Illustrative Visualization for Medicine and Science

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Abstract

This tutorial presents recent and important research and developments from academia in illustrative, non-photorealistic rendering (NPR) focusing on its use for medical/science subjects. Lectures are organized within a comprehensive illustration framework, focusing on three main components:

- *Traditional and computerized illustration techniques and principles for Technical and Science Subjects*
- *Evaluation and Practical Use*
- *Viewing & Rendering*

Presentation of topics is balanced between descriptions of traditional methods and practices, practical implementation motivated approaches and evaluation, and detailed descriptions and analysis of NPR techniques and algorithms.
We begin with a lecture presenting an overview of traditional illustration in technical, science, and medical subjects followed by a description of the main components in a NPR pipeline for developing systems to help technical and science illustrators with their work. The tutorial progresses with an overview of the NPR used in illustration as well as approaches to evaluate their use and effectiveness. Following lectures describe the latest techniques in computerized illustration algorithms for scientific and medical data for both surface and volumetric data, covering techniques from silhouette enhancement to stippling, to cut-away viewing, labeling, and focus+context rendering. Each of the lectures also discusses practical issues in making these techniques interactive and their use for different application domains. Tutorial concludes with discussion on specific medical case studies where the illustrative visualization has been effectively applied.

1. Organizers

David S. Ebert, *Purdue University*
Mario Costa Sousa, *University of Calgary*
Ivan Viola, *Vienna University of Technology*

2. List of prerequisites

Required: intermediate knowledge level of 3D computer graphics and scientific visualization algorithms. Programming experience using a 3D library for interactive graphics and some awareness of existing NPR techniques may be helpful. Not required: prior knowledge of or background in artistic techniques, traditional scientific illustration, or perceptual psychology.

3. List of topics beyond the prerequisites

The tutorial covers principles of traditional illustration, algorithms and numerical methods for interpreting form (silhouettes and shape features), aspects of the viewing & rendering pipeline (texturing, algorithms for scientific illustration, ink-based rendering solutions for meshes and volumetric representations), evaluation of techniques in medical applications.

4. Target audience

The intended audience consists of visualization researchers, programmers, illustrators and others interested in automated techniques for meaningful depictions of the data and its ap-

Topics	Speaker	Time
Introduction to Perceptual Principles in Medical Illustration	Andrews, B.	30 min
Overview of NPR for Computerized Illustration	Sousa, M.C.	30 min
Perception and Evaluation: Optimizing Computer Imagery for Communication	Gooch, B.	30 min
Break		
Volume Illustration for Medicine and Flows	Ebert, D.	30 min
Smart Visibility in Visualization and Focus of Attention	Viola, I.	30 min
Illustrative Rendering for Intervention Planning: Methods, Applications, Experiences	Tietjen, C.	30 min

Figure 1: *Tutorial schedule*

plicability to current visualization. The tutorial is suitable for domain experts such as medical doctors and biologists.

5. Tutorial Syllabus

The length of the tutorial is 180 minutes (half-day tutorial) and the level is intermediate. Detailed schedule of the tutorial is shown in Figure 1.

6. Description of Lectures

Introduction to Perceptual Principles in Medical Illustration

Bill Andrews, *Medical College of Georgia*

Medical illustrations are in essence drawings/paintings of measured accuracy, depicting subtleties without ambiguities. Though often highly representational (Ŧrealistic-lookingŤ), the main purpose of such illustrations is to communicate information and not necessarily to look real.

In medical subjects, there are four instances where good illustration is the best (and possibly the only) medium to use; this is the case where: (1) Areas of reference exist physiologically but not gross anatomically; (2) Superimposing one structure upon another gives related information; (3) Section views show instruments in place in body cavities, etc; (4) Eliminating much visual garbage from a photo can produce a simpler explanation.

In this lecture I will describe current traditional and digital illustration techniques that medical illustrator uses almost everyday to create the feel of traditional imagery in the digital age. Follow a step by step presentation that starts as traditional line art sketch and is then brought to life with color and style on the computer screen using glazes, airbrush, "wet" paintbrush, and more. I will also describe how medical illustrators would benefit from using illustrative visualization systems, including research and development requirements and ongoing collaborations between the computer graphics/visualization and medical illustrators communities.

Outline

- Introduction to medical illustration
- Traditional and digital techniques
- Current communication and production pipeline
- Using illustrative visualization systems: current status, research challenges, collaboration with computer graphics and visualization communities.

Contributions

This talk contributes the perspective on computer illustration from a faculty member who teaches traditional medical illustration and uses it in practice daily. Therefore, this talk gives a great historical perspective, as well as a very useful perspective on incorporating and guiding computer-generated illustration techniques and systems in medical applications.

Overview of NPR for Computerized Illustration

Mario Costa Sousa, *University of Calgary*

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 lecture I will present an illustrative scientific visualization framework incorporating general illustration principles, as well as NPR 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.

I will also present taxonomies and describe the key techniques behind recent works in applying computer-generated medical and scientific illustration techniques to the problems of depicting shape features, visualizing volumetric datasets, and applying existing tools on different science subjects.

Outline

- Traditional medical and scientific illustration
- The illustration production process
- Hybrid NPR solutions
- System components and algorithms
  - Interactive Modeling and Shape Analysis
  - Expressive Rendering and Composition
- Recent works: taxonomies, techniques, future work

Contributions

This lecture provides a detailed description of 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 can afford a high-level perspective of the recent technical contributions supplied by researchers and enable further contributions to abstraction and communication of medical and scientific data.

Perception and Evaluation: Optimizing Computer Imagery for Communication

Bruce Gooch, *Northwestern University*

Computers are becoming faster and more interconnected creating a shift in their primary function from computation to communication. While the computer industry has produced faster processors, larger disk drives and higher memory capacity, these advances do little to help people understand the meaning of their data. This lack of understanding stems from the fact that machines process data in numerical form, while humans more easily comprehend visual data. Visualization is the process of using computer graphics to transform numerical data into meaningful imagery, enabling users to observe information. The resulting display allows a viewer to detect and analyze features in numerical data that may not have been recognized otherwise. The transformed data can be represented as a picture, an animation, or an interactive computer application. The art of visualization lies in choosing perceptual representations that maximize human understanding. This talk will demonstrate how perceptual psychology and visual art cognition provide the framework for new visualization methods. This iterative two-part process consists of using artistic computer graphics techniques to enhance the presentation of important data features, then conducting perceptual studies to evaluate the effectiveness of the resulting imagery. The strength of this approach lies in the synergy achieved in the tight coupling of the two research areas.

Artistic images are often easier to understand than photographs. In their classic 1956 experiment, Ryan and Schwartz demonstrated that line drawings with exaggerated features of interest evoked a more rapid and accurate response than photographs or plain line drawings. More recently Gooch found increased learning speed using computer generated facial illustrations. NPR images convey information more effectively by: omitting extraneous detail; focusing attention on relevant features; and by clarifying, simplifying, and disambiguating shape. Control of detail in an image for the purpose of enhanced communication is becoming the hallmark of NPR. Control of image detail is often combined with stylization to evoke the perception of complexity in an image without explicit representation.

What the eye perceives is not always what the mind comprehends. A general knowledge of perception can guide the creation of a visualization method. However, attempts to understand human cognition are hampered by the fact the workings of the mind cannot be observed. We must rely on external signs of cognition as exemplified in behavior. Therefore, there will always be a need to evaluate the effectiveness of the resulting imagery to insure optimal results. The effectiveness of an image can be evaluated by measuring its ability to communicate. Measuring the communication content of a image can best be performed in an indirect manner: a behavioral study is conducted in which participants perform specific tasks on sets of visual stimuli. If participants are statistically better at performing a task given a certain type of imagery, then that imagery can be said to be more effective for the given task. The ability to measure the communication content of imagery, means that empirical methods can be used to establish principles to validate methods.

Outline

Manipulation of perceptually important artistic parameters (30 minutes)

- Outline
- Texture
- Color
- Using NPR to represent uncertainty

Evaluation of the resulting display (30 minutes)

- Task based evaluation
- Cognitive walkthroughs
- Reasoning with uncertainty

Contributions

This lecture will round out the tutorial by providing evaluation techniques specifically designed for visualization. This lecture will also address the cognitive aspects of decision making based on the presentation of visual data.

Volume Illustration for Medicine and Flows

David Ebert, *Purdue University*
Nikolai Svakhine, *Purdue University*

This talk will start by describing general techniques and principles for effective computer-generated illustrations of volumetric datasets and review the state-of-the-art of volume illustration. It will then describe unique techniques and problems of both medical and flow data and discuss specific solution techniques for each class of data. An in-depth presentation of the work by Ebert's group in this area will be discussed next, including work on interactive stipple rendering, example-based volume illustration, and then SvakhineŠs system for interactive medical and flow illustration. The talk will conclude with a discussion of implementation and optimization techniques for interactive volume illustration by Svakhine as well as an interactive demonstration of the use of the system for medical education illustration, surgical simulation training, and analyzing three-dimensional fluid flow datasets, such as flow past spacecraft and convective flows.

Outline

- Need and Motivation
- Principles for Effective Volume Illustration
- Common Techniques and Domain-specific Techniques
  - Medical and biological visualization data
  - Experimental and computation flow data
- Interactive Volume Stippling and Example-based Illustration
  - System overview and features
  - Techniques for stippling
  - An Example-based illustration system
- Interactive Volumetric Illustration System
  - System architecture
  - Specification of illustration styles
  - Tools and Techniques
- Interactive Volumetric Illustration System Details and Demonstration
  - Implementation Details
  - Interactive Demonstration
  - Use for temporal bone surgery training, medical illustration
  - Use for flow visualization

Contributions

The lecture presents the foundations as well as recent work in illustrative volume visualization for both medical and scientific datasets. Not only are techniques and approaches presented, but system implementation details, interactive demonstrations, and discussion of use in both medical and fluid dynamics research are presented.

Smart Visibility in Visualization and Focus of Attention
Ivan Viola, *Vienna University of Technology*

In this part of the tutorial we first discuss smart visibility techniques that provide maximal visual information through dynamic change in visual representation. Such techniques originate from technical illustration and are called cut-away views or ghosted views. We discuss basic principles and techniques for automatic generation of cut-away and ghosted visualizations. One approach is importance-driven feature enhancement, where the visibility of a particular feature is determined according to assigned importance information. The most appropriate level of abstraction is specified automatically to unveil the most important information. Additionally we show the applicability of cut-away views on particular visualization examples. The specific application of cut-away views in computer-assisted angiography will be discussed in more detail.

The second category of smart visibility techniques are based on modification of the spatial arrangement of structures. Such techniques include exploded views, often used for assembly instructions, and distortions. We discuss visualization techniques that separate context information to unveil the inner focus information by splitting the context into parts and moving them apart. Another visualization technique enables browsing within the data by applying distortions such as leafing, peeling, or spreading. In the case of time-varying data we present another visualization technique which is related to exploded views and is denoted as fanning in time.

In the last part of the tutorial we demonstrate the applicability of smart visibility techniques in visual story of known classified data. Here user's only required interaction is to specify object of interest. Viewpoint is changed to a characteristic view at the focus. Focus feature is visually emphasized while context is suppressed. Finally smart visibility is applied to resolve occlusion and textual information is added in form of labels to enrich visualization.

