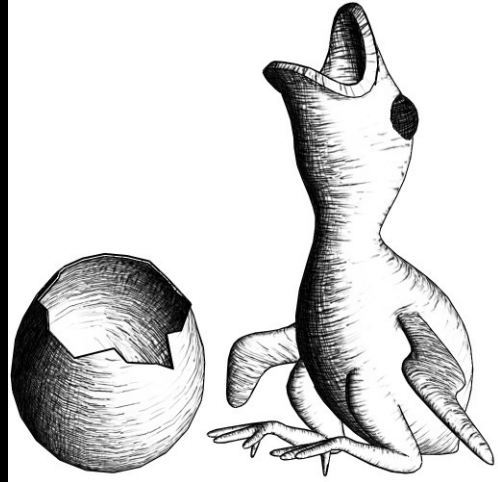
Another drawing element prevalent in more sophisticated line drawings is called hatching. Many small lines can be combined in such a way that they simultaneously convey tone and material, and as you can see in the figure, the arrangement of strokes can also enhance our perception of the object's shape.

Throughout this course we will mostly focus on outline drawings, and de-emphasize hatching. Therefore, for completeness I'm going to take a few slides here to digress on hatching.

Stippling
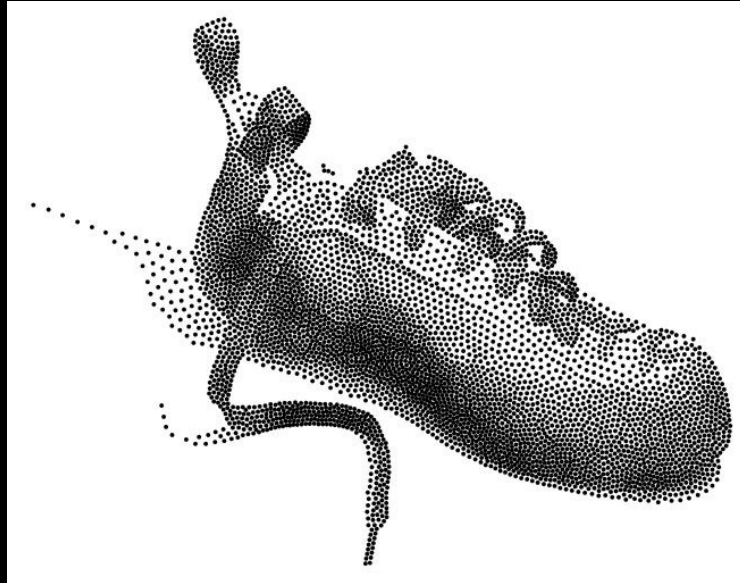
I should also mention stippling, which can use a collection of small dots to convey tone. This is an important drawing technique and may be used in conjuction with lines. In contrast with hatching, these marks do not follow the curvatures of the shape and generally do not have the expressiveness to suggest surface texture.
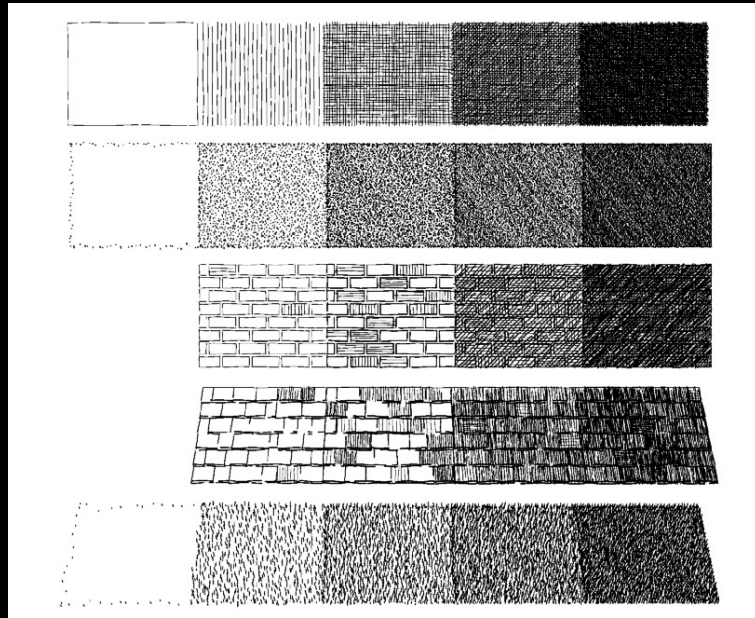
Off-line hatching methods
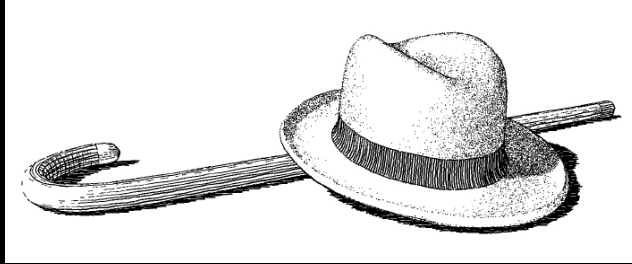
[Winkenbach 94, 96]
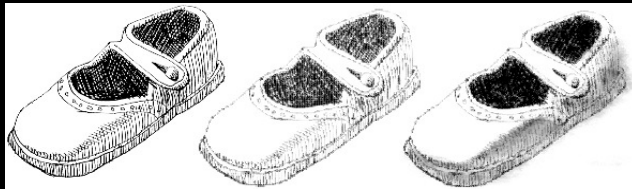
[Sousa 99]

