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# Computer-Generated Graphite Pencil Rendering of 3D Polygonal Models

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**Abstract**

*Researchers in non-photorealistic rendering have investigated the display of three-dimensional worlds using various display models. In particular, recent work has focused on the modeling of traditional artistic media and styles such as pen-and-ink illustration and watercolor painting. By providing 3D rendering systems that use these alternative display models users can generate traditional illustration renderings of their three-dimensional worlds. In this paper we present our graphite pencil 3D renderer. We have broken the problem of simulating pencil drawing down into four fundamental parts: (1) simulating the drawing materials (graphite pencil and drawing paper, blenders and kneaded eraser), (2) modeling the drawing primitives (individual pencil strokes and mark-making to create tones and textures), (3) simulating the basic rendering techniques used by artists and illustrators familiar with pencil rendering, and (4) modeling the control of the drawing composition. Each part builds upon the others and is essential to developing the framework for higher-level rendering methods and tools. In this paper we present parts 2, 3, and 4 of our research. We present non-photorealistic graphite pencil rendering methods for outlining and shading. We also present the control of drawing steps from preparatory sketches to finished rendering results. We demonstrate the capabilities of our approach with a variety of images generated from 3D models.*

***Keywords:*** Nonrealistic rendering, rendering systems, natural media simulation, paint systems.

## 1. Introduction

The display of models using highly realistic illumination models has driven much of the research in computer graphics. Research in non-photorealistic rendering (NPR) seeks to provide alternative display methods for 3D models or reference images. In particular, recent work has focused on the modeling of traditional artistic media and styles such as pen-and-ink illustration [10, 11] and watercolor painting [21]. By providing rendering systems that use these alternate display models users can generate traditional renderings. These systems are not intended to replace artists or illustrators, but rather to provide a tool for users with no training in a particular medium, thus enabling them to produce traditional images.

In this paper we present results from our research in pencil illustration methods for NPR. The main motivation for this work is to investigate graphite pencil as a useful technical and artistic NPR production technique in order to provide alternative display models for users. We chose pencil because it is a flexible medium, providing a great variety of styles in terms of line quality, hand gesture, and tone building. It is excellent for preparatory sketches and for finished rendering results. Pencil renderings are used by many people in different contexts such as scientific and technical illustration, architecture, art, and design.

The main contribution of our research is on the modeling and implementation of an integrated framework for graphite pencil rendering tailoring media simulation, drawing primitives, and 3D rendering techniques correspondent to the graphite pencil media. Our approach was to break the problem of simulating pencil drawings down into the following sub-problems:

1. Drawing materials: low-level simulation models for wood-encased graphite pencil and drawing paper [25], and for blenders and kneaded eraser [26].
2. Drawing primitives: pencil stroke and mark-making (for tones and textures) built on top of the drawing materials.
3. Rendering methods built on top of the drawing primitives. Algorithms for outlining, shading, shadowing, and texturing of reference images [25, 26] and 3D objects with a look that emulates real pencil renderings.
4. High-level tools: partial control of the drawing composition through ordering and repeating of drawing steps.

In this paper we present the drawing primitives (sub-problem 2), automatic rendering methods for 3D models (sub-problem 3), and introduce sub-problem 4.

### 1.1. Related Work

Our work is related to research on 3D non-photorealistic rendering dealing with display methods which approximate technical illustration [1, 2, 5, 6, 16, 27], stylized line illustrations [3, 14, 15, 17, 23], artistic hand-drawn illustration [11, 12, 18, 20], or painting styles [9, 19, 21].

We were inspired in our work by recent approaches that tailored 3D NPR techniques to particular media models, specifically the work of Winkenbach and Salesin [11] in which results were produced from emulating the pen-and-ink illustration style, and the work of Curtis *et. al.* [21] describing a detailed simulation model for watercolor with its painting style. Our research has focused on developing a simulation model for the graphite pencil medium on drawing paper and implementing the basic rules for achieving traditional illustration styles adapted to the 3D rendering pipeline.

Our model for graphite pencils includes parameters for pencil lead composition and paper texture [25]. In addition to this our model allows the use of blenders and erasers [26]. Previous work on pencil simulation has addressed some of these issues. Vermeulen and Tanner [4] introduced a simple pencil model as part of an interactive painting system that does not include a model to handle textured paper, blenders, or erasers. Takagi and Fujishiro [22] presented a model for paper micro structure and pigment distribution for colored pencils to be used in digital painting. In the commercial realm, some interactive painting systems such as Fractal Design Painter† offer a pencil model with some interaction with the paper. Our pencil models improve the approximation of graphite pencil on drawing paper and the basic pencil drawing primitives.

† Even though a number of systems offer "pencil" mode it is difficult to determine what physical model, if any, is being used to simulate the graphite pencil and the corresponding drawing primitives.

### 1.2. Overview

This paper presents rendering methods based on traditional pencil illustration techniques found in the pencil literature [28, 29, 30, 31, 32, 33, 34, 35, 36, 37]. The paper is organized into six parts:

1. Brief description of our pencil and paper model presented in Sousa and Buchanan [25] (section 2).
2. Description of the pencil stroke and mark-making primitives built on top of the pencil and paper model (sections 3 and 4).
3. The architecture of the pencil rendering system (subsections 5.1 and 5.2).
4. Pencil-based outlining methods and results for 3D models (section 6).
5. Description of what is necessary to build tone using graphite pencils and how we modeled the processes involved. We also present results for the fundamental methods for rendering 3D objects in pencil tonal contrast (section 7).
6. Description of the control of pencil drawing steps from preparatory sketches to finished rendering results (section 8).

All the results were generated on an OCTANE$^{TM}$ Power Desktop‡ and printed at 200 *dpi* on a 600 *dpi* HP LaserJet 5Si MX printer. The images from the results are in 8-bit mode. They show that our simulation model produces similar results to strokes, swatches (tone samples), outlines, and tone renderings generated with real graphite pencils.

## 2. Graphite pencil and paper model

This section briefly describes our pencil and paper model [25]. Our approach is based on an observational model of how real graphite pencils interact with drawing paper. The goal was to capture the essential physical properties and behaviors observed in order to produce quality pencil marks at interactive rates. Our model has four main aspects:

**Pencil hardness**: Every pencil contains a writing core (or "lead") which is made from a mixture of graphite, wax, and clay. The hardness of the lead depends on the amount of graphite and clay. The more graphite it contains, the softer and thicker it is. Pencil hardness is graded in nineteen degrees ranging from 9H (hardest) to 8B (softest).

**Pencil points**: Sharpening a pencil in different ways changes the shape of the contact surface between the pencil and the paper. A pencil point is defined by a polygonal shape and pressure distribution coefficients over the point's surface. Pressure distribution coefficients are values between 0 and 1 representing the percentage of the pencil's tip polygonal surface that, on average, makes contact with the paper. This

‡ All rendering is done in software.