Outline

- Visual modifications
  - Traditional Illustration
  - Importance-Driven Volume Visualization
  - VolumeShop: Interactive Direct Volume Illustration
- Exploded Views and Deformations
  - Traditional Illustration
  - Deformation in Information Visualization
  - Exploded Views in the Scientific Visualization
- Focus of Attention with Smart Visibility
  - Focus Discrimination
  - Characteristic Viewpoint
  - Focusing Approach

Contributions

The lecture provides an overview on the latest expressive visualization techniques inspired by traditional illustration. Illustration techniques such as cut-aways or exploded views are realized in scientific visualization through smart visibility techniques. The discussion on latest smart visibility techniques is the contribution of the lecture.

Illustrative Rendering for Intervention Planning: Methods, Applications, Experiences

Bernhard Preim, *University of Magdeburg*
Christian Tietjen, *University of Magdeburg*

In this part of the tutorial, we describe special problems of using illustrative techniques in medical applications. We discuss the suitability of illustrative techniques with respect to different categories of anatomic structures, such as elongated, branching, compact or planar structures. In medical applications, such as intervention planning or intraoperative navigation, visualization is often based on binary volumes representing segmentation results of a particular patient dataset. A straightforward surface extraction from these binary volumes leads to jaggy surfaces not appropriate for applying illustrative rendering styles. We describe strategies to obtain suitable surface models without strongly compromising accuracy. The use of illustrative techniques for emphasis in medical visualizations is a central aspect. Illustrative techniques are used in isolation or in combination with other visualization techniques such as surface and volume rendering. Among the techniques involved are silhouettes, feature lines, stippling as well as illustrative techniques which enhance 2d slice visualizations. Two case studies are presented: neck dissection planning and liver surgery training. In these case studies, low level and high level Illustration techniques are applied. In particular, smart visibility techniques introduced by Viola are essential.

Outline

- Silhouettes, feature lines and stippling
- Combination of Rendering Methods
- Slice-based illustrations
  - Emphasis in slice-based illustrations
  - Applications in Intraoperative visualization
- Case Study: Neck Dissections
  - Opacity Mapping
  - Cutaways and Ghostviews
- Case Study: Liver Surgery Planning
  - Illustrative rendering styles
  - Illustrative visualization of intrahepatic vasculature
- Concluding Remarks

Contributions

The lecture provides an overview on the potential of illustrative visualization for medical visualization. It is based on many discussions with surgeons from different disciplines and publications at EuroVis 2005 and 2006

7. Tutorial presenter information

(In alphabetical order):

Bill Andrews, *Medical College of Georgia*

Bill Andrews received his BA in Art in 1978 from the University of Texas at Austin and his MA in Biomedical Communications in 1980 from the University of Texas Health Science Center at Dallas. He is currently pursuing a PhD in Health Promotion, Education and Behavior at the University of South Carolina, Columbia. Bill began his professional career as a medical illustrator at the University of Arizona Health Science Center at Tucson before moving to Houston, Texas in 1981. He worked in varying capacities in the Texas Medical Center, including as Art Director for the Texas Heart Institute and as Manager of Medical Illustration & Graphic Design Services at the University of Texas M.D. Anderson Cancer Center. He was honored to join the MCG faculty in 1999. He currently serves as Education Program Coordinator, Gallery Director and Webmaster. Bill has won numerous professional awards and has had works included in juried exhibits around the world. Bill has presented numerous seminars and workshops across the United States and in Canada, France, Italy and the Netherlands. He has been an active Professional member of the Association of Medical Illustrators since 1982. He has served as President of the AMI and on the Board of Governors, and is a Fellow of the AMI. Bill has been Editor of the national newsletter and is currently the Editor for the Source Book of Medical Illustration. He has been recognized as a Certified Medical Illustrator since 1993. In 1988, Bill became the founding President of the Vesalius Trust, an educational foundation supporting research and education in visual communications for the health sciences.

David Ebert, *Purdue University*

David Ebert is an Associate Professor in the School of Electrical and Computer Engineering at Purdue University and directs both the Purdue University Rendering and Perceptualization Lab and the Purdue University Regional Visualization and Analytics Center. His research interests are scientific, medical, and information visualization, computer graphics, animation, and procedural techniques. Dr. Ebert performs research in volume rendering, illustrative visualization, realistic rendering, procedural texturing, modeling, and animation, and modeling natural phenomena. Ebert was one of creators of the subfield of illustrative visualization, applying the principles of illustration to the problem of visualizing scientific data. Ebert has been very active in the graphics community, teaching courses, presenting papers, serving on and co-chairing many conference program committees, serving on the ACM SIGGRAPH Executive Committee and serving as Editor in Chief for IEEE Transactions on Visualization and Computer Graphics. Ebert is also editor and co-author of the seminal text on procedural techniques in computer graphics, Texturing and Modeling: A Procedural

Approach, whose third edition was published in December 2003.

Bruce Gooch, *Northwestern University*

Bruce Gooch is a professor of Computer Science and Cognitive Science at Northwestern University. Illustrative Visualization, the research of Professor Gooch, combines computer graphics techniques for creating artistic imagery with the evaluation methods of perceptual psychology to provide effective data visualization. Gooch is the author of over twenty research papers in the areas of computer graphics and visualization. He is also a coauthor of the books "Non Photorealistic Rendering" and "Illustrative Visualization" published by A.K. Peters. Gooch has taught courses at SIGGRAPH 1999, 2002 and 2003 as well as an NPR course for Disney feature films.

Mario Costa Sousa, *University of Calgary*

Mario Costa Sousa is an Assistant Professor of Computer Science at the University of Calgary and coordinator of the Render Group, the Illustrative Visualization/NPR research wing at the Computer Graphics Lab at the University of Calgary. He holds a M.Sc. (PUC-Rio, Brazil) and a Ph.D. (University of Alberta) both in Computer Science. His current focus is on research and development of techniques to capture the enhancement and expressive capability of traditional illustrations, leading to a comprehensive formal illustrative visualization framework, methodology and software environment for computer-generated medical and scientific illustrations. This work involves topics centered on interactive modeling, shape analysis and expressive rendering for illustrative volume visualization and interactive simulations. Dr. Sousa has active collaborations with illustrative visualization research groups, medical centers, scientific institutes and with illustrators/studios affiliated with the Association of Medical Illustrators and the Guild of Natural Science Illustrators.

Christian Tietjen, *University of Magdeburg*

Christian Tietjen is a Ph.D. candidate in Computer Science at the Otto-von-Guericke-University of Magdeburg, Germany. His research focuses on illustrative medical visualization. In detail, he tries to combine different rendering styles like silhouettes, surface and volume rendering. Furthermore, he is working on synchronized 2D and 3D visualizations. He is currently developing visualization techniques for preoperative planning systems. Tietjen is author and co-author of some publications, for instance at the EuroVis and the IEEE Visualization.

Ivan Viola, *Vienna University of Technology*

Ivan Viola graduated in 2002 from the Vienna University of Technology, Austria with a MSc in the field of computer graphics and visualization. He received his PhD in 2005 for his thesis "Importance-Driven Expressive Visualization". Currently he is managing the ExVisation research project (www.cg.tuwien.ac.at/research/vis/exvisation) focusing on development of novel methods for automatically generating expressive visualizations of complex data. Viola co-authored several scientific works published on international conferences such as IEEE Visualization, EuroVis, and Vision Modeling and Visualization and acted as a reviewer for conferences in the field of computer graphics and visualization. Recently he co-organized tutorials on Illustrative Visualization presented at Eurographics 2005 and IEEE Visualization 2005 conferences.

8. Organizers contact information

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Eurographics 2006 Tutorial

Illustrative Visualization for Medicine and Science

Introduction to Perceptual Principles in Medical Illustration

Bill Andrews, Medical College of Georgia

Introduction to Perceptual Principles in Medical Illustration

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1. Introduction

Pen & ink, or line, illustration is without a doubt one of the most difficult graphic techniques to master. In this presentation, we will take a sightseeing tour of the perceptual phenomena involved in creating and reading line art. Our primary vehicle for this journey will be optical illusions. By having some fun with illusions we will hopefully gain insight into line illustration.

Line illustration, whether with traditional pen & ink techniques or digital media, is perhaps the most difficult artform to learn and to use effectively. This is because line illustrations are so highly abstracted from the full-color, continuous-tone real world. The difficult is two-fold: not only must the artist effectively render the abstraction, but the audience must be able to ”decode” the abstraction as a believable representation of reality.

For our purposes, ”Line Illustration” refers to any illustration technique that can be reproduced exclusive in black and white, without any shades of gray. For you techies, that means any illustration that may be reproduced in bitmap mode. However, even with pure black and pure white, we will see that it is possible, through optical blends, to create the perception of shades of gray.

When the perceptual cues that allow us to ”read” a line illustration are contradictory the result is visual dissonance. Sometimes, this dissonance is intriguing. Often, especially for medical and scientific illustrators, the dissonance impedes effectiveness.

This illustration by M.C. Escher is not accurate or even logical; yet, most of us find it charmingŮwhy? In classic impossible geometry illusions, the individual pieces and vertices make sense, but taken together they do not work in harmony to explain the whole. Most of us find this disharmony conceptually interesting while realizing instantly that it is an impossible object. This is a more recent variation on the impossible geometry, and is derivative of the famous Moebius Loop. ”In 1858, it was discovered by a German mathematician called August Moebius that a strip of paper could be made into a loop without beginning and end, upper and lower side, inside and out. This design has been used over and over through the years to represent systems without a beginning and end. Escher demonstrated in this model that an insect walking along a Moebius loop never comes to the end of the paper.” Ůhttp://collections.ic.gc.ca/environmental/culture/ss-striptease.html.

2. The Geometry of Lines

We take it as axiomatic that a line segment is the shortest distance between two points, that a line is one-dimensional, having no thickness (or height), only length. Therefore, because lines have no thickness, only length, then they cannot exist in nature. A shape in which the length is sufficiently greater than its width may be called a line. Therefore, we may also say that the lines we use to build illustrations are, in fact, shapes. Lines also can have ”plane-ness.” That is, lines can be described as planes seen on edge. We more commonly refer to planes as shapes. The duality of a line lies in its ability to represent both planes, or shapes, and edges, or lines.

For those of you keeping score: Shape = Plane = Edge = Line. Part of the difficulty of rendering illustrations in line techniques is this duality of natureŮ its ability to be both shape and edge. And, this duality lies at the heart of the abstract nature of line illustration.

A line illustration can be a believable representation of the real world if the rendering is internally consistent and in harmony with the fundamental processes of visual perception. It is useful to know something of visual perception, since most of the frustrations we encounter in the rendering of a line illustration can be attributed to a dissonance between competing visual elements.

3. The Line Between Light & Dark

The perceptual cues at work in constructing and reading a line illustration include:

- Relationships between light and dark
- Shape, pattern and edge recognition
- Line direction, and the interaction of lines going in different directions
- Focus, and relationships between hard and soft edges
- Gradients of detail and texture.

Now that the esoteric definitions are done, we can begin to look at the perceptual phenomena involved with line illustration. The basic properties of black vs. white are a good place to start.

The center-surround principle of perception seems to play a large part in cues of relative size. The classic white/black square-within-square and ring-around-the-rosie illusions demonstrate this well.

If we add a bit of complexity to the geometry the black and white shapes, we can confuse the eye, possibly because of conflicting center-surround related size cues. If the balance between light and dark is roughly equal, then there can be ambiguity between the figure and the ground. In general, the more recognizable or familiar shape becomes the figure. The old/young woman illusion and duck/rabbit are fine examples of this figure/ground ambiguity, as are many of the parlor trick illusions of the Victorian era.