[Hertzmann 2000]

A number of systems have concentrated on producing high-quality renderings of static scenes. These systems tend to be slow and do not not address frame to frame cohere, and are therefore unsuitable for on-line animation.
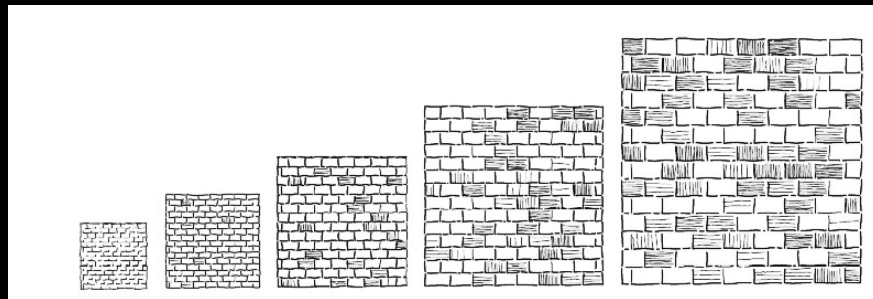
Prioritized Stroke Textures [Winkenbach94]

One of the early landmarks in this area is the work of Winkenbach and Salesin, where they developed the notion of prioritized stroke textures. These textures can convey a continuum of tone for various hatching textures, by varying the number of strokes.

Prioritized Stroke Textures
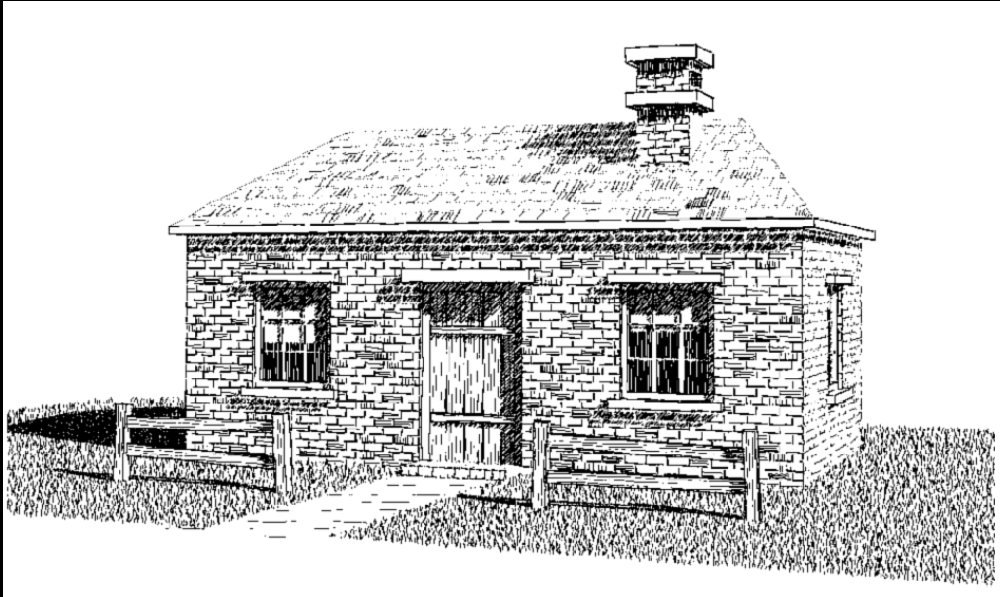
Level of Detail Control