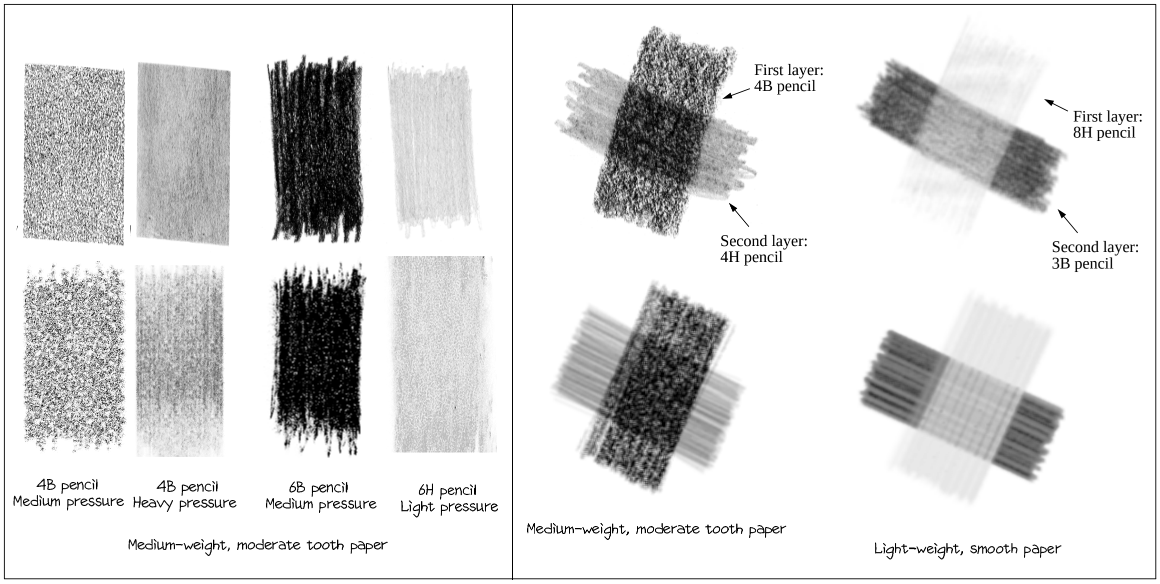


**Figure 1:** *Our pencil and paper simulation model* [25] *applied over drawing paper (bottom row). Compare results with real pencil work (top row). Real samples were scanned at 150* dpi *and printed at 200* dpi*. The set of four swatches made with one single pencil (left box) was generated by adapting our model to an interactive illustration system. The set of blended swatches (right box) was generated by adapting our model to the mark-making primitive which automatically models the variations of a series of parallel pencil strokes to create tones and textures (section 4.)*

value is used to locally scale the pressure being applied to the pencil.

**Drawing papers**: Paper textures for pencil work (categorized as smooth, semi-rough, and rough) have a slight roughness ("tooth" or grain) that enables lead material (graphite, clay, and wax particles) to adhere to the paper. We model the paper texture as a height field $(0 \leq h \leq 1)$ as was reported by Curtis *et al.* [21]. These height fields can be either procedurally generated or digitized from a paper sample. Each paper location $(x, y)$ accumulates lead material. The amount of material depends on the pencils that have crossed the location.

**Pencil and paper interaction**: Lead material is left on paper through friction between the lead and the paper. The amount of lead material depends on the pencil tip shape, the pressure applied to the pencil, and the pencil hardness. A pencil stroke changes these parameters to achieve different effects. In addition to depositing lead, a pencil stroke may alter the texture of the paper by destroying its grains. Figure 1 illustrates two sets of results from our pencil and paper model [25].

## 3. Pencil stroke primitive

When using pencils, different types of strokes are produced depending on the pencil's hardness, its point, and how it is applied to the paper. Also there are many ways of handling the pencil and various effects over the stroke can be achieved [29]pp. 24-25, [36]pp. 39-42, [37].

We define a pencil stroke $S$ consisting of a number of line segments, a path, and a character function. The path $P(t) : [0,1] \rightarrow R^2$ results from using a curve to approximate the line segments (Figure 2, top row). Different approximation functions can be applied. We use Bezier curves and B-Splines.

The character function varies stroke parameters at particular scalar distances $t$ along the path. We extend the character function, $C(t) = (C_w(t), C_p(t))$ (waviness and pressure parameters respectively), defined by Winkenbach and Salesin for a pen-and-ink stroke [11] to include parameters that relate to the factors that influence a real pencil stroke. Each of the seven character parameters are pressure $C_p(t)$, point shape $C_{ps}(t)$, pressure distribution coefficients $C_{pdc}(t)$, waviness $C_w(t)$, finger distance $C_{fd}(t)$, pencil slanting $C_\alpha(t)$, and wrist/arm movements $C_\beta(t)$. Figure 2 shows a series of closeups of individual pencil strokes generated with our model. They illustrate various effects (varying pressure, angle, etc) from the character function $C(t)$ of the stroke primitive. The strokes are rendered by scan-converting copies of the pencil tip polygon modified by the character function $C(t)$ placed at each pixel location along the path defined by the base curve with the waviness function added. Waviness functions simulate the hand movements by randomly modulating the curve defining the path. Previous researchers have reported using this approach [9, 10, 11, 12, 20]. We apply periodic waviness functions with random noise and turbulence