4. Mark Orientation

Orientation to the vertical or horizontal also has an effect on our perception. When asked to judge the relative length of two lines, a vertical and a horizontal, most people will say that the vertical one is longer even though they are of identical length. This illusion is at work when judging between a stack of vertical lines and a stack of horizontal lines. In fact, when used with a stack of quarters or poker chips, this misperception is the basis of a classic short con. This leads us to the Müller-Lyer effect, or inside/outside corners illusion. It is related to the vertical-horizontal line illusion, but with the added bonus of rays at the ends of the lines to reinforce or diminish the length of the line.

5. Lines as Shapes

Enough about ”lines as lines” for a moment. LetŠs look at a few ”lines as shapes” tricks. There is something in human perception that has an affinity for simple geometric shapes, even to the point of ”seeing” shapes where none exist. The way our visual systems are wired, shape preference is an incredibly potent perceptual cue. What seems to be at work here is that our perception prefers simplicity over complexity and order over chaos. In addition, we are good at organizing pieces into wholes and readily make associations by proximity.

Shape preference is so potent a cue, that we need not even show a complete shape for the viewer to ”see” it. This is called shape completion. Sometimes this is a good thingŮthe illustrator does not need to draw everything, and that shape recognition explains why overlapping works as a cue to spatial relationships between objects. And sometimes this is a bad thingŮas with self-reinforcing attractors (which we will see in a few moments).

Manipulations of shape preference and the Poggendorf illusion are the two most powerful and most useful tools in the illustrators kit. J. C. Poggendorf, a physicist, discovered this illusion in the 1860s. The Poggendorf illusion allows us to convey the idea that objects are continuous behind opaque or semitransparent foreground objects. Indeed, the Poggendorf illusion is the basis of many ”disappearing” tricks performed by magicians.

When shape preference meets figure/ground ambiguity, we get the unfortunate ”Cookie Cutter” condition. That is, visual dissonance occurs when our perception of a simple shape overwhelms our perception of the three-dimensional form in an object. Fortunately, this condition is easy to remedyŮbreak the shape.

BullŠs eyes, or self-reinforcing attractors are a special case of shape preference. Nested concentric circles share a come center point. In effect, they are ring waves that draw the viewers eye into the center and back out, ad infinitum. This self-reinforcing attractor can be deadly to the intended focus of an illustration (assuming the bullŠs eye is not the center of viewer focus). Fortunately the fix is simpleŮ use shape completion cues to ”see” the circles without actually drawing them in whole.

After shape preference, we come to shape constancy. The principle is that if items are the same shape they must be the same thing, and therefore the larger one must be closer. However, the Jastrow Illusion, named for psychologist Joseph Jastrow, demonstrates a weakness in our ability to count on shape constancy as a cue to distance and depth.

If we take shape constancy and add a 3rd dimension, we come to object constancy. This is the ”closed door, open door” analogy. A door is a rectangleŮunless seen in perspective. In which case, it is a trapezoidŮbut also still a door. Place this trapezoid in context and there is no doubtŮit is a door. As with familiarity in resolving figure/ground ambiguities, context seems to be essential for correctly using and viewing reading images utilizing object constancy.

Necker cubes are a demonstration of when shape/object constancy runs amok with figure ground ambiguity. In the absence of any other clues, Necker cubes are unresolvable in terms of their three-dimensional structure. In fact, Necker cubes show, by negative example, the power of simple overlapping as a potent cue to the spatial relationship among a set of forms. An appreciation of apparent overlapping can be gained through the Kanzisa Triangles illusion. Using only shape completion and constancy along with overlapping and the Poggendorf illusion, Kanzisa has created a believable layering of objects and a sense of depth. Apparent overlapping, through shape/object constancy, allows us to draw what appears to be complete shapes using only partials.

Apparent overlapping is a very potent technique for developing believable representations of three-dimensional objects. However, Necker-like ”violations” of spaceŮthat is, multiple shapes that share edges or otherwise occupy the same spaceŮcan be powerful destructors of believable representational images.

6. Line as Edges

The edge of a shape, even an incompletely drawn (open) shape does not need to be uniform. Using variations of line width (stroke width) in combination with apparent overlapping and shape/object constancy we increase our ability to create believable representative images. In fact, taken to its fullest extent the use of shapes and these plastic, or expressive, lines will allow for construction of a convincing, albeit, graphic representation of the world.

From expressive, plastic line-as-edge illustrations, we move to more general discussion of edge treatments in general. There are two primary cues at work: thickness and softness. Hard and thick advance toward the eye, soft and thin recede.

This concludes the section on line-as-edge and line-as-shape. We will now look at line-as-tone.

7. Lines as Tones

A very powerful technique in line illustration is to use groups of marks (lines, stipples, hatchmarks) as shapes. We may also call these groupings of marks ”compounded lines.” How can you tell if lines are compounded? A group of marks is compounded if the viewer perceives the group as a whole rather than as individual lines. Compounded lines are ideal for adding shading and texture gradients.

Two concepts are important when producing compound lines: the stroke of the line (weight) and the distance between succeeding lines (periodicity). As we shall see, all sorts of wonderful and horrible effects can happen simply by varying these two parameters. The ultimate goal of a compounded line is to produce a tone not a collection of individual lines.

When done well, it is possible to achieve the fine tonal qualities of the engravings by Pisan from the drawings by Gustave Doré for Miguel CervanteŠs ”Don Quixote.” A more contemporary example would be the line illustrations of James Montgomery Flagg, who gave us many Impressionistic examples of fine tonal line work.

Compound lines work best when they reinforce the underlying, or gross, form. Secondary, they can be used to describe local variation in the surface geometry. And lastlyŮalways lastlyŮthey can be used to describe surface texture and local variations in tone. Exceptional artists can achieve all three functions in one set of lines.

When the relationship between stroke width and line spacing within a compounded line is out of balance, then the perception of individual lines negates the effect of the grouping. We call this ”zebra stripes.” It is a relative judgmentŮto see it, look for the place where the stroke and periodicity of the lines is greater than the smallest important detail.

8. Lines and Patterns

Just as with shape and object constancy, we seem also to prefer and preserve patterns. Patterns are groups of marks that appear to be organized and that may trigger perception of:

- Repetitive phantom geometries
- Familiar objects
- Unintended signal in the noise

Along with shape preference, pattern recognition ranks as one of the most potent of visual cues. The spotted dog illusion is one of the best examples of this. Upon seeing the black spots scattered seemingly at random across the page, we can, with just the briefest glimpse, find order in the chaos. In large part, both familiarity and context will determine what pattern one sees in the noise. And faces are the most familiar and potent pattern of all. The man in the moon is perhaps the most famous example.

When we combine lines-as-edges, lines-as-shapes and lines-as-tones we can more effectively create representations of the world. There are no rules or formulas I am aware of that can do this for you automaticallyŮit is a subjective art. We can, however, describe some guiding principles by examining the flawed use of the aforementioned principles.

Crosshatching is often used as a means on building tonal areas. If two or more sets of compounded lines are layered one over another, an interference pattern created as one set of lines intersects another. The sets of line must be relatively long in order for this to happen. This interference is the basis of several problems in line illustration. The first is phantom rays, or string-of-pearls. Also called the illusion, this interference pattern is due to two or more sets of parallel lines that cross at a shallow angle. Akin to the phantom rays, the Herman illusion involves seeing nonexistent dots at the interstices of two sets of intersecting lines. Both of this illusions work in black on white and the reverse.

A related interference pattern is the screen-wire effect. When two sets of lines intersect at right angles, or nearly so, they set up a grid. This screen-wire grid tends to flatten any illusion of three-dimensional forms. However, this last problem can actually be used to advantage if one is drawing gauze or a similar textile.

An even more problematic interference pattern is Moiré, which is characterized by the fluid ripple patterns that form as two or more sets of geometrically arrayed lines intersect each other. In general, machine precision of the periodicity of lines is required to create MoiréŮso sloppy drawing reduces the likely hood of this problem occurring.

There are numerous techniques for overcoming these interference pattern problems. Arguably, the best methods involve using shorter stroke lengths, which disrupt any pattern from forming. The ultimate short-mark method for creating tone in an illustration is the stipple. Though tedious to produce by hand, and difficult to control for the novice, it does allow a great deal of finesse in depicting subtle gray tones.

There are scores of other interference pattern illusions, as well as geometry distortion illusions, but time does not permit their coverage here. It will have to be sufficient to say that investigation of these illusions provides insights on how better to construct and read line illustrations.

9. A Linear System

In addition to many of the cues mentioned above, the principles illuminated by the Ponzo, or railroad track, illusion can be useful in illustrating distance between objects. Distance-by-proximity is another useful principle. That is, the closer to the horizon an object appears to be, the farther from the viewer it seems. (This is true in Western cultures but not in some other cultures.) With these cues, the system of linear perspective is possible.

Contouring, or eye-lashing, is a special case of perspective, and quite separate from linear perspective. Rather than utilizing a universal horizon line in a scene, an internal horizon line (zero-arc line) is created, usually perpendicular to the long axis of the object being drawn. Starting from this internal horizon line, outward-radiating lines trace the contours of the form. As complex forms bend and move in space, more than one internal horizon line may be employed. Gerald Hodge, Russell Drake and Eleanor Fry were perhaps the best at this technique.

10. Conclusion

This has been an exceedingly brief look at some of the principles and visual cues artists manipulate to create believable representations of our world. Deciding whether to use some or all, and under what circumstance, is the true art. Ultimately, we will probably be best served by letting the purpose of the illustration determine the technique of mark-making employed.

Introduction to Perceptual Principles in Medical Illustration

A presentation by Wm. M. Andrews, MA, CMI, FAMI
Summer, 2006

A Line of Abstraction

Line illustration, whether with traditional pen & ink techniques or digital media, is perhaps the most difficult artform to learn and to use effectively. This is because line illustrations are so highly abstracted from the full-color, continuous-tone real world.

What Is Line Illustration?

- For our purposes, “Line Illustration” refers to any illustration technique that can be reproduced exclusive in black and white, without any shades of gray.
- For you techies, that means any illustration which may be reproduced in bitmap mode.

When Good Lines Go Bad

- When the perceptual cues that allow us to “read” a line illustration are contradictory the result is visual dissonance
- Sometimes, this dissonance is intriguing
- Often, especially for medical illustrators, the dissonance impedes effectiveness

Intriguing?

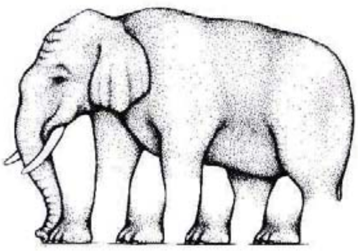
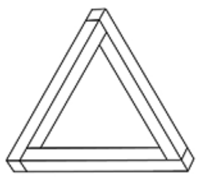
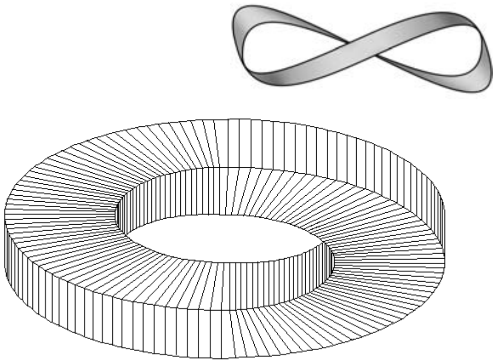


Illustration by M.C. Escher





The Geometry of Lines

- A line segment is the shortest distance between two points
- A line is one-dimensional, having no thickness (or height), only length
- Because lines have no thickness, only length, then they cannot exist in nature.

Shapely Lines

A shape in which the length is sufficiently greater than its width may be called a line.

Therefore, we may also say that the lines we use to build illustrations are, in fact, shapes.