[Winkenbach94]

They also address level of detail for a constant tone texture, though the LOD is targeted at static imagery.
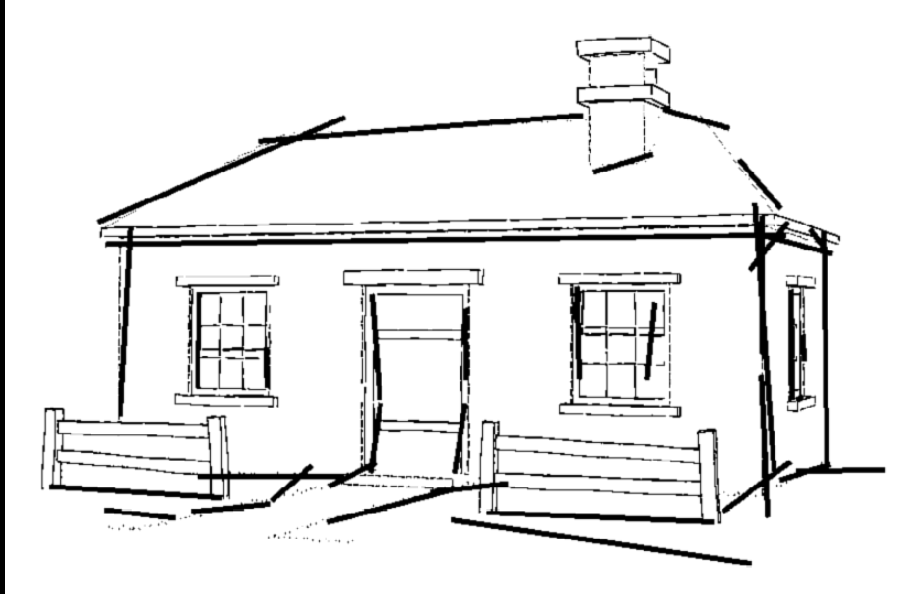
Little House on the Prairie   [Winkenbach94]