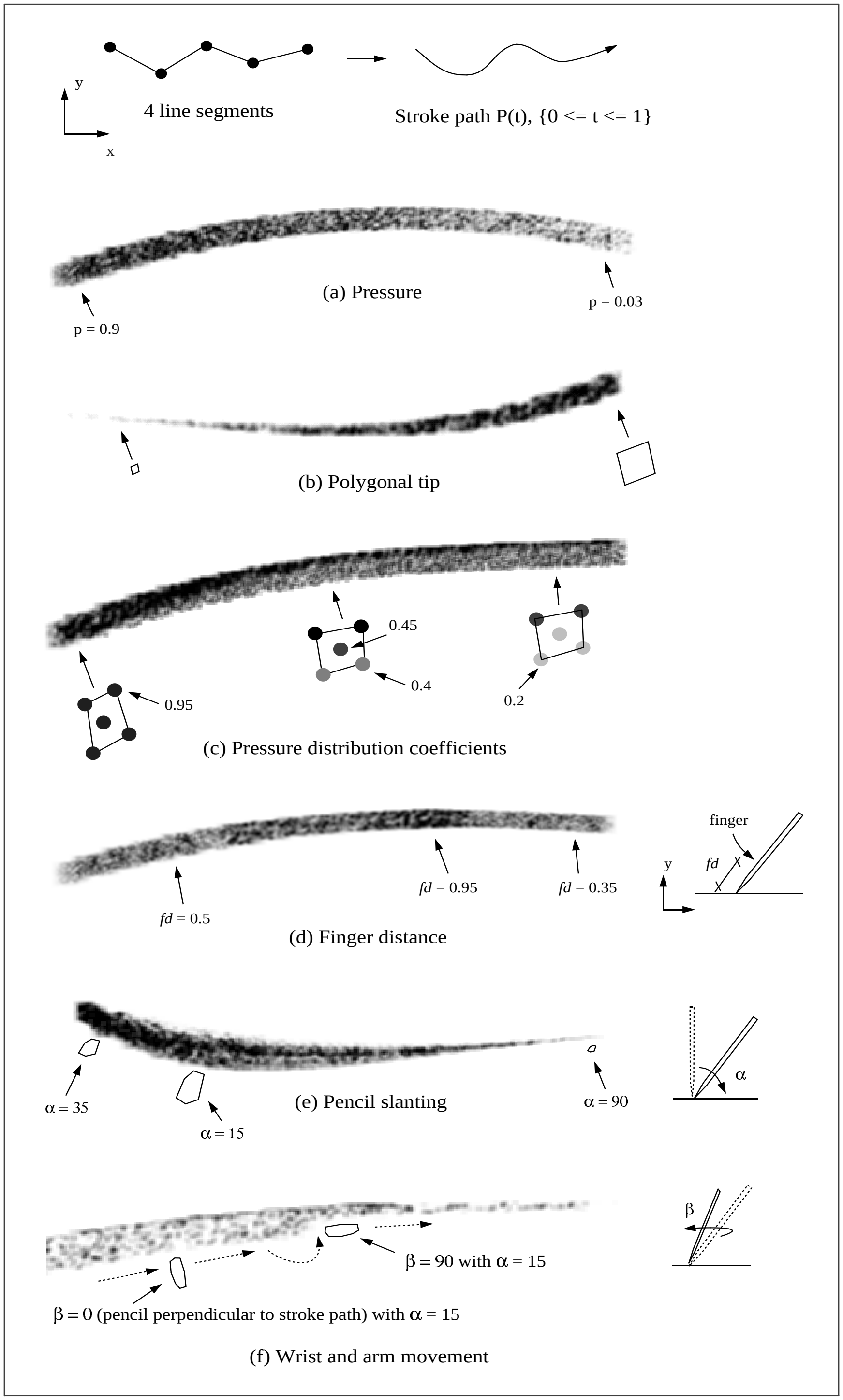


**Figure 2:** *Example of a path for a pencil stroke (top row) and variation of six parameters from the character function $C(t)$ defining the pencil stroke primitive (section 3), rubbed with soft leads over a rough, medium-weight paper.*

to each pair of coordinates $(x,y)$ at scalar distances $t$ along the stroke's path. Each stroke parameter from the character function $C(t)$ has a specific range of values that gives satisfactory results for outlining (Table 1, section 6) and shading (Table 2, section 7). Random noise and turbulence are also applied to these values to enhance the effects of hand gestures.

## 4. Mark-making primitive

The mark-making primitive models a collection of strokes parallel to each other in a specific direction. It can be done in a formal, structured way or in a loose, "scribbled" way (sic.), according to the drawing style and approach. The main purpose of this primitive is to create areas of tone and texture [34].

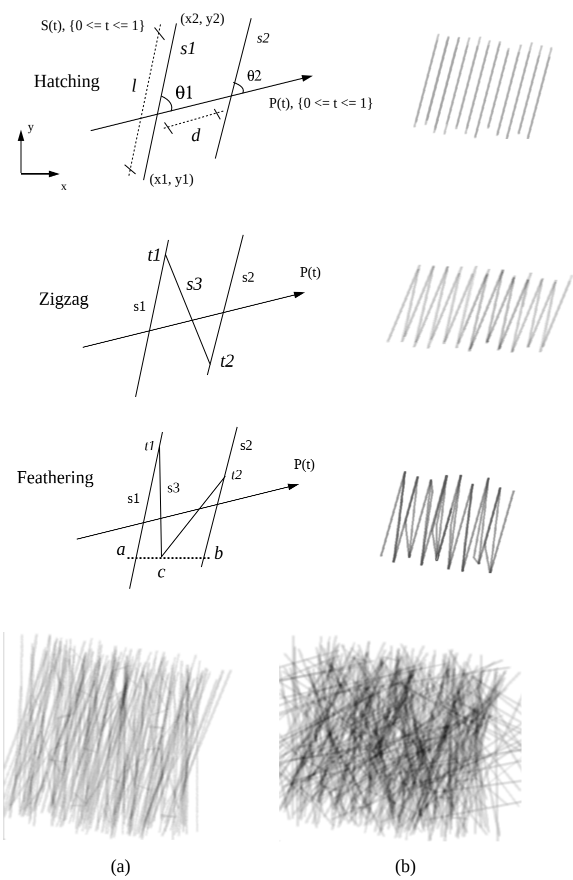


**Figure 3:** *The mark-making primitive is used to build up tones and textures. This figure illustrates three variations of the mark-making primitive with results from our model. The two images (a) and (b) at the lower part of the figure start with one layer zigzagging and feathering in one direction over the path $P(t)$ with a medium soft pencil. Another layer of the primitive was laid at different angles variations $(-10 \leq \theta \leq 10)$ for (a) and $(-45 \leq \theta \leq 45)$ for (b).*

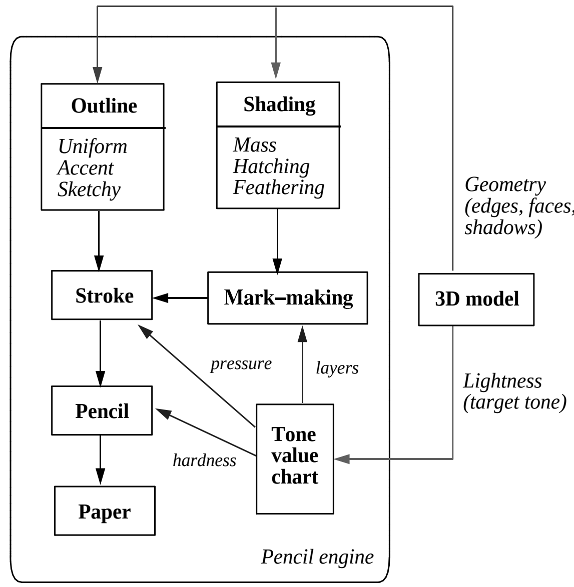


**Figure 4:** *Architecture of our pencil rendering system.*

In our model, the mark-making $M$ consists of a path $P(t) : [0,1] \rightarrow R^2$ and a character function $C(t)$. The path $P(t)$ consists of one or more line segments. The character functions $C(t)$ varies its parameters along the path as a function of $t$. Figure 3 illustrates the parameters and results from our model of three basic kinds of mark-making techniques [34]:

1. Hatching, where each stroke $S \in [0,1]$ along the path has a specific length $l \in [0,1]$ and angle $\theta$. The parameter $d \in [0,1]$ determines the distance between pair of strokes.
2. Zigzag or back-and-forth has the hatching parameters where each pair of strokes $S1$ and $S2$ along the path has a scalar distance $t1 \in [0,1]$ and $t2 \in [0,1]$ respectively which determines the connection point to the third stroke $S3$.
3. Feathering, which is a different style of zigzagging. It has the zigzag parameters where each pair of strokes $S1$ and $S2$ along the path has a scalar distance $a \in [0,1]$ and $b \in [0,1]$ respectively. Another point $c \in [0,1]$ between $a$ and $b$ defines the breaking point of the stroke $S3$.

Each parameter from the character function $C(t)$ has a specific range of values that gives satisfactory results for shading (Table 2, section 7). Random noise and turbulence are also applied to these values to enhance the effects of hand gestures in pencil mark-making.