Plane Speaking ‘bout Lines

- Lines can be described as planes seen on edge
- We more commonly refer to planes as shapes

Black vs. White

- For those of you keeping score:
  Shape = Plane = Edge = Line
- As we will see, part of the difficulty of rendering illustrations in line is this duality of nature— its ability to be both shape and edge
- And this duality lies at the heart of the abstract nature of line illustration

Pushing the Line

A line illustration can be a believable represent-ation of the real world if the rendering is internally consistent and in harmony with the fundamental processes of visual perception.

Linear Perceptions

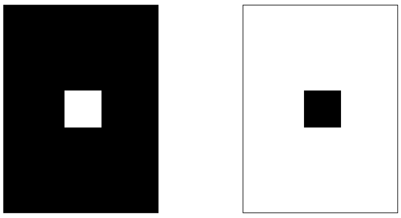
It is useful to know something of visual perception, since most of the frustrations we encounter in the rendering of a line illustration can be attributed to a dissonance between competing visual elements.

Between the Light and the Dark

The perceptual cues at work in constructing and viewing a line illustration include:

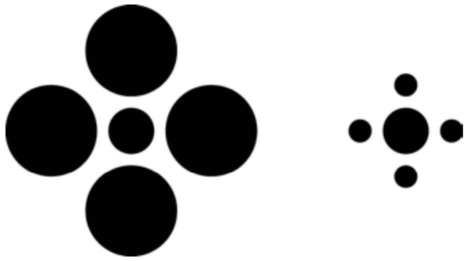
- Relationships between light and dark
- Shape, pattern and edge recognition
- Line direction, and the interaction of lines going in different directions
- Focus, and relationships between hard and soft edges
- Gradients of detail and texture.

Contrast Effects Size



Looking at the inner squares, which one is the larger of the two?

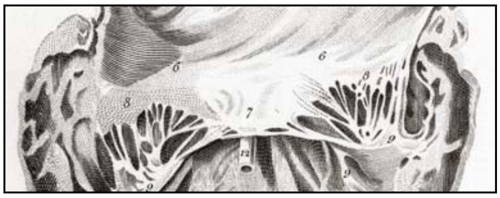
Size is Relative

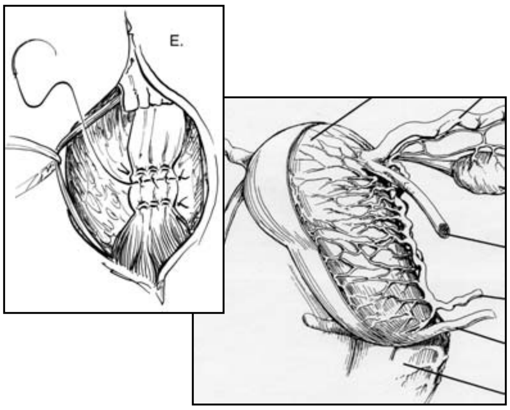


Looking at the inner circles, which one is larger—the one on the left or the one on the right?

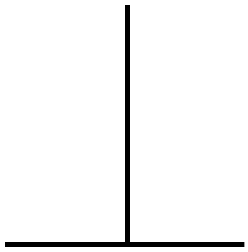
Figure Ground Ambiguity

If the balance between light and dark is roughly equal, then there can be ambiguity between the figure and the ground. In general, the more recognizable or familiar shape becomes the figure.



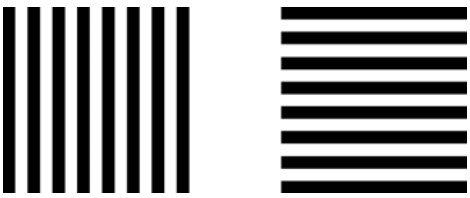


Horizontal vs. Vertical



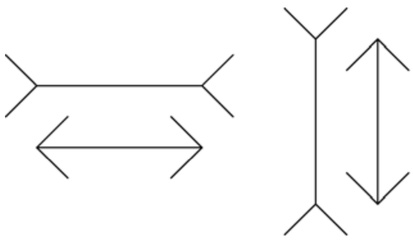
Which line is longer, the horizontal or vertical?

More H & V



Which stack of lines is taller, the horizontal or the vertical one?

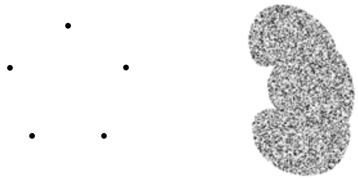
Müller-Lyer Effect



Which of the horizontal lines above is longer? And which of the verticals?

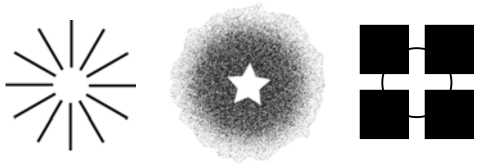
Shape Preference

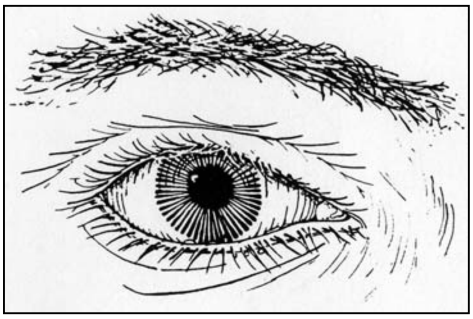
There is something in human perception that has an affinity for simple geometric shapes, even to the point of "seeing" shapes where none exist.



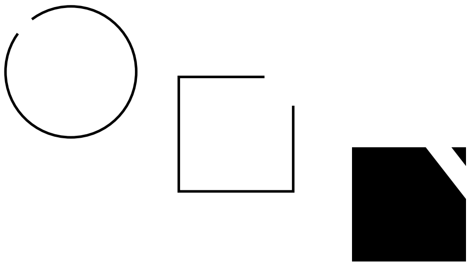
Shape Preferences

- Simplicity
- Order out of chaos
- Signal in the noise
- Association by proximity





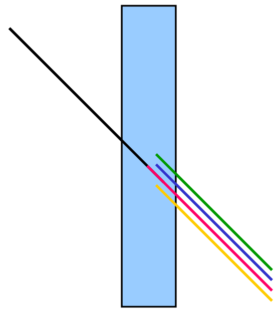
Completion—A Special Case of Shape Constancy

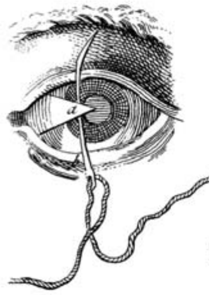


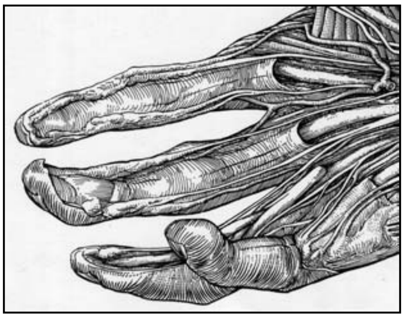
Preferential Treatment

- How powerful is the need to perceive shapes where none exist? Herr Dr. Rorschach thought it was very powerful indeed.
- For the illustrator, it is enough to know that because of shape recognition, one does not need to draw everything, and that shape recognition explains why overlapping works as a cue to spatial relationships between objects.

Poggendorf Illusion







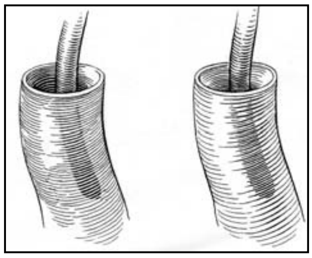
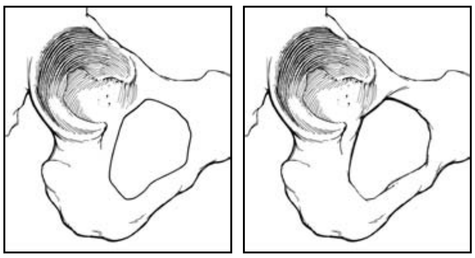


Illustration by Gerald Hodge

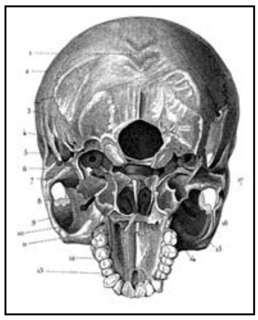
"Cookie Cutter" Condition

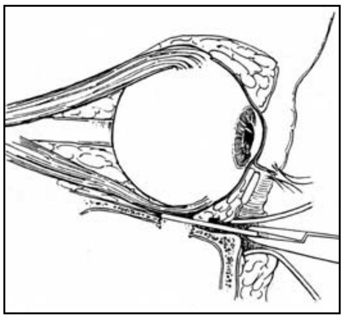


Visual dissonance occurs when our perception of a simple shape overwhelms our perception of three-dimensional form in an object.

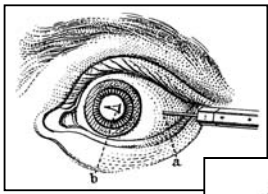
Illustration by Bill Andrews

Cut it Out...

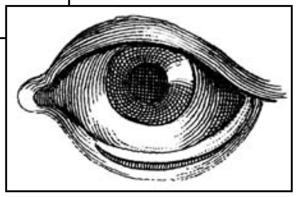


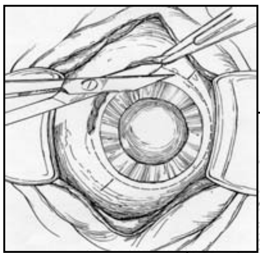


"Bull's Eye" Effect



Concentric circles are a special case of shape preference, because they are self-reinforcing.





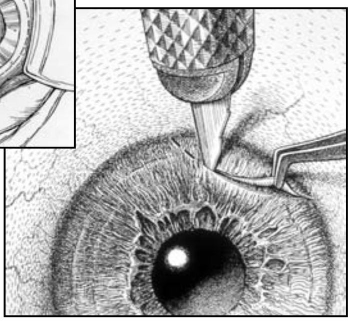


Illustration at right by Gerald Hodge

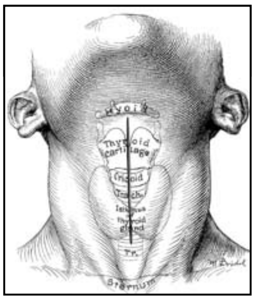
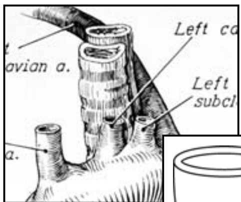


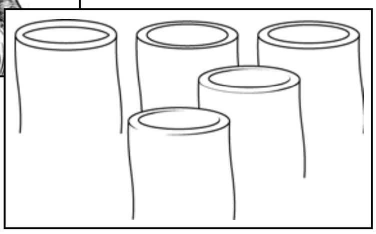
Illustration by Max Brödel

Tube Ends, A Special Case

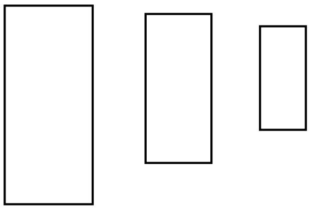


The problem…

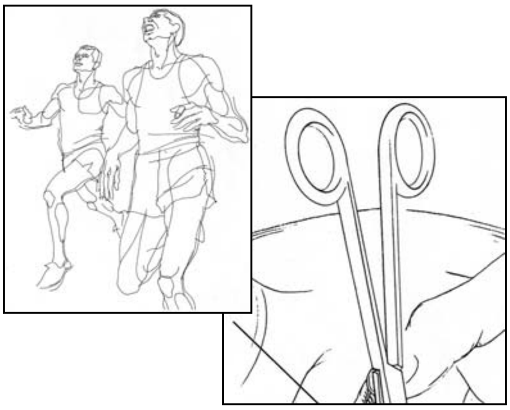
…the fix.



