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Illustrative Scientific Visualization Framework

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Abstract

Current scientific visualization techniques create complex images that may be difficult to interpret and do not have the expressiveness of illustrations. Incorporating traditional scientific illustration techniques into a visualization system enables artists and non-artists to harnesses the power of traditional illustration techniques when visually representing scientific data. In this paper we present an illustrative scientific visualization framework incorporating general illustration principles, as well as techniques and aesthetics of various styles. Such a framework provides a basic foundation for categorizing and communicating research and may stimulate future illustrative visualization systems.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques

1. Introduction

Over the centuries, scientific illustrators have developed techniques to convey important and complex information of various disciplines (i.e. medicine, botany, zoology) in a very compact and effective illustration [Hod03] (Figure 1). The real power of traditional illustration techniques comes from the illustrator's subtle understanding of how to effectively manipulate the media to create subtle cues to aesthetically represent (abstract or realistic) and effectively communicate data to viewers through emphasis or subjugation of information.

Current scientific visualization techniques create complex images that may be difficult to interpret and do not have the expressiveness and aesthetics of illustrations. This paper provides a classification of current rendering techniques and a review of a traditional scientific illustration pipeline in order to enable artists and non-artists to apply effective illustrative scientific visualization (ISV) for the creation of computer-generated images of scientific data. The goal is to provide novel ways of exploring and visualizing complex scientific datasets by presenting abstractions to users in ways that reconcile expressiveness, aesthetics and ease-of-use. Research in ISV is very recent [BGKG05a, LM02, ONOI04, SE05a, VKG04, VGB*], rooted in two other established areas: non-photorealistic rendering (NPR) and scientific visualization. Figures 3-7 show some of the published results generated using NPR systems for scientific application domains of medicine, archaeology, zoology, botany and cartography.

ISV systems benefit scientists as well as medical and scientific illustrators. Current digital medical and science illustrations are typically produced by scanning preliminary hand-drawn sketches, then developed through a series of commercial software packages for vector drawing (i.e. Illustrator), bitmap painting (i.e. Photoshop), 3D applications (i.e., Maya), until a finished rendering is produced [Hod03]. This approach is not cost-effective, has high learning curves and does not offer specific functionalities required for medical and science illustration production [SE05b, Sou05]. Illustrative visualization systems offer a more *integrated* set of advanced tools for helping (not replacing) illustrators in all phases of illustration production, preserving their style and adapting to their preferred ways of thinking and working. An illustrative visualization system allows illustrators to create imagery never before possible with a set of new techniques by decreasing content creation costs and increasing productivity and computational efficiency.

We present an ISV system framework based on traditional techniques, guidelines, processes that scientific illustrators follow during the entire illustration production

Figure 1: From left to right *Traditional scientific illustrations for archaeology, zoology, © Emily Damstra, botany, © Siriol Sherlock, and medicine © Bill Andrews, all rights reserved. All illustrations used by permission.*

pipeline [Hod03]. Such a framework provides a basic pedagogy and foundation for categorizing and communicating research, and support for developing future ISV systems.

Our ISV framework has been iteratively developed in collaboration with medical and scientific illustrators [Hod03, SE05a]. We carefully observed the communication and production processes of traditional illustration, as shown in the first two columns on table in Figure 2. We then broke the illustrator's tasks into various distinct components further categorized in three main components (diagram in Figure 2):

1. **interactive modeling**, to create, edit, manipulate and annotate 3D models by interactive sketch input integrated with acquired scientific datasets (Section 2);
2. **shape analysis**, to extract features, measure and depict the 3D form of the models and datasets (Section 3);
3. **expressive rendering**, to provide illustrative renditions incorporating general illustration principles, techniques, abstractions and aesthetics of different styles (Section 4).

Each component builds upon the other and aids in the creation of a solid framework for ISV research and development. Our framework reduces the effort of scientists and illustrators during content creation, analysis and rendering, allowing focus on discovery, creativity, and end results.

In the next sections, we will describe each of these three components in more detail by first presenting how the component relates to traditional illustration and describing topics related to graphics.