## 5. Rendering in pencil

The next sections describe the modeling and implementation of the basic traditional pencil rendering techniques for outlining and shading using the pencil stroke and mark-making

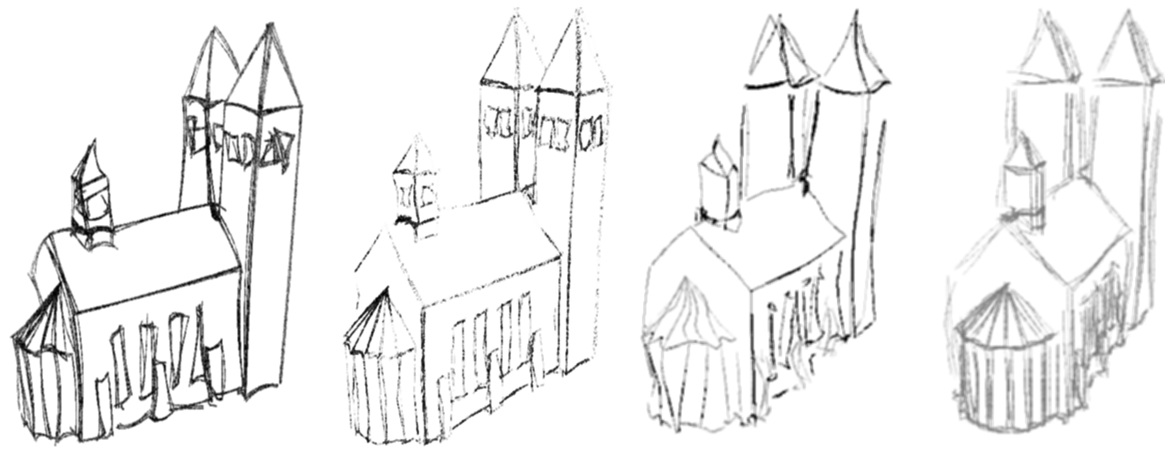
(a) (b) (c) (d)

**Figure 5:** *Outline results over semi-rough paper of 3D model of a church (298 edges, 100 faces) from our system: (a) uniform with 2B pencil (10 secs), (b) accent with 3B pencil (7 secs), (c) sketchy with H and B pencils (10 secs) , and (d) less sketchy with 2H and HB pencils (9 secs).*

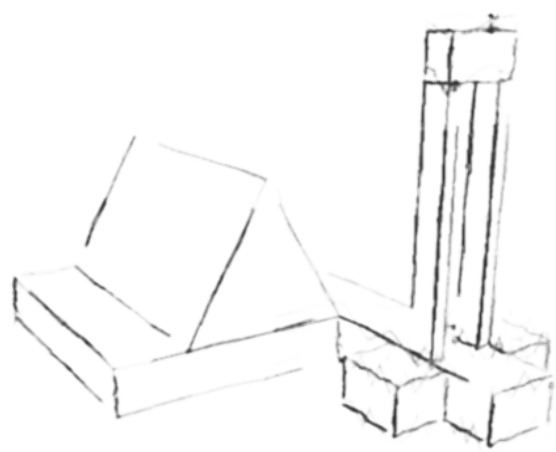

**Figure 6:** *Accented outline using medium-soft pencil over smooth paper. Model of church has 62 vertices on 8 primitives with 93 edges in total (20 secs to render).*

primitives, and the pencil and paper model [25]. Figure 4 illustrates the basic architecture of our pencil rendering system.

### 5.1. 3D models

Our pencil engine is built on the 3D modeling and rendering system presented in Glaeser [13]. The 3D models were generated using the modeling language from the same reference. Our system currently works just for polygonal models. The inputs are the visible edges, faces, and shadows. The lightness values for edges, faces, and shadows are evaluated using the Phong illumination model with flat shading, either as a pre-computation step, yielding a reference gray-scale image, or directly as the pencil strokes are generated. Most of the processing described in this paper assume that we have 3D information as well as the visible polygons and edges projected in the normalized coordinate space.

### 5.2. Pencil engine

Our pencil engine is organized in three main subsystems: (1) materials (pencil, paper), (2) primitives (stroke, mark-making), and (3) rendering methods (outline, shading, tone value chart). Outline methods (section 6) use the pencil stroke primitive. Each stroke primitive is procedurally generated by functions written in a C-based interpreted language. These functions get as input parameter values for the stroke primitive within the range given in Table 1. Shading methods (section 7) use the pencil mark-making primitive which also uses the stroke primitive. Each mark-making primitive is also procedurally generated. These functions get as input parameter values for the mark-making primitive within the range given in Table 2. A tone value chart (subsection 7.1) controls the number of pencil passes (layers) applied to the mark-making primitive, the pressure applied to each stroke, and the lead hardness of a particular pencil. This results in matching the target tone of the 3D model (subsection 7.3). The user also has the option of modifying the parameter values for the stroke and mark-making primitives during run-time while receiving feedback in real-time, thus guiding the rendering process.

## 6. Drawing objects in outline

The simplest and most direct type of rendering is that of outlining or shape description. Salwey [28] states that "pencil lines for outlining are usually a convention considered as depicting the boundaries between different tone values". He also states that "as the work becomes more advanced and approaches what may be termed "highly finished work," the hard line, unless it is specially retained and accentuated for decorative effect, should gradually be eliminated. At the same time realism must not be carried to such an extent that the characteristics of the pencil rendering technique or the manner in which the drawing has been rendered is lost."

In our system, outline pencil strokes are drawn for each visible edge $e(t)$ from every visible face and shadow of the model. We have implemented three classes of traditional pencil-based outlines [29, 32, 33]:

1. **Uniform or flat**: This method uses lines with a fixed degree of thickness and pressure for the whole drawing (Figure 5(a)). It is good for illustration but it lacks sensitivity [32].
2. **Accented**: The pressure applied to the pencil is adjusted to lighten and darken the line giving more character and expressiveness to the outline [29]. The accented effect can be achieved by using the "sine wave" pressure function presented by Winkenbach and Salesin [11] (see Table 1, waviness function $w4$) or by adjusting the pressure of the pencil according to the interpolated lightness values $ei(t)$ along the edge with the function $p(t) = 1.0 - ei(t)$. This means that in order to achieve a darker intensity more pressure is required (Figure 5(b) and Figure 6).
3. **Sketchy**: The lines are drawn with quick and spontaneous strokes until the user is satisfied that the shape is adequately represented (Figure 5(c), (d)). It emphasizes the vitality of the drawing marks themselves, making the drawing more subjective, because the focus is balanced between representation (what is drawn) and characterization (how it is drawn) [33].

Figures 5 and 6 illustrate outlines of 3D models generated by our system. These results use default parameters which are given in Table 1.

## 7. Rendering objects in tonal contrast

Drawing media differ in the techniques used to achieve shading that matches the target tone of the subject. In pen-and-ink the approach is to alternate the lines with the white of the paper itself. Each kind of line, depending on its proximity and thickness, can produce planes having different values and textures. This approach was implemented by Winkenbach and Salesin using prioritized stroke textures for the pen-and-ink renderer [11]. Graphite pencils on the other hand can produce gradations of values between black and white. This section describes the processes involved.

### 7.1. Building the tone values chart

In pencil drawing, values between black and white are usually organized into a tone value chart with three basic tones (light, mid and dark), or ten values, the lightest value being the white of the paper [29, 30, 32, 37].

We define a tone value chart as an array $tvc_i$, $\{3 \leq i \leq 11\}$. Although we are not limited to this tone value range we decided to use it to be consistent with the traditional practices and guidelines in pencil rendering. Each entry in $tvc_i$ has the following information (see Figure 7):

1. Lightness intensity range $v_{min}, v_{max}$.
2. Average intensity value: $av = \frac{(v_{min}+v_{max})}{2}$
3. Pencil hardness $ph$.
4. Pressure value $p$.
5. Number of pencil passes (or layers of marks) $np$.