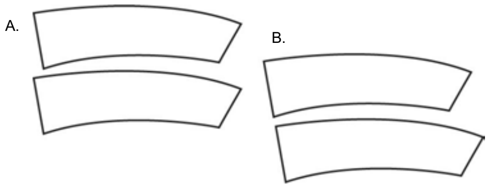
Shape Constancy



Consider the three "doors" above, which one is closer to us? Shape constancy holds that if items are the same shape they must be the same thing, and therefore the larger one must be closer.

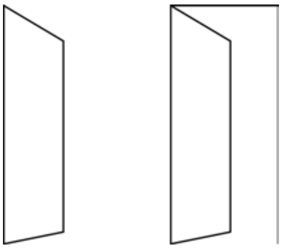


Constant Trouble



In Figure A, which shape is larger or longer—the upper or lower? How about in Figure B? Actually they are all identical. This is the Jastrow Illusion.

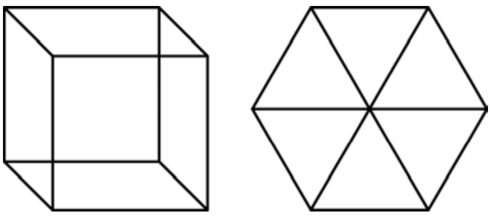
Object Constancy



Then there is the idea of object constancy. A door is a rectangle—unless seen in perspective. In which case, it is a trapezoid—but also still a door. Place this trapezoid in context and there is no doubt—it is a door.

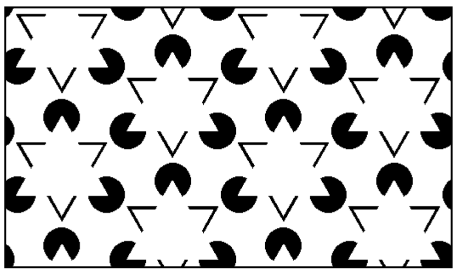
Illustration by Windsor McCay

Necker Cubes

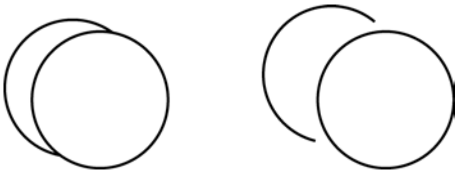


These Necker cubes are a demonstration of when shape/object constancy runs amok with figure ground ambiguity. Which face is closest to us? Are you sure?

Kanzisa Triangles

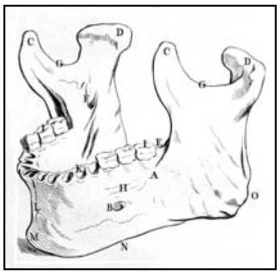


Apparent Overlapping



Shape/object constancy allows us to draw what appear to be overlapping complete shapes using only partials.

Overlapping = Depth



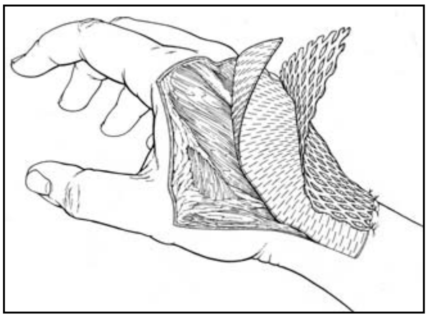
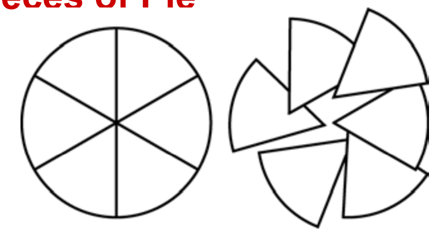


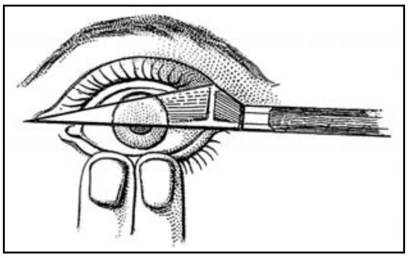
Illustration by Bill Andrews

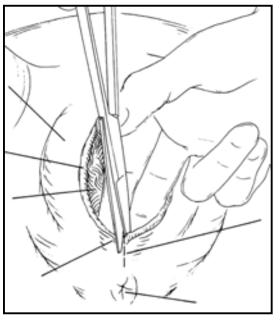
Pieces of Pie

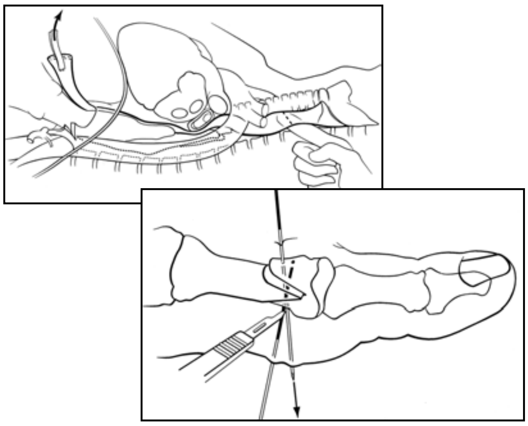


Using shape constancy and overlapping, we can rearrange the pieces of pie to clarify a spatial relationship. This technique is a very potent technique for developing believable representations of three-dimensional objects.

Problems with Pie...







Lines & Shapes Together

The edge of a shape does not need to be uniform. Variations in width can be quite expressive. This figure was developed using four overlapping circles.It demonstrates Shape and object constancy, as well as overlapping.

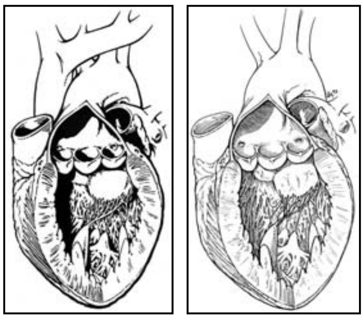
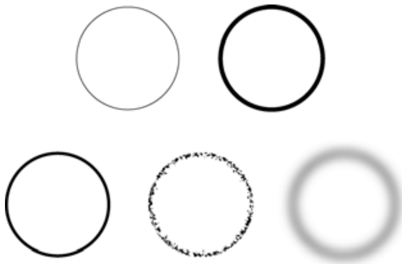


Illustration by Bill Andrews

Edge Treatments



Which edge treatments advance and which recede? Thick and hard advance relative to thin and soft.

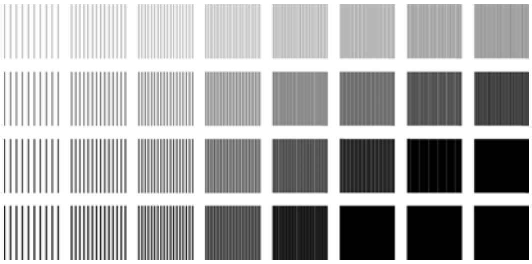
Edge Treatment = Depth

Illustration by Bill Andrews

Compounded Lines

- A very powerful technique in line illustration is to use groups of marks (lines, stipples, hatchmarks) as shapes. We may also call these groupings of marks compounded lines.
- How can you tell if lines are compounded? A group of marks is compounded if the viewer perceives the group as a whole rather than as individual lines.
- Compounded lines are ideal for adding shading and texture gradients.

Compounds as Shaders

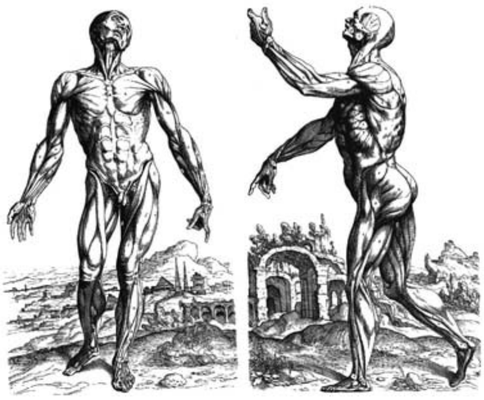


Drawing by Gustave Doré, engraved by Pisan

Drawing by Gustave Doré, engraved by Pisan

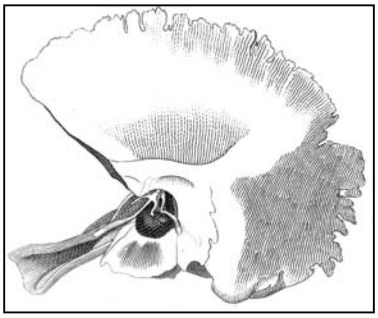
Illustration by James Montgomery Flagg

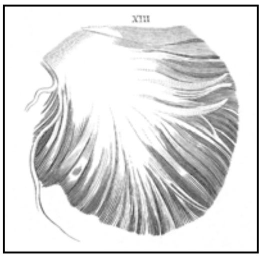
Detail of Illustration by James Montgomery Flagg



Illustrations by Andreas Vesalius and Jan Van Calcar?

Compound Lines





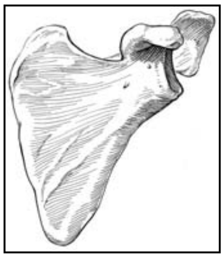
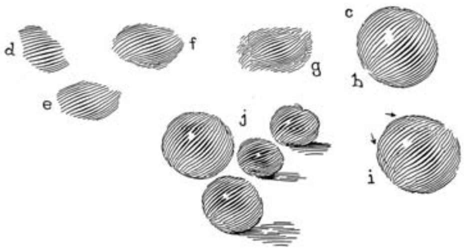
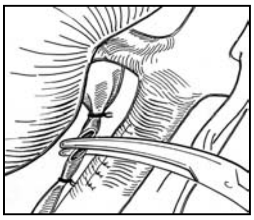


Illustration on right by Bill Andrews



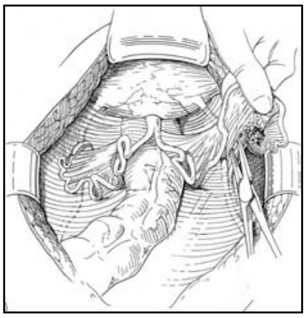
Illustrations by Russell Drake

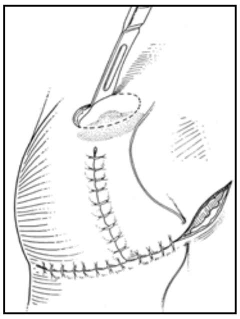
Zebra Stripes

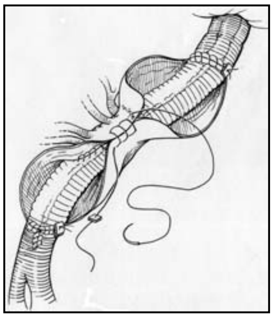


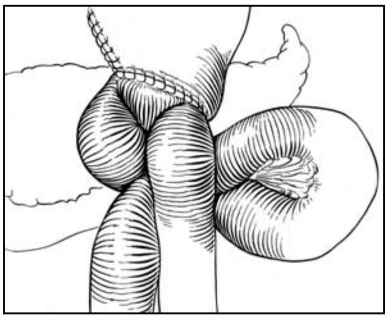
When the relationship between stroke width and line spacing within a compounded line is out of balance, then the perception of individual lines negates the effect of the grouping. We call this “zebra stripes.”

Zebra Trouble?