Using such textures applied to a 3D model, they were able to make pictures like these. However, they noted that such drawings are too busy -- with too much detail everywhere -- and that an artist would typically omit many of these lines.
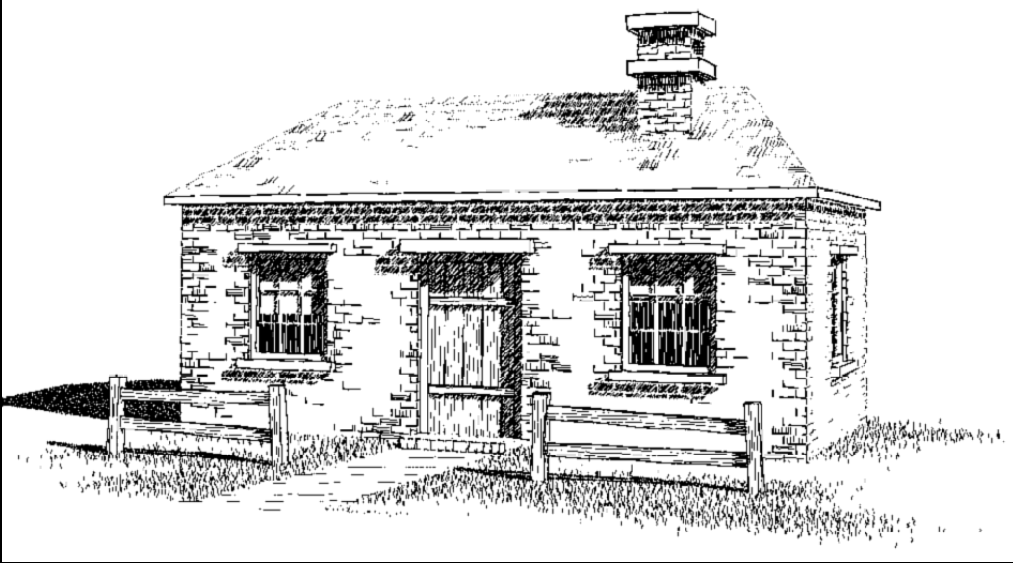
User marks important areas [Winkenbach94]

Therefore they offer a mechanism whereby a designer can mark areas of importance on the image.

Little House with "indication"
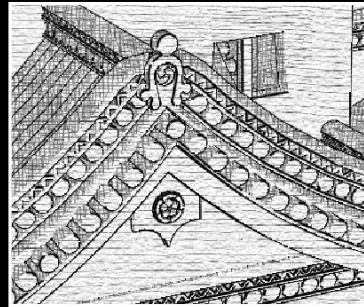
[Winkenbach94]

And then their system can render the image providing more hatching detail in these important areas. Thus the textures, for example the brick texture on the wall facing us, is suggested with detail omitted. This principle is known as indication.
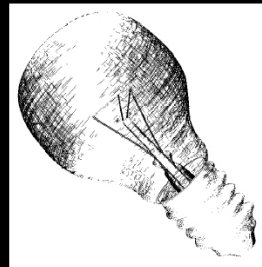
Temporal coherence for hatching


- Image space coherence
  [Lake2000]

- Object space coherence
  [Elber99]

Several systems have addressed hatching for real time applications. The work of Lake et al. renders scenes using strokes embedded in screen space. In contrast Elber presented a system with object-space coherence, so the hatching helps to convey the shape of the object.

Coherence and LOD for Hatching

Prioritized Stroke Textures
[Salisbury 94]
[Winkenbach 94]

Art Maps
[Klein 00]

← scale →
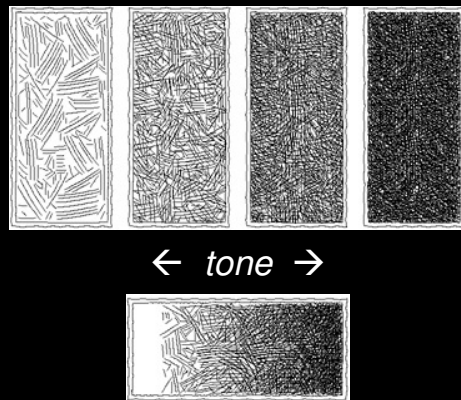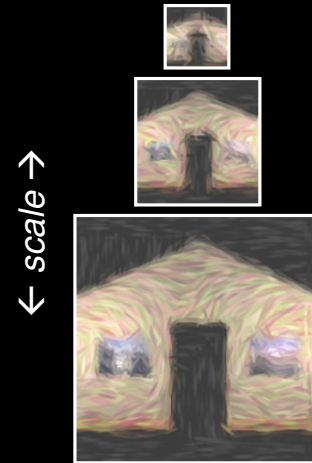
← tone →

The aforementioned "prioritized stroke textures" were introduced by Salisbury et al. and Winkenbach et al. in 1994. They represent an ordered collection of strokes, where each stroke is annotated by the tone that would be produced by rendering it and all the previous strokes in the collection. You can see here several tones being rendered using prioritized stroke textures. At the bottom of the figure, you can see a continuous tone gradient.