We implemented two traditional approaches used to create charts of a graded tone from value 0 (black) to 10 (white):

1. Use one pencil hardness that will make a dark enough tone to create a solid black. All tone values from 0 to 9 are created by changing the pencil pressure and varying the number of pencil passes. The pressure applied to the pencil is adjusted according to the averaged tone intensity value and is given by: $p = 1.0 - av$. This means that in order to achieve a darker intensity more pressure is required (Figure 7 top chart).
2. Use seven pencils of grades 6B, 4B, 2B, HB, 2H, 4H, and 6H. Pencils are changed to create a gradual blending of the tones. There are slight or no variations on the pencil pressure and variations on the number of pencils passes from one value to the next (Figure 7 bottom chart).

Figure 7 illustrate examples for the two approaches with $i = 11$ tone values.

### 7.2. Placing linear marks

Linear marks allow the creation of tones. For each visible face and shadow in the 3D model the following steps are followed:

1. Compute the shading direction. This direction expresses the form and depth of the planes of the subject being drawn and there are no fixed rules to determine it [29, 35, 38]. The default shading direction is the projected surface normal $P(N)$ in the projection plane (Figure 8(a)).
2. Place a mark-making primitive (see Figure 3):
   a. The path $P(t)$ is defined in the projection plane as being orthogonal to the shading direction and passing over the center of the face being shaded (Figure 8(b)).
   b. Generate collection of parallel strokes along $P(t)$ with angle $\theta$ with respect to the computed shading direction (Figure 8(c)). The distance $d$ between every pair of strokes should be the same. It has been observed that this is the case for most shading approaches using graphite pencil [28, 38].

PENCIL

| | | Uniform | Accent | Sketchy |
|---|---|---|---|---|
| | Pencil hardness | 2B | HB, B | F, HB, 4B |
| Point | Shape | Typical | Broad | Broad, Chisel |
| | Size | Lead thickness | Lead thickness | Lead thickness |
| | Pressure distribution coefficients | 1.0 | 0.7, 1.0 | 0.2, 0.5, 1.0 |

STROKE

| | Uniform | Accent | Sketchy |
|---|---|---|---|
| $C_p(t)$ | 0.7 | 1 – ei(x,y) | 0.4, 0.8, 1 – t |
| $C_{ps}(t)$ | Typical | Broad | Typical, Broad |
| $C_{pdc}(t)$ | 1.0 | 0.7, 1.0 | 0.2, 0.5, 1.0 |
| $C_w(t)$ | *w2*, *w4* with *noise* | *w4* with *turbulence* | Any *w* with *turbulence* |
| $C_{fd}(t)$ | 0.5 | 0.4 .. 0.7 | 0.5 .. 0.8 |
| $C_\alpha(t)$ | 10 ... 45 | 30.0 | 20 ... 40 |
| $C_\beta(t)$ | Perpendicular with the path | Perpendicular with the path | Perpendicular with the path |

**Waviness functions**

$$w1_{x,y}(t) = sin(t) + (sin(a \times t) / b) + (sin(\ b \times t) / c)$$

$$w2_{x,y}(t) = a \times sin(t) + sin(a \times t)$$

$$w3_x(t) = cos(a \times t) - cos(b \times t) \times sin(a \times t)$$

$$w3_y(t) = b \times sin(a \times t) - sin(b \times t)$$

*a, b, c: random values [0,1]*

$$w4_{x,y}(t) = p + A \times sin \times (2 \times \pi \times t / w),$$

*p = pressure [0,1], A = amplitude with noise [0,1], w = wavelength with noise [0,1]*

**Table 1:** *Default range values for the outlining parameters.*

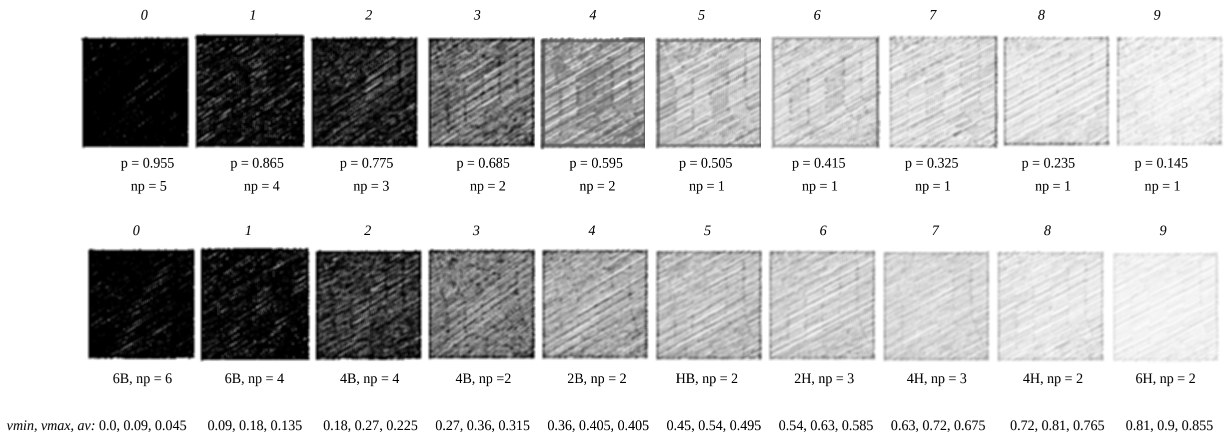


**Figure 7:** *Examples of tone values charts generated by our system for $i = 11$ values. The values of $v_{min}$, $v_{max}$, and av for both tables are listed. The eleventh entry uses the white of the paper (vmin $= 0.9$, vamx $= 1.0$, av $= 0.95$). Pencil marks are rubbed using layers (indicated by $np$) of the hatching mark-making primitive over a medium-rough paper texture. The chart on the top row was created by using the same pencil (4B) for the values. The chart on the bottom row was created by using the same pressure (0.5) for the values.*

c. Collection of strokes along $P(t)$ are clipped against the surface being shaded (Figure 8(c)).

The parameters of the mark-making primitive can now be adjusted in order to match the target tone (next subsection) and according to a particular shading method (see subsection 7.4).

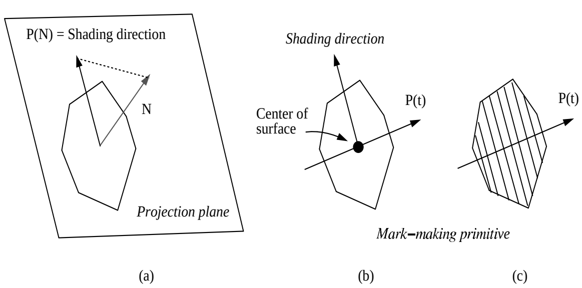


**Figure 8:** *Main steps on placing linear marks.*

### 7.3. Matching the target tone

Every visible face and shadow from the 3D model are flat shaded resulting in a target tone $tt$. Tone values that match the target tone can be created with the same methods that were used to make the value charts. Given a target tone *tt* we find the necessary parameters in the pre-computed look-up tone value chart *tvc* (Figure 4, subsection 7.1, Figure 7). These parameters are *np*, *p*, and *ph*, where *np* defines the number of times the mark-making primitive will be placed on the surface being shaded, *p* defines the pressure applied to the stroke, and *ph* defines the pencil hardness.

### 7.4. Results

In this section we present results from our implementation of two fundamental graphite pencil tone rendering categories: “realistic” and line-based methods.