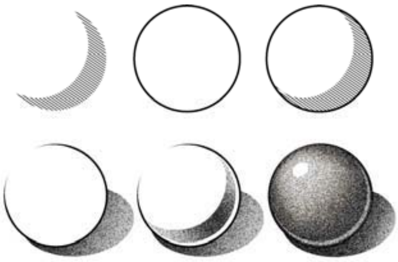




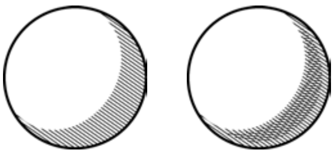




Compounded Lines & Forms

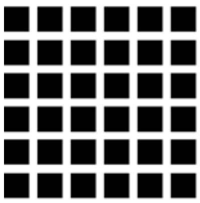


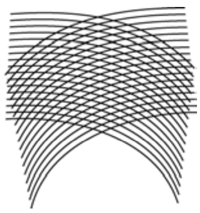
Crosshatching



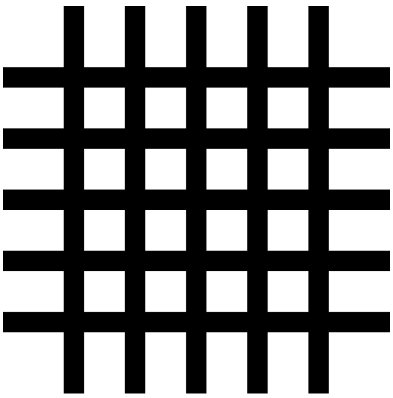
Simple hatching and crosshatching

Confounded Lines

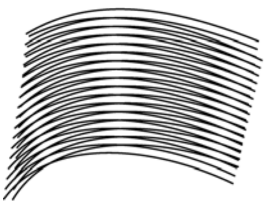


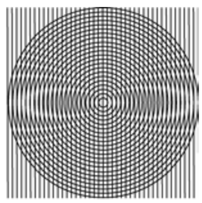


Here are two optical illusions—”Intersection Dots” or Hermann Illusion and “Phantom Rays”—that result from crossed lines, either real or perceived.

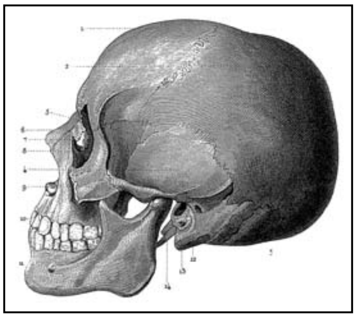


More Confounding

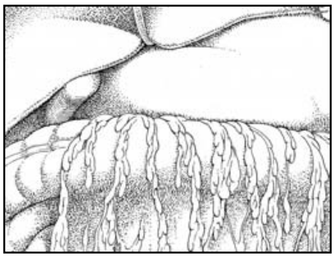


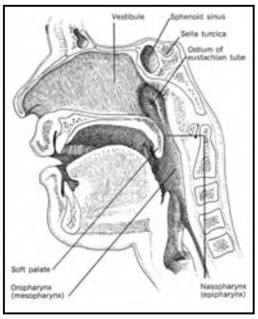


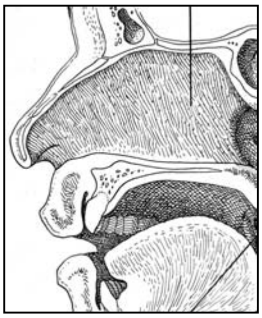
In addition to phantom rays, sets of overlapping lines can also create Moiré patterns.



Short-stroke Hatching







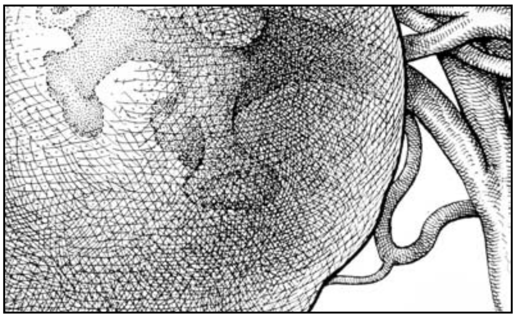
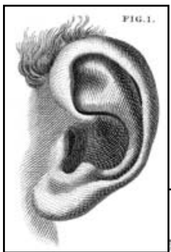
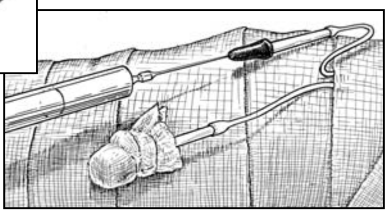


Illustration by Gerald Hodge





Stippling

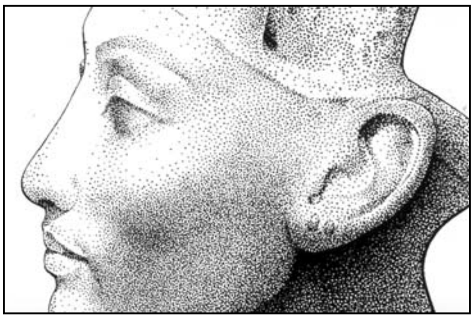


Illustration by Gerald Hodge

Compounded Lines, A.K.A.

Just as with shape and object constancy in human perception, we seem also to prefer and preserve patterns. Patterns are groups of marks that appear to be organized and that may trigger perception of:

- Repetitive phantom geometries
- Familiar objects
- Signal in the noise

Patterns are special, and perhaps unintentional, cases of compounded lines. The “Man in the Moon” is just one example.

Pattern Recognition

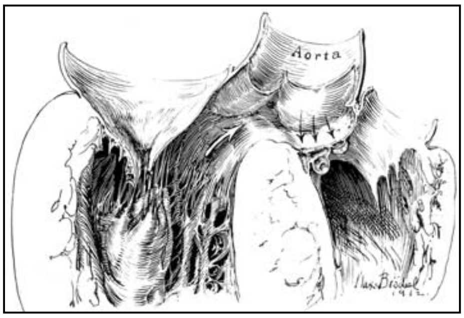
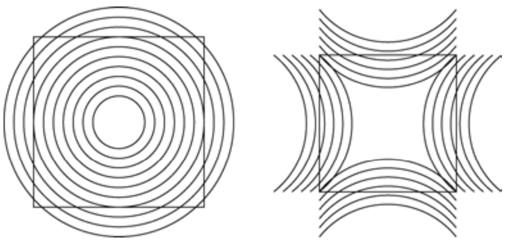


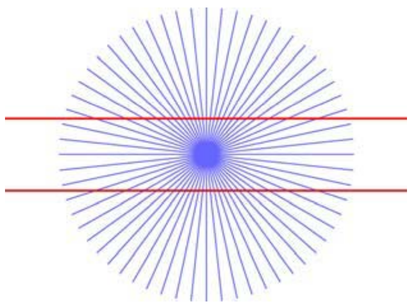
Illustration by Max Brödel

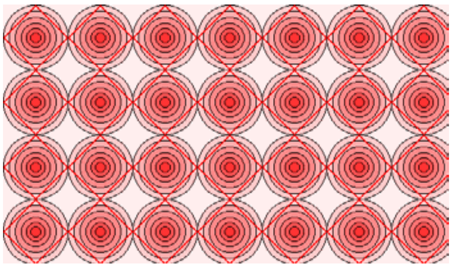
Distorting Lines



In the Ehrenstein Illusion, straight lines can appear bent by overlapping curves.

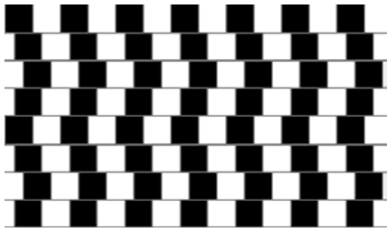
Hering Illusion

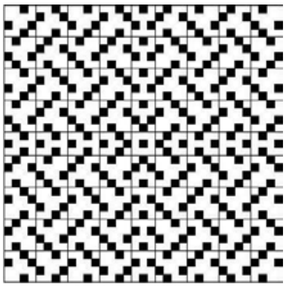




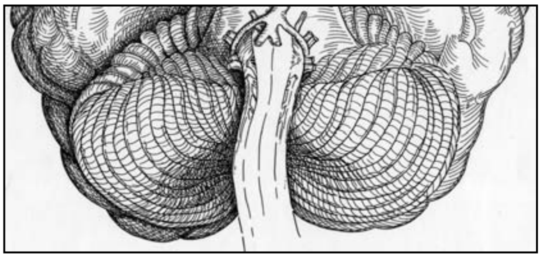
Café Wall Illusion

And sometimes, straight lines can even be bent by a matrix of off-set squares.

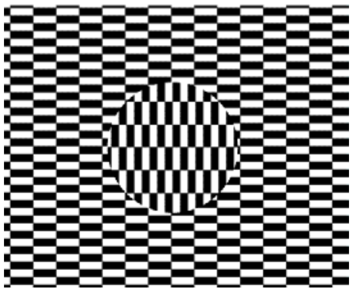


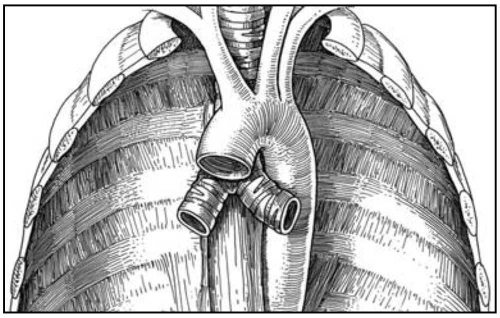


Zöllner Illusion

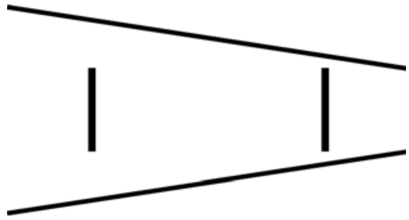


Ouchi Illusion



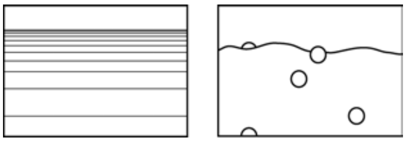


Ponzo Illusion



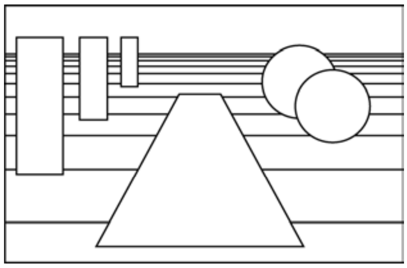
Which of the vertical lines is taller?

Distance by Proximity



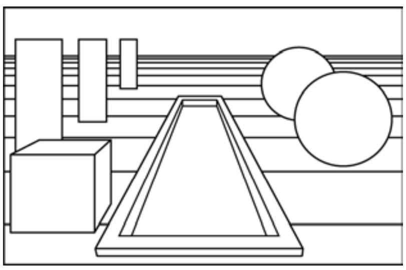
The closer to the horizon an object appears to be, the farther from the viewer it seems. This percept is true in Western cultures but not in some other cultures.

Depth Perception or Perspective ?



This scene incorporates shape constancy, object constancy, overlapping, and distance by proximity.

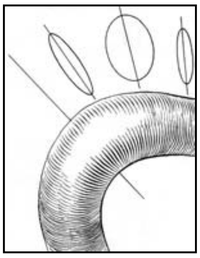
Perspective?

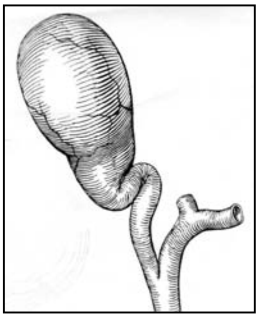


Elements utilizing the Müller-Lyer effect have been added to the previous drawing. Is this now a perspective drawing?