In 2000, Klein and collaborators presented a system for NPR-rendering of virtual environments. The basic idea was to apply NPR filters to the textures in the scene. The goal was to keep the character and size of the strokes, regardless of resolution at which the surfaces were being rendered. They achieved this by constructing custom mipmap levels, each level being produced by running the NPR filter with the same size strokes. Since the different levels were produced independently, there was no coherence between strokes at different levels, so the strokes appeared to be swimming as one zoomed in and out from a surface.

Tonal Art Maps

Collection of stroke images

Will blend → design with high coherence

Stroke nesting property

← scale →

← tone →

[Praun2001]
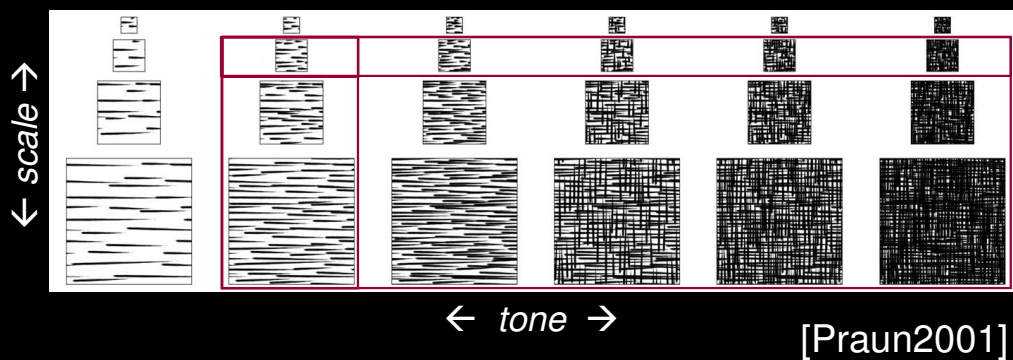
Combining the 2 approaches, Praun et al created Tonal Art Maps, a collection of stroke textures parameterized by both tone and resolution. When rendering a 3D object they blend some of these textures, that they be designed with a very high degree of coherence, in order to avoid blending artifacts.

Specifically, they imposed a stroke nesting property: all the strokes in one image appear in all the finer resolution images, and all the darker tone images. By transitive closure, they appear in the images to the right or down, in the Tonal Art Map array.
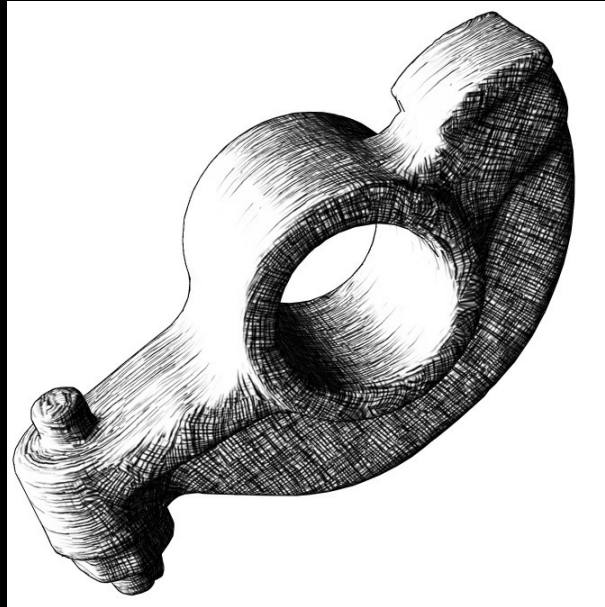
Real-Time Hatching
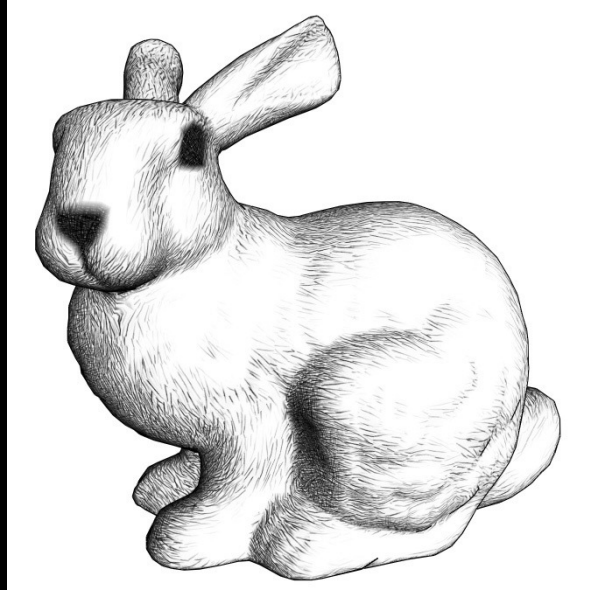
[Praun2001]