#### 7.4.1. “Realistic” methods

Of the various methods of toning or shading, perhaps the most natural for the beginner’s first use is what might be called the “realistic” method [29]. In this method, the artist renders, by “mass” shading every visible tone in the subject as literally as possible. In *mass shading* the component pencil lines are so merged that their individual identity is wholly or largely lost [29]. The zigzag mark-making primitive (see Figure 3) is used with the strokes very close together to make a continuous tone. The side of the pencil is used by slanting it to 30-40 degrees (see Figure 2(e)), bringing the tone out very smoothly. Layers of the mark-making primitive can be repeatedly placed over the surface in different shading directions until all traces of line disappeared. Another “realistic” method is smudging or burnishing [32, 36, 37]. We implemented it for automatic and interactive image-based pencil rendering using our blender and eraser model [26].

Figures 9, 10, 13(a), 14 illustrate mass-shading of 3D models generated by our system. These results use default parameters which are given in Table 2.

#### 7.4.2. Line-based marking methods

These are methods where at least some lines are plainly visible. We implemented two techniques:

PENCIL

| | | Mass | Hatching | Feathering |
|---|---|---|---|---|
| Pencil hardness | | B, 2B | F, HB, B, 2B | HB, 2B, 4B |
| Point | Shape | Typical | Typical, Broad | Broad, Chisel |
| | Size | Lead thickness | Lead thickness | Lead thickness |
| | Pressure distribution coefficients | 1.0 | 0.8, 1.0 | 0.3, 0.7, 1.0 |

STROKE

| | Mass | Hatching | Feathering |
|---|---|---|---|
| $C_p(t)$ | Tone value chart | Tone value chart | Tone value chart |
| $C_{ps}(t)$ | Typical, Broad | Typical | Typical, Broad, Chisel |
| $C_{pdc}(t)$ | 0.7, 0.8, 1.0 | 0.7, 1.0 | 0.5 ... 1.0 |
| $C_w(t)$ | *w2, w3* with *noise* | *w1, w2, w4* with *turbulence* | Any *w* with *noise, turbulence* |
| $C_{fd}(t)$ | 0.4 ... 0.7 | 0.4 ... 0.7 | 0.3 ... 0.8 |
| $C_\alpha(t)$ | 30 ... 40 | 45 .. 70 | 10 ... 50 |
| $C_\beta(t)$ | Perpendicular with the path | Perpendicular with the path | Perpendicular with the path |

MARK–MAKING

| | Mass | Hatching | Feathering |
|---|---|---|---|
| $l$ | 1.0 | 0.9 – 1.0 | 0.7 – 1.0 |
| $\theta$ | shading direction + range of –45 ... +45 degrees | shading direction + range of –5 ... +5 degrees | shading direction + range of –15 ... +15 degrees |
| $d$ | 0.01 ... 0.2 | 0.05... 0.3 | 0.03 ... 0.5 |
| $t1, t2$ | t1: 0.8 ... 1.0<br>t2: 0.0 ... 0.2 | — | t1: 0.7 ... 1.0<br>t2: 0.0 ... 0.3 |
| $a, b, c$ | — | — | a: 0.1 ... 0.3<br>b: 0.4 ... 0.8<br>c: 0.1 ... 0.4 |

**Table 2:** *Default range values for the shading parameters. Waviness functions are given in Table 1.*

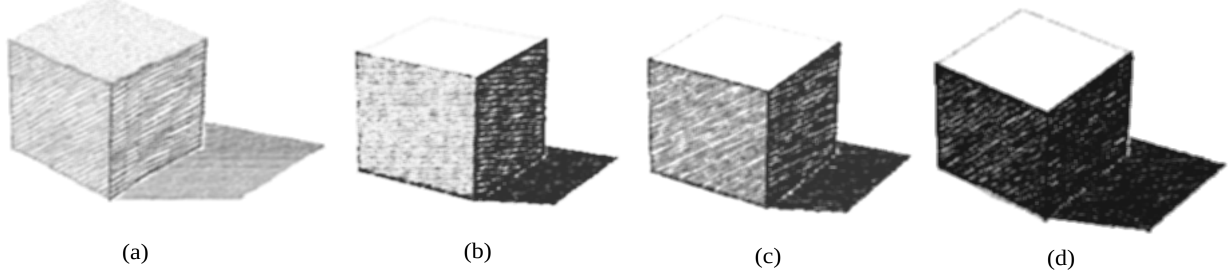

**Figure 9:** *Four variations of tone value study with mass, hatching/crosshatching, and feathering shading over a cube using different charts. With a 2H pencil (a) the light value, the middle value, and the dark value are indicated. A stronger light effect is obtained with a 2B pencil (b), or (c) by keeping the light side white, the middle tone a 6th value with a 2H pencil, and the dark side a 2nd value by using a 4B pencil. In order to create the strongest effect of light possible (d), the light side is left white and the middle tone a 2nd value with a 2B pencil and the darks a 1st value with a 4B pencil.*

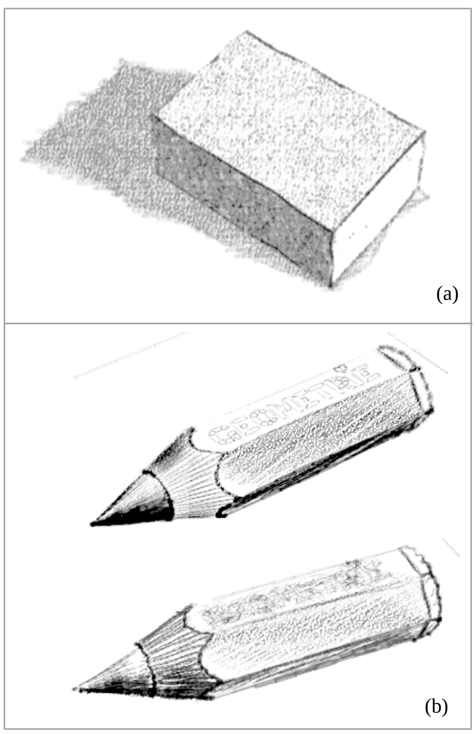

**Figure 10:** *Examples of pencil rendering of 3D objects in mass shading using our system: (a) parallelepipeds, 3H, 2H, HB, and B pencils used firmly over rough paper (22 secs), (b) pencil (602 edges, 206 faces), 2B pencil used lightly over semi-rough paper, (1.20 min for top pencil, 1.10 min for bottom pencil).*

1. **Hatching/Crosshatching**: the principle of hatching is drawing lines with one definite and continuous movement, parallel to each other, and very near together to produce an even tone. The hatching mark-making primitive (see Figure 3) is used with the collection of strokes in the shading direction and equal distance *d* between every pair of strokes. Cross-hatching is the rendering of tone values by superimposing one series of parallel lines diagonally across another series of parallel lines [28]. It can be achieved by placing additional layers of the hatching mark-making primitive at different shading directions on top of the current pencil marks.
2. **Feathering or scumble**: With this technique the strokes are plainly visible because the pencil is used with a greater degree of freedom, blending tones optically so that while individual strokes are retained, they are also overlaid to create smoother tones [29, 32, 37]. The feathering mark-making primitive (see Figure 3) is used.

Figures 9, 13(b), 14(a, step 3) illustrate hatching, and Figures 9, 11, 12, 13, 14(b, step 2) illustrate feathering tone rendering of 3D models generated by our system. The default variations for the pencil, stroke, and mark-making parameters are given in Table 2.