Illustration by Windsor McKay

Contouring: A Special Case of Perspective





Illustrations by Gerald Hodge

Gross Form Before Local Form

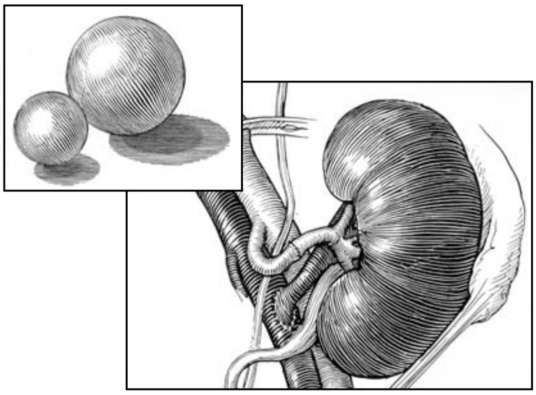


Illustration by Gerald Hodge

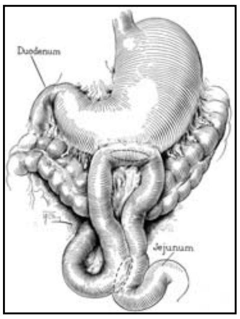


Illustration by Eleanor Fry

Examples by the Author...

Illustration by Bill Andrews

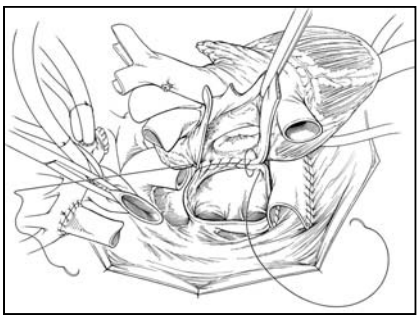


Illustration by Bill Andrews

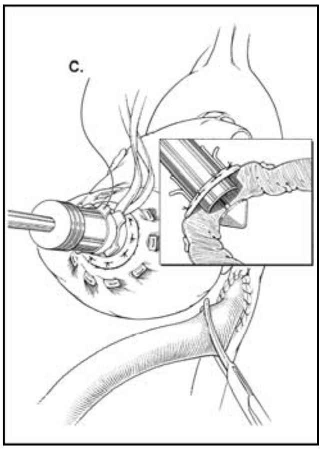


Illustration by Bill Andrews

Introduction to Perceptual Principles in Medical Illustration

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Eurographics 2006 Tutorial

Illustrative Visualization for Medicine and Science

Overview of NPR for Computerized Illustration

Mario Costa Sousa, University of Calgary

Illustrative Visualization for Medicine and Science

Overview of NPR for Computerized Illustration

Mario Costa Sousa

University of Calgary

Purpose of an Image

- Communicate information
- Key question concerning **imagery** in art, engineering, science:

  "Illustration or photo...which?"

Illustration or Photo . . . Which? Medical Subjects

Illustration is the best choice when:

- **Areas of reference** exist physiologically but not gross anatomically
- **Superimposing** one structure upon another gives related information

Illustration or Photo . . . Which? Medical Subjects

Illustration is the best choice when:

- **Section views** show instruments in place in body cavities, etc
- **Eliminating** much **"visual garbage"** from a photo can produce a simpler explanation

Illustration or Photo . . . Which? Medical Subjects

Photograph is the best choice when:

- **Overall posture**, or **before and after** pictures are necessary;
- **Vast areas** such as large skin areas, burns, etc., are to be shown;

Illustration or Photo . . . Which? Medical Subjects

Photograph is the best choice when:

- **Emotional impact** is achieved only by authentic photos (i.e. medico-legal problems)
- A **multitude of detail** is necessary as in retinal pathology or photo-micrographic studies.

Scientific Illustrations

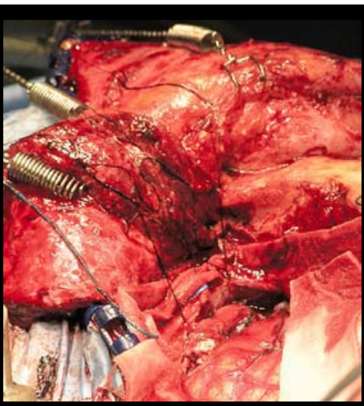
- Often highly representational ("realistic-looking")
- Might or might not be visually realistic.
- Main purpose: communicate information and not necessarily to look “real”
  - This makes scientific illustrations differ from photo-realism and other representational genres.

Scientific Illustrations

Knowledge ← *SI* (Information)

- Unseeable
- Difficult to understand
- Poorly contextualized
- Dauntingly complex

“Visually-Oriented Knowledge Media Design in Medicine”
Nick Woolridge and Jodie Jenkinson
Biomedical Communications, University of Toronto



“Visually-Oriented Knowledge Media Design in Medicine”
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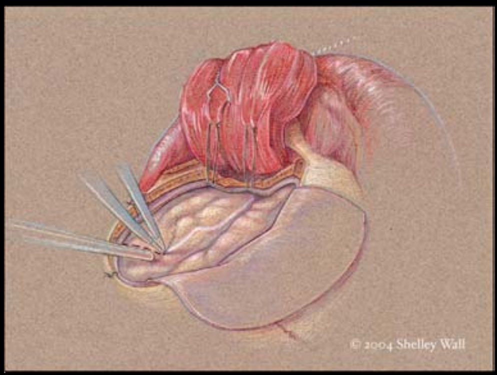


“Visually-Oriented Knowledge Media Design in Medicine”
Nick Woolridge and Jodie Jenkinson
Biomedical Communications, University of Toronto

Photorealistic images

- Much of the research in computer graphics
- Efficiency and quality
- **Not always the best option for representing information**
- **But why?**

Scientific Illustrations

 ← *SI* ()

NPR Definitions and Goals

- **Illustrations:** Interpretations of visual information expressed in a particular medium.
- **Goal of NPR:** enable interpretive and expressive rendering in digital media
- **NPR = Computer Graphics as an Interpretive and Expressive Medium**

NPR Focus

1. The **analysis** of types of structural correspondence and styles already developed by artists and illustrators
2. The **development** of algorithms/heuristic methods to duplicate and/or extend such visual analogies on a computer

Result → alternate display models

Key Points

- Technical and Scientific Illustration
- Non-Photorealistic Rendering (NPR)
- Illustrative Graphics Pipeline

NPR Pipeline

- Painters, illustrators, designers are interested in the computer as a medium for communication rather than solely a fast and automatic image production device.

NPR Pipeline

Most NPR systems are either:

- **Fully interactive**, expecting the user to produce traditional images from scratch (drawing/painting systems) or…
- **Fully automatic**, producing images using automatic techniques (renderers, post-processors).

NPR Pipeline

- Trends in NPR involve the investigation of hybrid NPR solutions, resulting in

  "**NPR Interactive Rendering**" [Schofield 94],

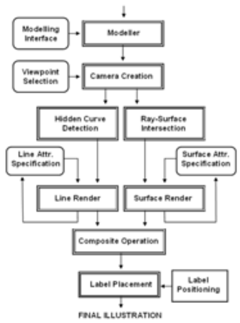
  where traditional renderings are produced partly by the system and partly by the user.

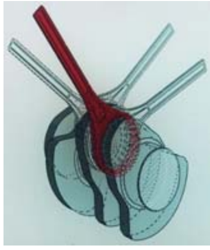
Interactive NPR Pipeline

- The modeling of such systems becomes more intuitive if we look at the traditional techniques used in illustration/painting.
- Four system pipelines:
  - [Dooley and Cohen 1990]
  - [Schofield 1994]
  - [Sousa et al. 2003]
  - [Svakhine et al 2005]

Technical Illustration System

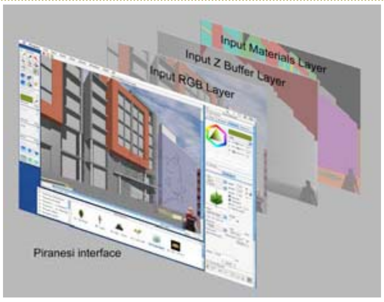
[Dooley and Cohen 1990]





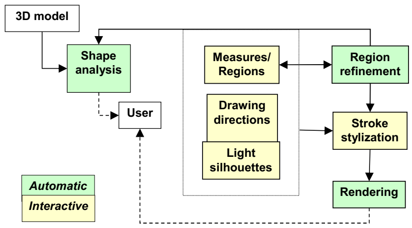
Piranesi System

[Schofield 1994]



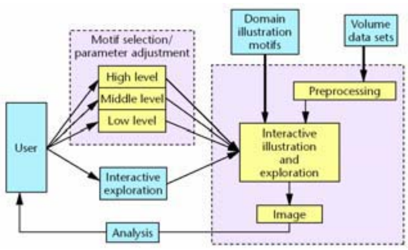
Precise Ink Drawing System

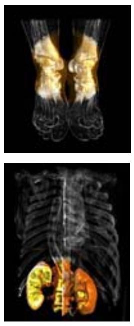
[Sousa et al 2003, 2004, Pakdel and Samavati 2004]



Volume Illustration System

[Svakhine et al 2005]





Interactive NPR Systems

- [Dooley and Cohen 1990] Dooley, D. L., and Cohen, M. F. 1990. **Automatic illustration of 3d geometric models: Surfaces**. Proc. of Visualization '90, 307-314.
- [Schofield 1994] Schofield, S. 1994. ***Non-photorealistic Rendering: A critical examination and proposed system***. PhD thesis, School of Art and Design, Middlesex University.
- [Sousa et al. 2003] Sousa, M., Foster, K., Wyvill, B., and Samavati, F. 2003. **Precise ink drawing of 3d models**. Computer Graphics Forum (Eurographics '03) 22, 3, 369-379.
- [Sousa et al 2004] Sousa, M., Samavati, F., and Brunn, M. 2004. **Depicting shape features with directional strokes and spotlighting**. Proc. of Computer Graphics International '04, 214221.
- [Pakdel and Samavati 2004] H. R. Pakdel and F. F. Samavati, **Incremental Adaptive Loop Subdivision**, ICCSA2004. Lecture Notes in Computer Science 3045, 237-246, 2004.
- [Svakhine et al 2005] Svakhine, N., Ebert, D.S., Stredney, D., **Illustration Motifs for Effective Medical Volume Illustration**, IEEE Computer Graphics and Applications, May/June 2005 (Vol. 25, No. 3).

Illustrative Graphics Pipeline

- A more general NPR pipeline can be devised by looking at the communication/production processes of traditional illustration…

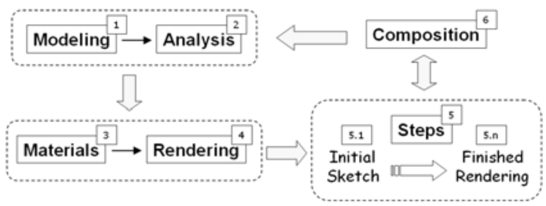
SCIENTIST	ILLUSTRATOR
Provides material	Requests information
description	Records information
specimen	Studies specimen
-	Makes rough drawing
-	Prepares scaled drawing
-	Makes detailed preliminary drawing
Checks detailed preliminary drawing	-
-	Corrects preliminary drawing
Checks corrections	Produces rendering
Checks rendering	Labels drawing
Checks labeling	-
-	Return specimen

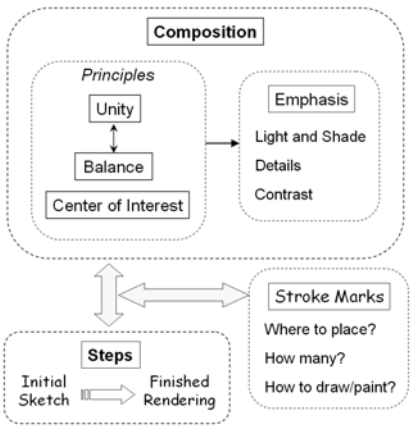
Responsibilities of the scientist and the illustrator
Table 1-1, page 11 of chapter 1 from
[Hodges 2003] Hodges, E. R. S. 2003.
The Guild Handbook of Scientific Illustration, 2nd Edition.
John Wiley and Sons.