2. Interactive Modeling

Illustrators are increasingly using 3D modeling tools (i.e., Maya, Poser) as part of the digital illustration production pipeline, primarily to create 3D representations from preliminary conceptual sketches. However, most illustrators agree that available methods of constructing, editing and manipulating 3D models (i.e. control points manipulation, multiple menus and parameter adjustment, etc) do not lend to a natural interaction metaphor and forces them to diverge from their preferred ways of thinking and working. Sketch-based interfaces and modeling (SBIM) approaches can potentially offer intuitive solutions to these problems and to the actual modeling task and goal (i.e. translate sketches to 3D models). The main goal of SBIM systems is to allow the creation, manipulation, and subsequent annotation of 3D models by using strokes extracted from user input and/or existing drawing scans [NJC*02]. SBIM is a relatively new area of research in modeling, especially for 3D content creation involving free-form objects and complex structures commonly found in natural science subjects. Four topics are of particular importance for ISV systems: stroke capturing, overall form, conceptual marking and shape augmentation.

Stroke capturing: a fundamental process in SBIM systems, in which different types of input strokes (i.e. single or clusters) and their qualities (i.e. main path, hand gesture details) should be properly recorded and parameterized [CSSJ05].

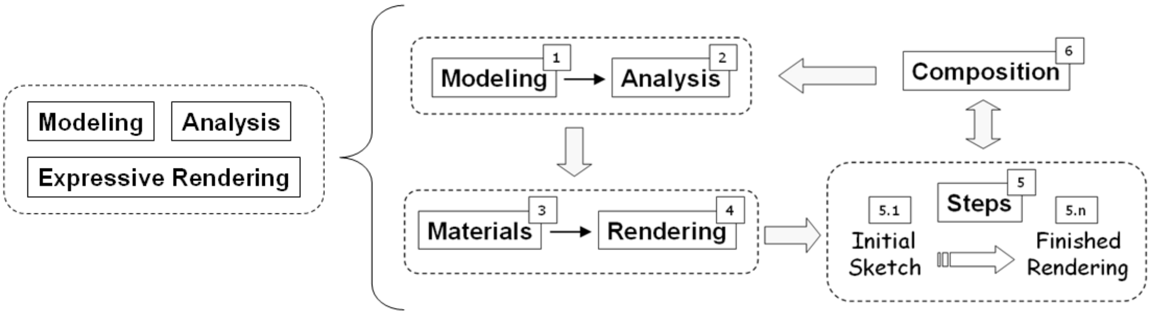
Overall form: refers to the process of constructing and editing 3D shapes using few key strokes which define the overall form, geometry, topology, proportions, scale, etc. of the model. Existing works can be categorized in two groups: (1) architectural, engineering shape modeling [ZHH96]; (2) more generic free-form shapes [IMT99], commonly found in medical and scientific domains [CSSJ05, DAJS*04, SWSJ05].

Conceptual marking: refers to the process of using the strokes to indicate, manipulate (i.e. cut, deform), label, and annotate visual references to aid in the overall visual communication, manipulation and exploration of the data [CSSJ05, ONOI04, TBvdP04].

Shape augmentation: refers to the process of using input strokes to add details (i.e. sharp features, convex and concave regions) to the surfaces of existing 3D shapes [LF03, NSACO05, OSSJ05].

3. Shape Analysis

Form interpretation is an important early stage in the production pipeline of traditional scientific illustrations. It involves careful analysis and study of the subject to be illustrated (third row in the table of Figure 2). Shape analysis allows the elimination of extraneous details and the reduction of image marks to the most representative features. Shape



SCIENTIST	ILLUSTRATOR	NPR component $\sharp$
Provides material	Requests information	1
description	Records information	1
specimen	Studies specimen	2
-	Makes rough drawing	3, 4, 5.1, 6
-	Prepares scaled drawing	3, 5.2, 6
-	Makes detailed preliminary drawing	3, 4, 5.3, 6
Checks detailed preliminary drawing	-	
-	Corrects preliminary drawing	1, 2, 3, 4, 5
Checks corrections	Produces rendering	3, 4, 5.4 $\cdots$ 5.n, 6
Checks rendering	Labels drawing	3, 4, 6
Checks labeling	-	
-	Return specimen	