## 8. Drawing steps control

The control of the drawing composition is an important aspect of both traditional illustration practices and non-photorealistic rendering methods. Composing an illustration means putting together things and arranging them in order, to make one unit out of them all. Composition issues include proportion of the picture space according to the subject, focal points in the drawing, tone value studies, atmospheric effects, and so on [29, 30, 31, 32]. Some of these issues have been investigated in NPR research. Strothotte et. al. [12] control the placement of lines depending on the ar-

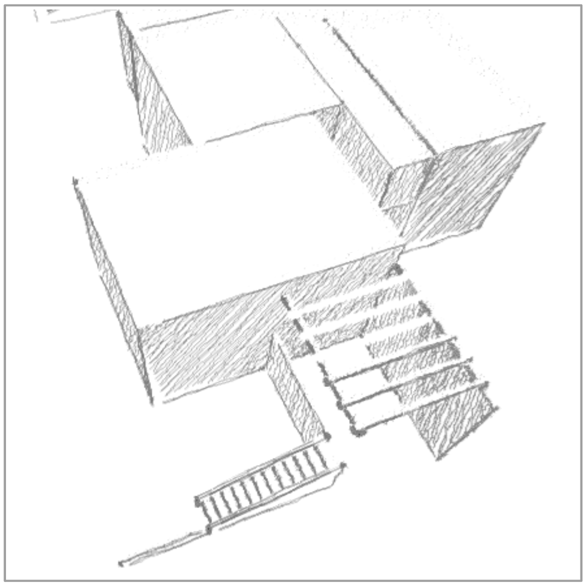

**Figure 11:** *Initial stages of feathering shading using tone value chart with three values (7th and 8th values from chart on Figure 7 and white of the paper). Model has 450 edges and 224 faces (1 min. to render).*

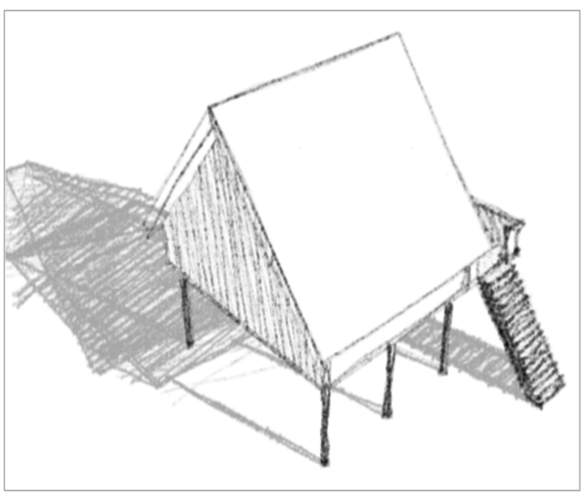

**Figure 12:** *Feathering shading using H and 4B pencils over semi-rough paper. The H pencil with a broad points is applied firmly across the shadow to smooth the strokes. Model has 510 edges and 238 faces (1.25 min. to render).*

eas of the image needing more attention. Winkenbach and Salesin [11] interactively control the placement of strokes indicating where details should appear on the surfaces of the objects. Streit and Buchanan [24] present techniques for creating non-photorealistic half toned images by controlling importance functions and the type and number of drawing primitives. Seligmann and Duncan [8] describe an automated intent-based approach to illustration which fulfills high-level description of the communicative intent and stylistic choice.

With our system it is possible to control the composition of a drawing work from the initial sketch to the finished rendering, a process achieved in a variety of drawing steps [29, 30, 31, 32]. The rendering proceeds in layered steps emulating the process that artists take in order to make sure that the composition is correct at specific steps. Each drawing step is implemented by configuring the parameters of the pencil and the rendering methods described (see Tables 1 and 2). Each step can be repeated a number of times before moving to next step. Figure 14 shows an example of how an illustration is improved by rendering in progressive steps in this way. The parameters for each step are configured according to the guidelines found on pencil drawing literature and by using the values from Tables 1 and 2. Figure 15 illustrates different steps on a rendering study of a chair.

## 9. Conclusions and future work

In this paper we presented non-photorealistic rendering methods that simulate the basic rendering techniques used by artists and illustrators familiar with graphite pencil rendering. The methods are based on traditional pencil illustration techniques recommended by review of pencil literature. We implemented rendering techniques for automatic outlining and shading of 3D polygonal models. These techniques are built on top of an observational model of graphite pencil and drawing paper [25], and on the mark-making and stroke primitives. We also describe the partial control of the drawing composition through ordering and repeating of drawing steps from preparatory sketches to finished rendering results.

Several research issues remain open for future study in computer-generated pencil drawing. Methods to alter the texture of tones to simulate natural material textures are needed. Other pencil outlining and shading techniques may also be explored and extended to render various classes of 3D models from different contexts (architecture, art, design). User interface metaphors and techniques should be investigated. Drawing composition techniques (section 8) can be further explored and modeled into a computer-generated pencil rendering system.

## Acknowledgments

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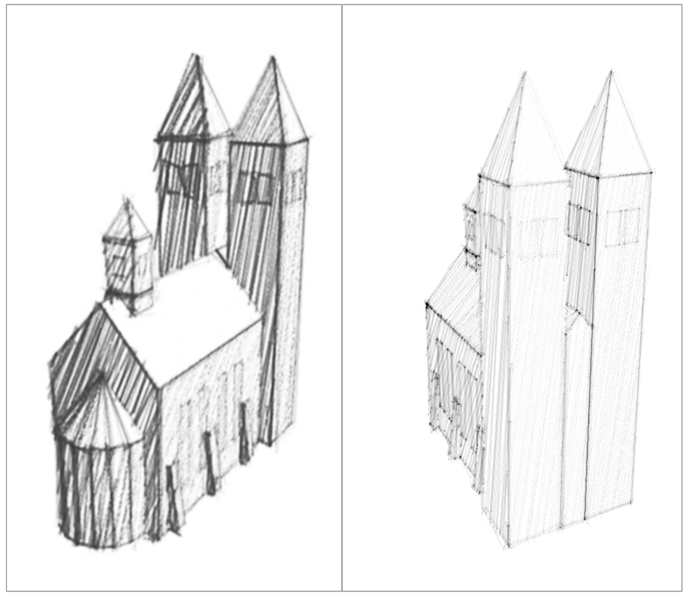
(a)



(b)

**Figure 13:** *Examples of pencil rendering of 3D objects in tonal contrast using our system: (a) computer desk (3374 edges, 1195 faces), The three shading methods with 8H, 5H, B, and 5B pencils over rough paper. Accented outline (48 secs), mass shading (1.23 min), hatching/cross-hatching, and feathering (1.10 min), total time is 3.20 min, (b) church (298 edges, 100 faces), mass and feathering shading with B, 2B, and 4B pencils over medium-rough paper (left church, 50 secs); light mass and feathering shading with B, 2B, and 4B pencils over smooth paper (right church, 33 secs).*