This is the kind of image they produce. Note that these hatching textures have object space temporal coherence, and control of both LOD and tone as the viewing and lighting conditions change.
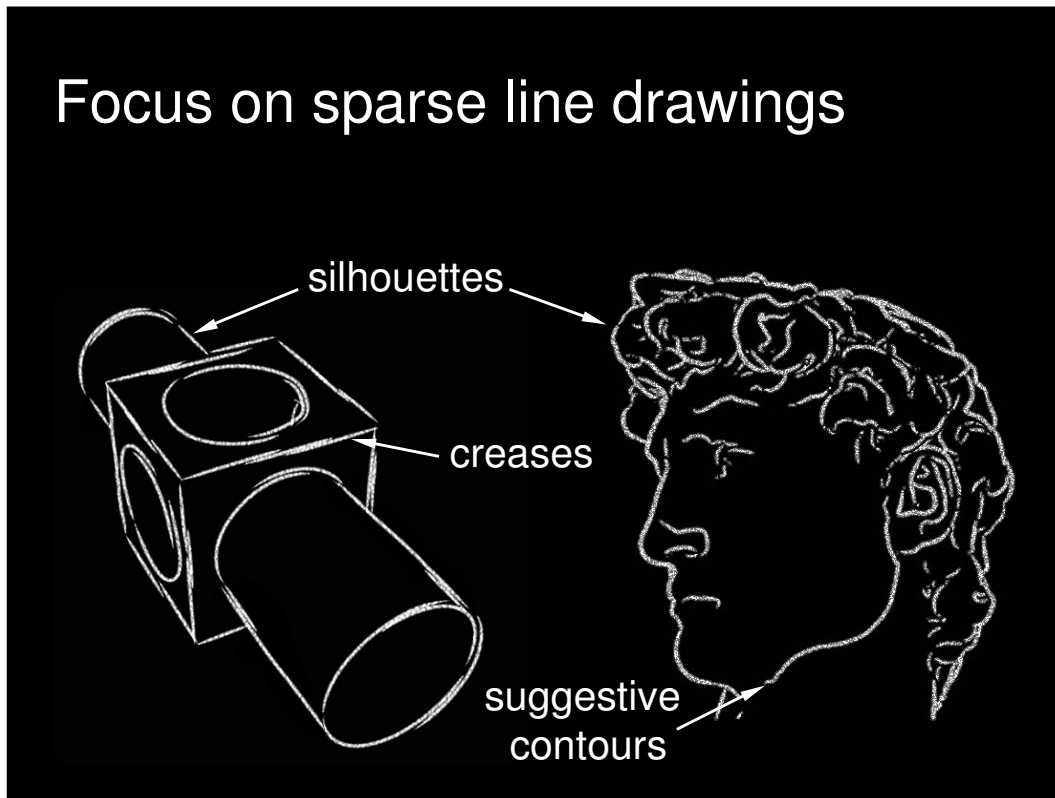
Real-Time Hatching

[Praun2001]

Here is another example with a different texture.

Focus on sparse line drawings

silhouettes

creases

suggestive
contours

Returning to line outlines, for the remainder of this course, we're going to focus mostly on such sparse line drawings, only touching on hatching once or twice again.