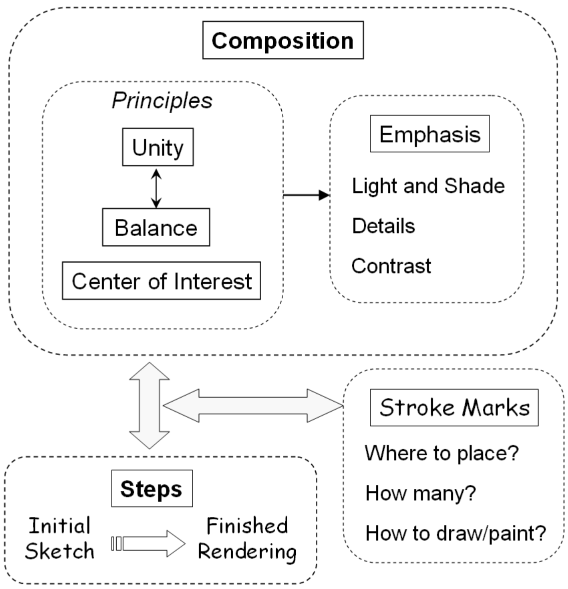


Figure 2: *The diagram on top shows the illustrative visualization pipeline with its six main components: (1) modeling and (2) analysis, (3) materials and (4) rendering, (5) steps and (6) composition. In the table, the first two columns describe the responsibilities of the scientist and the illustrator (adapted from Table 1-1, page 11 of Chapter 1 from [Hod03]). Copyright 2003 The Guild of Natural Science Illustrators. Used by permission.*

features, or measures (i.e. contours, folding regions, surfaces areas, volumes, curvatures) are accurately identified and rendered as ink line drawings to provide a preliminary depiction of form and also to serve as the basis for more detailed rendering [Hod03, Raw87].

Silhouettes: the view-dependent outline of a solid object; this has been the main focus of NPR research on feature extraction.

Silhouette drawings are a simple form of line art used in cartoons, technical illustrations, architectural design and medical atlases. Silhouette curves of a polygonal model are useful in realistic rendering, in interactive techniques, and in non-photorealistic rendering (NPR).

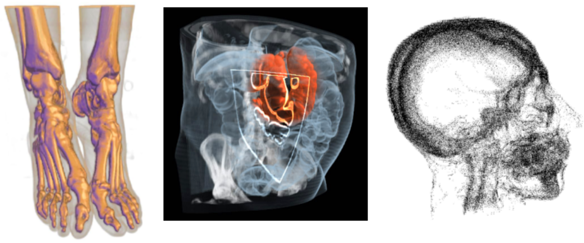


Figure 3: *Selection of NPR results for medical illustration. (Left) © [LM02], (middle) © [SES05], (right) © [LME*02]. Used by Permission.*

In realistic rendering, silhouettes are used to simplify shadow calculation. Sander et al. demonstrate that complex models can be rendered at interactive rates by clipping the polygons of a coarse geometric approximation of a model along the silhouette of the original model [SGG*00]. Hertzmann and Zorin have shown that silhouettes can be used as an efficient means to calculate shadow volumes [HZ00]. Haines demonstrated an algorithm using silhouettes for rapidly rendering soft shadows on a plane [Hai01]. Silhouettes are used for interactive haptic rendering [JC01]. Some authors [JRP02, CPSC98] have described the use of silhouettes in CAD/CAM applications. Systems have also been built which use silhouettes to aid in modeling and motion capture tasks [FPT99, LGMT00, BL01]. Isenberg et al. [IFH*03] describe, categorize, discuss, and recommend algorithms for computing the silhouette of a polygonal model. This work is meant to complement the work of Isenberg et al. by quantifying the time, complexity, and runtime parameters involved in developing silhouette algorithms.

In NPR, complex models and scenes are often rendered as line drawings using silhouette curves. Lake et al. present interactive methods to emulate cartoons and pencil sketching [LMHB00]. Gooch et al. built a system to interactively display technical drawings [GSG*99]. Rheingans and Ebert and Lum and Ma have built a NPR volume visualization system which uses silhouettes to emphasize key data in volume renderings [RE01, LM02].