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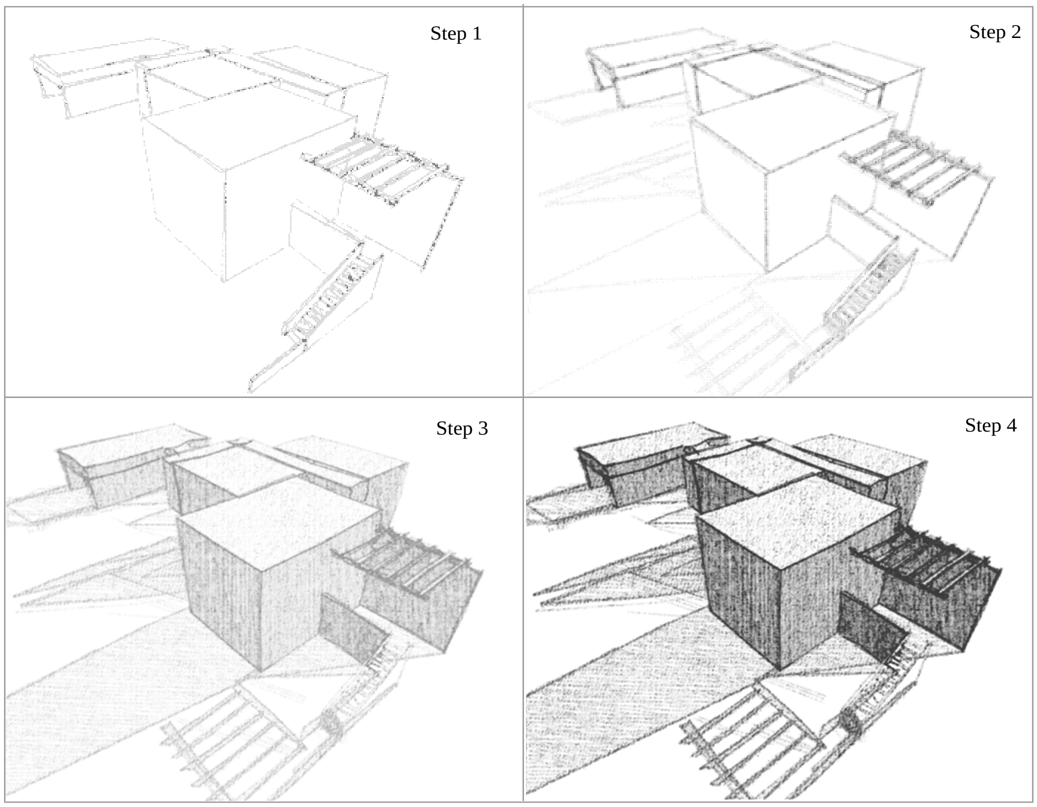
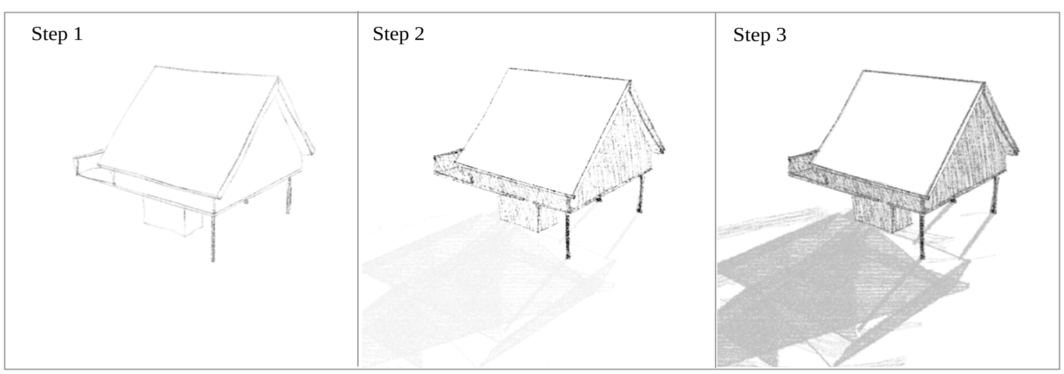
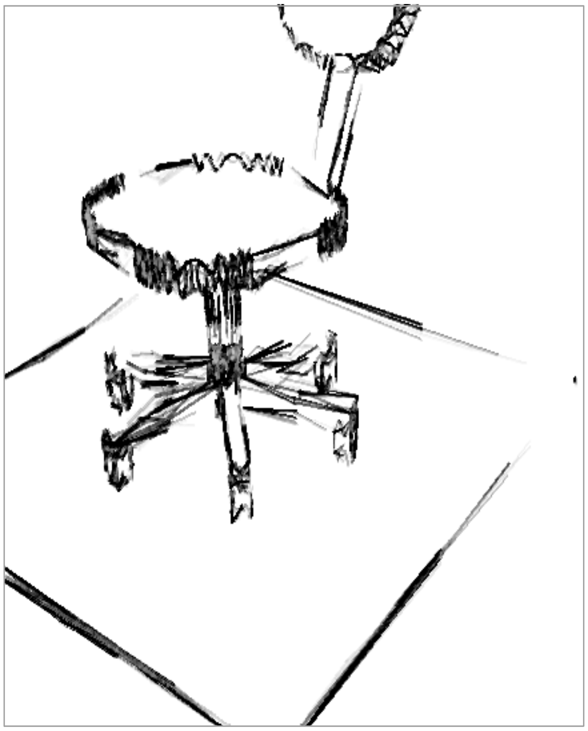



(a)

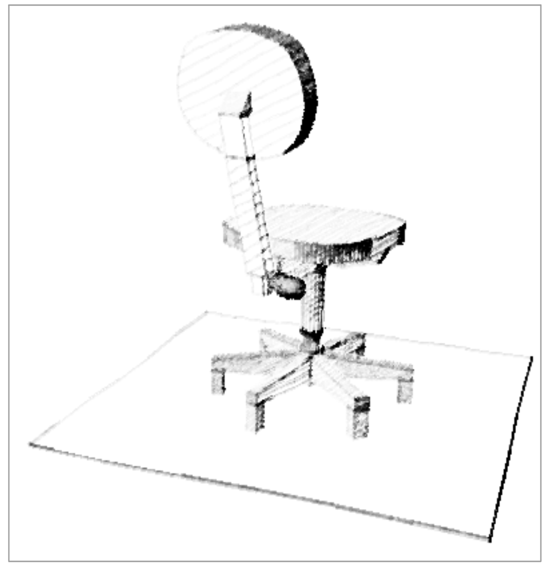



(b)

**Figure 14:** *The evolution of a pencil drawing over semi-rough paper in traditional steps* [29, 30, 31, 32] *implemented in our system: (a)* step 1*, B pencil, accented outline (7 secs.);* step 2*, 55 secs. later, HB, 2H pencils, uniform outline, delineation of shadows. This step is repeated 2 times;* step 3 *after 1.40 min., HB, 3B pencils, mass shading, light hatching and feathering. This step is repeated 2 times;* step 4 *after 2 min., 3B pencils with increased pressure. Steps 2 and 3 are repeated 2 times. (b)* step 1*, HB pencil, uniform outline (45 secs.);* step 2*, 1.05 min. later, 3H, B pencils, light mass shading, very light feathering;* step 3 *after 1.15 min., 2B, 3B pencils with increased pressure, with high pencil slanting in the shadow. Step 3 is repeated 3 times.*



(a)



(b)

**Figure 15:** *Examples of a pencil rendering study of a chair using our system. Model has 2 groups, 624 vertices on 27 primitives, 976 edges, and 406 faces. (a) sketchy outline using 4B pencil (40 secs to render), (b) hatching and mass shading with various pressures applied to B and 2B pencils (50 secs to render).*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