The silhouette set of a polygonal model can be computed in object space or in screen space. Object space algorithms require computations in three dimensions and produce a list of silhouette edges for a given viewpoint. Screen space algorithms are usually based on 2D image processing techniques and are useful if rendering silhouettes is the only goal of the algorithm. While all of the object space methods evaluated in this work compute the silhouette set of a polygonal model from a given viewpoint, it should be noted that these algorithms solve different aspects of this common problem. For example, the method of Gooch et al [GSG*99] works only for orthographic viewing, the method of Hertzmann and Zorin [HZ00] which uses a different definition for the silhouette set, while the method of Markosian et al. [MKT*97] is an anytime algorithm which does not require a lengthy preprocess.

Form Measures: include interior features of the model, such as ridges and valleys, creases [KMM*02], curvatures [GIHL00, HZ00, KWTT00, RKS00, ACSD*03, SSB04], suggestive contours [DFRS03], morphological operators [RKHP00], and morphometric variables [SFWS03].

Light on Form: includes experiments with alternate light models based on techniques used by illustrators for light manipulation and effects [Hal95, GGSC98, Ham00, ALK*03, SSB04].

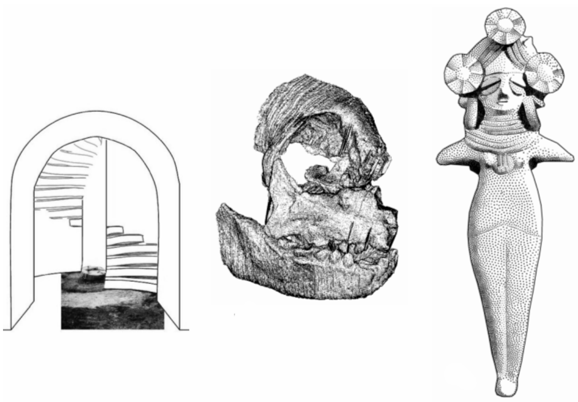


Figure 4: *Selection of NPR results for archaeology. (Left) © [SMI99], (middle) © [SFWS03], (right) © [DHvOS00]. Used by Permission.*

4. Expressive Rendering

Expressive rendering provides new visual representations and tools that precisely convey the information to be depicted, with images embodying aesthetic qualities. Expressive rendering entails four components in the ISV framework (Figure 2): **materials and rendering** (Section 4.1), to replicate the visual effects and physical behaviours of traditional illustration media (i.e. pencil) and corresponding rendering techniques (i.e. hatching) and **steps and composition** (Section 4.2) to incorporate principles from perception and illustration to control various composition effects (i.e. focus of attention, emphasis). By integrating these four components, we can approximate traditional media and techniques resulting in images with an aesthetic quality that impart, according to scientific illustrators, a more “organic" look to the digital images (i.e. it does not look like sterile plastic) and discover new visual effects and representations that are due to computer graphics imaging only, thus presenting unique advantages compared to other traditional illustration media, techniques and styles. The next two subsections describe these components in more detail.

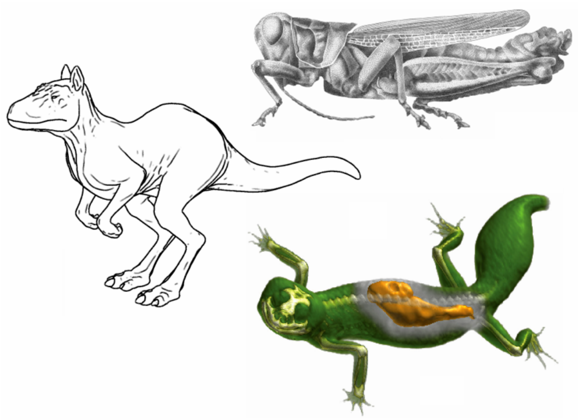


Figure 5: *Selection of NPR results for zoology. (*Killeroo*) © 2003 Doug DeCarlo [DFRS03] (model provided by headus.com.au) (*Grasshopper*) © [DHvOS00], (*Leopard Gecko*) © [VKG04]. Used by Permission.*

4.1. Materials and Rendering

The phenomena of natural media has three main elements: *applicator* (i.e. pen, pencil, brush), *substance* (i.e. ink, graphite, paint), and *surface* (i.e. canvas, paper). The primary functionality of the simulation can be divided in three main components:

Applicator dynamics: update applicator according to user input and/or algorithm.

Substance behaviour: update substance distribution according to applicator motion.

Substance rendering: compute color and display resulting media to the screen.

In any type of simulation there is inevitably a trade-off between realism, control, and efficiency. We can have three main types of simulation models along this trade-off curve:

Visual: simple heuristics allowing fast interactive response, while still offering a number of attributes of the medium being simulated, including integration with applicator models.

Observational: involves careful observation of the real medium to capture its essential physical properties and behaviours to reproduce quality rendering and a variety of real-world conditions at interactive rates.

Physical: involves computing an accurate solution for specific real-world conditions on the look and/or behaviour of the natural medium.

Natural media simulation models are usually integrated in two types on NPR systems: interactive painting systems and automatic stylized depiction systems.

Interactive Painting Systems. In these systems, the user has total control over the resulting work. Given a blank-screen (i.e. the canvas) each of the three main components of the simulation is performed repeatedly until the user considers the drawing/painting complete. The history of painting systems goes back over thirty years. In that time many different algorithms for each of the three media simulation components (dynamics, behaviour, rendering) have been proposed and implemented. Painting systems have been an active area of interest both in academia and in the commercial world, from early experiments with paint programs [Smi78] to novel observational and physically-based models for oil-like painting [BI04].

Automatic Rendering Systems. In these systems the computer decides algorithmically how to generate expressive renditions of existing images or 3D scenes. The main goal of automatic NPR systems is to incorporate the many types of structural correspondence and styles already developed by artists and illustrators. The system algorithms/heuristics should be able to duplicate and/or extend such visual analogies on a computer, with little or no user intervention. Existing automatic systems operate over the following representations: image from photographs/video/syhnthetic 3D scenes, cloud of points, polygonal surfaces, parametric surfaces, implicit surfaces/CSG, and volume data.

4.2. Steps and Composition

The term *steps* refers to the control of the production of an illustration work from the initial sketch to the finished rendering. It bridges the components of rendering with composition (Figure 1). Composition means assembling elements and arranging them in order, to make one unit of them all and is a non-trivial task. It can be applied to any kind of subject matter and to any kind of drawing/painting (from quickest sketch to highly finished rendering) [Lew84]. Figure 1 shows an expanded view of the steps and composition components of the NPR pipeline.

At each step the illustrator is carefully thinking about three questions [Cra00, Raw87]:

Where to place the strokes? This decision is usually made during modeling and analysis. Before starting to draw, illustrators thoroughly study the subject to be rendered, focusing on the geometric forms that give the subject its overall shape. They consider both the lines that define the outline of the object (silhouettes and boundaries) and features that define the interior volumes and surfaces, such as creases, ridges, and valleys. After such analysis, illustrators lightly outline the regions related to the shape measures; those regions are then filled with stroke marks, with a gesture that conveys either a careful or loose constructed look [Sim93].

How many strokes to place? Illustrators control the amount of strokes to be placed by following the principle that "less in a drawing is not the same as less of a drawing" [Raw87]. Extraneous details are eliminated, producing a drawing depicting key shape features.

How to draw/paint the strokes? A significant challenge for the illustrator is to achieve a 3D sense in a drawing, given that a strokes is by nature a 2D trace of an object in a plane. To address this challenge, the illustrator shapes and connects the feature stroke marks of the objects in different ways, subtly varies their thickness and lengths, adding inflections and breaks in the strokes, and places strokes in various relations with respect to each other.

Individual strokes are typically categorized in three fundamental groups:

1. **Contour**: usually long lines, varying its weight (or thickness) to delineate form without reliance on rendering. These variations in line weight can accentuate important points and add depth and activity to the drawing.
2. **Hatching**: arranging a series of parallel lines of various lengths, widths, at various angles to indicate shape measures and/or constructs areas of tone and texture.
3. **Precise**: short-lines and stippling. Short, straight lines allow for some crosshatching and also the simulation of a great variety of textures at different levels of precision. Stippling is the effect obtained by using a series of properly scaled and spaced dots. It is the most precise of all pen techniques.

Also, at each step, fundamental principles of composition are applied:

Unit: composition is a homogeneous whole. All the parts must be related, merged or blended together to they become a single unit, expressing one main thought. A good unit depends on the proper selection/study and emphasis of the subject. The amount of attention given to each detail is proportional to its importance.

Balance: part of the principle of unity; without balance there could be no unity. Balance results from establishing the equilibrium by arranging all the parts of the composition such that each receives a proportional share of attention.

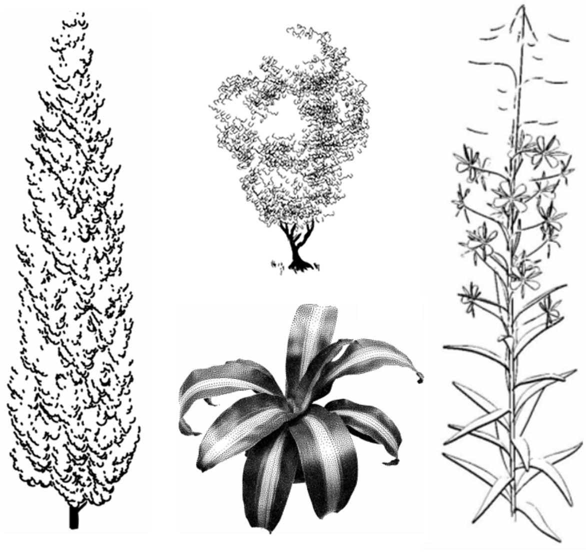


Figure 6: *Selection of NPR results for botany. (Left) © [DS00], (middle, bottom) © [SWHS97] (middle, bottom) © [Sec02], (right) © [SP03]. Used by Permission.*

Center of Interest: with the assumption the viewer is looking in one fixed direction at an object, then the object becomes the center of interest or the point of focus. The strongest contrasts and sharpest details appear at this center of interest, and grow less and less distinct towards the edges of the paper. In NPR, Strothotte et al. [SPR*94] presented a system that allows the user to interactively control the level of detail in selected areas of the rendered image, by increasing or decreasing the number of strokes. The system enhances these details by varying line styles. Winkenbach and Salesin [WS94] presented a related semi-automatic approach, in which the user controls the number of strokes. More recently, researchers have proposed techniques inspired by traditional illustration to create and control center of interest applied to volumetric datasets [VKG04, SES05, BGKG05b, BG05, WZMK05].

Emphasis: common approaches to achieve emphasis involve experimenting with different light and shading effects, tone value charts, contrast patterns, and placement of stroke and texture details and patterns to create focal points. In NPR, Sousa and Buchanan [SB00] and Majumder et al. [MG02] experimented with contrast effects. DeCarlo and Santella [DS02] presented a technique to stylize and abstract photographs by initially establishing a focus of attention model that records the user's eye movements in looking at the photo; their system then renders a new image emphasizing and de-emphasizing different parts of the photo depending on the focus of attention previously recorded.

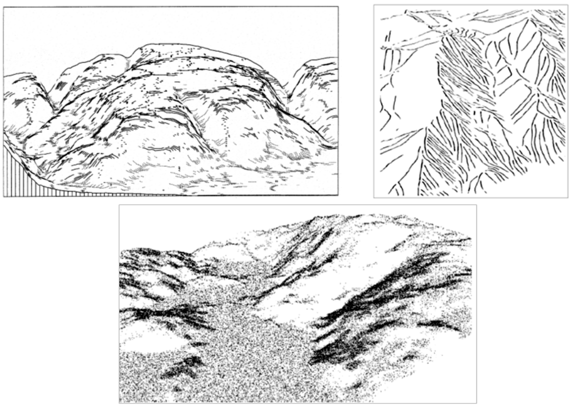


Figure 7: *Selection of NPR results for cartography. (Top, left) © 1998 Mahes Visvalingam and Kurt Downson [VD98] (http://www2.dcs.hull.ac.uk/CISRG/), (middle, bottom) © [BSS04], (right, top) © [BSD*04]. Used by Permission.*

5. Conclusions

We provide a global framework for illustrative scientific visualization which parallels the pipeline used by traditional illustrators. By providing terminology and an order of events for the creation of effective illustrations, we hope to afford a high-level perspective of the recent technical contributions supplied by researchers and enable further contributions to abstraction and communication of scientific data.

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