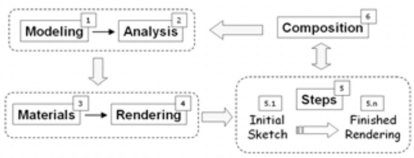
Illustrative Graphics Pipeline

- We broke the illustrator's tasks into six distinct components:
  - **Modeling** (object construction and representation)
  - **Analysis** (feature extraction, shape measures)
  - **Materials** (media + tools)
  - **Rendering** (stroke marks, tone, texture)
  - **Steps** (rendering progression)
  - **Composition** (principles, effects)

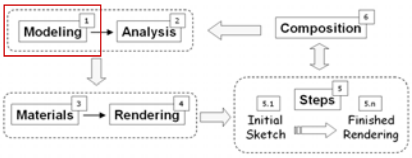
Illustrative Graphics Pipeline







SCIENTIST	ILLUSTRATOR	NPR component
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 ··· 5.n, 6
Checks rendering	Labels drawing	3, 4, 6
Checks labeling	-	
-	Return specimen	



SCIENTIST	ILLUSTRATOR	NPR component ♯
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 ··· 5.n, 6
Checks rendering	Labels drawing	3, 4, 6
Checks labeling	-	
-	Return specimen	

Modeling

- The first step in traditional illustration is to select the subject (first two table rows).
- In terms of NPR, this is equivalent to model construction and representation.
- In NPR a model can be represented as an image of photographed, video-taped and synthetic scenes or as a 3D object.

3D NPR Representation

- Mesh (~170)
- Volumetric (~28)
- Parametric (~16)
- Implicit/CSG (~9)
- Point Cloud (~4)

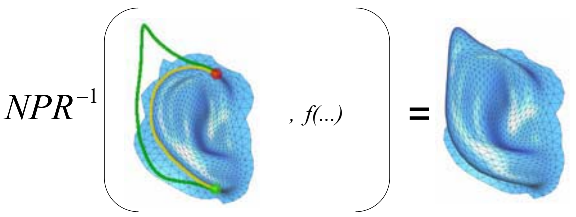
3D NPR Construction

- Defined by **sketch-based systems**, which involves the use of freehand drawings and existing sketches as a way to create and edit 3D geometric models.

NAYA, F., JORGE, J. A., CONESA, J., CONTERO, M., AND GOMIS, J. M. Direct modeling: from sketches to 3d models. *Proc. of the 1st Ibero-American Symposium in Computer Graphics (2002)*, 109–117.

SBM = *Inverse* NPR

Nealen et al, **A Sketch-Based Interface for Detail-Preserving Mesh Editing,** *SIGGRAPH 2005*



Sketch-based Modeling (SBM) Gestural Modeling

Uses gestures as commands for generating solids from 2D segments

*Category #1 – **SKETCH***
*Category #2 – **Quick-Sketch***
*Category #3 – **Teddy***
*Category #4 – **GIDeS***

Technical Illustration

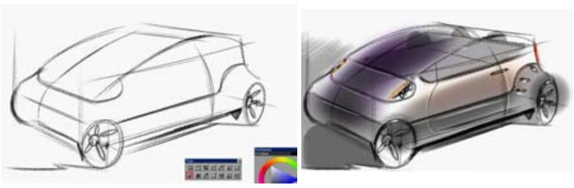
Zeleznik, R. C., Herndon, K. P. and Hughes, J. F. **Sketch: An interface for sketching 3D scenes** Proc. of SIGGRAPH '96, pp. 163--170

Eggli L., Hsu C., Brüderlin B.D., Elber G. **Inferring 3D Models from Freehand Sketches and Constraints** Computer-Aided Design, 29(2), 101-112, 1997.

Igarashi, T., Matsuoka, S. and Tanaka, H. **Teddy: A Sketching Interface for 3D Freeform Design** Proc. of SIGGRAPH '99, pp. 409--416.

Pereira J., Jorge J., Branco V., Nunes F. **Towards calligraphic interfaces: sketching 3D scenes with gestures and context icons** WSCG '00

SBM Technical Illustration
Car Design

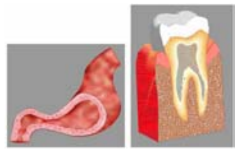


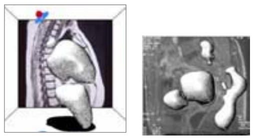
Smart Sketches
Department of Information Systems and Computer Science
INESC-ID/IST/Technical University of Lisbon

[Dias and Jorge 2003] Dias, F.R.M, Jorge, J.A. **Task Analysis and Scenario-Based Design of Calligraphic Interfaces** Proc. of 12th Portuguese Meeting on Computer Graphics (2003)

SBM Medical Illustration

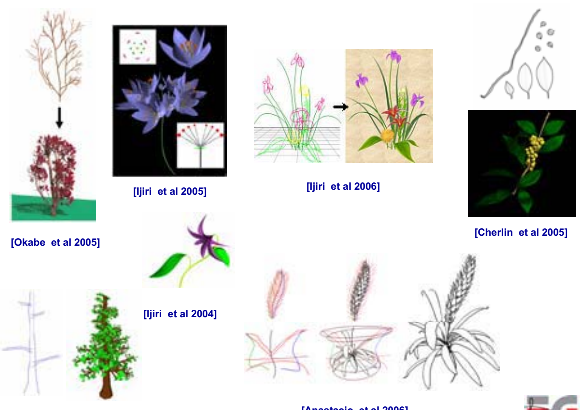
- [Owada et al 2004] Owada, S., Nielsen, F., Okabe, M., Igarashi, T., **Volumetric Illustration: Designing 3D Models with Internal Textures**, Transactions on Computer Graphics (SIGGRAPH 2004), 322-328
- [Owada et al 2003] Owada, S., Nielsen, F., Nakazawa, K., Igarashi, T., **A Sketching Interface for Modeling the Internal Structures of 3D Shapes**, 3rd International Symposium on Smart Graphics (SG 2003), 49-57
- [De Araujo et al 2004] De Araujo, B.R., Jorge, J.A., Sousa, M.C., Samavati, F., Wyvill, B. **MIBlob: A Tool for Medical Visualization and Modeling Using Sketches,** SIGGRAPH 2004 (poster #149 -- "Biomedical Visualization")





SBM Botanical Illustration

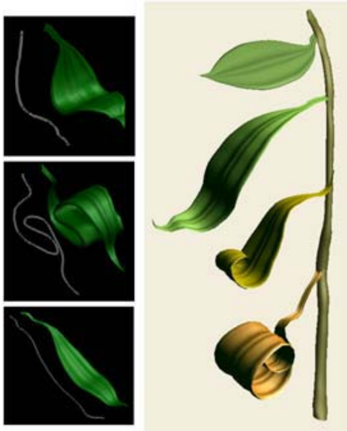
- [Ijiri et al 2006] Ijiri, T., Owada, S., Okabe, M., Igarashi, T. **Seamless Integration of Initial Sketching and Subsequent Detail Editing in Flower Modeling**, Computer Graphics Forum, (Eurographics 2006)
- [Anastacio et al 2006] Anastacio, F., Sousa, M.C., Samavati, F., Jorge, J.A. **Modeling Plant Structures Using Concept Sketches**, NPAR 2006
- [Ijiri et al 2005] Ijiri, T., Owada, S., Okabe, M., Igarashi, T. **Floral diagrams and inflorescences: Interactive flower modeling using botanical structural constraints** Transactions on Computer Graphics (SIGGRAPH 2005)
- [Okabe et al 2005] Okabe, M., Owada, S., Igarashi, T. **Interactive Design of Botanical Trees Using Freehand Sketches and Example-based Editing**, Computer Graphics Forum, (Eurographics 2005)
- [Cherlin et al 2005] Cherlin, J., Samavati, F., Sousa, M.C., Jorge, J.A. **Sketch-based Modeling with Few Strokes**, 21st Spring Conference on Computer Graphics (SCCG 2005)
- [Ijiri et al 2004] Ijiri, T., Igarashi, T., Shibayama, E., Takahashi, S., **Sketch interface for 3D modeling of flowers**, Technical Sketch, SIGGRAPH 2004
- [Okabe and Igarashi 2003] Okabe, M., Igarashi, T. **3D Modeling of Trees from Freehand Sketches**, Technical Sketch, SIGGRAPH 2003



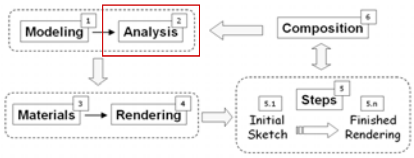
[Okabe et al 2005] [Ijiri et al 2005] [Ijiri et al 2006] [Cherlin et al 2005] [Ijiri et al 2004] [Okabe and Igarashi 2003] [Anastacio et al 2006]

[Cherlin et al 2005]

[Cherlin et al 2005]

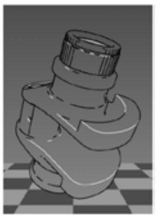


[Cherlin et al 2005]



SCIENTIST	ILLUSTRATOR	NPR component
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 ··· 5.n, 6
Checks rendering	Labels drawing	3, 4, 6
Checks labeling	-	
-	Return specimen	

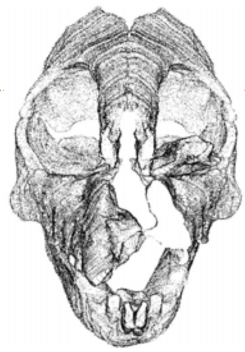
Analysis



Silhouette, creases
[Gooch et. al 1999]

Suggestive contours
[DeCarlo et. al 2003]

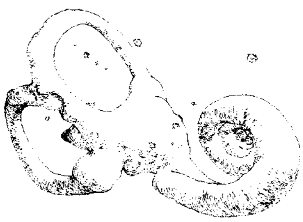
Analysis



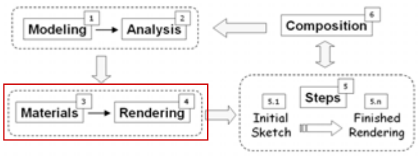
Morphometric Variables
[Sousa et. al 2003]

Analysis

Principal directions of curvature
[Girshick et. al 2000]



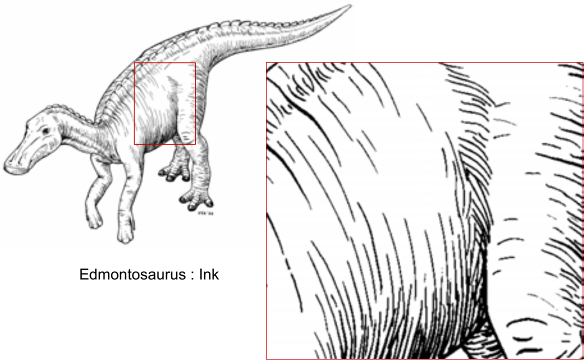
Directional Fields
[Sousa et. al 2004]



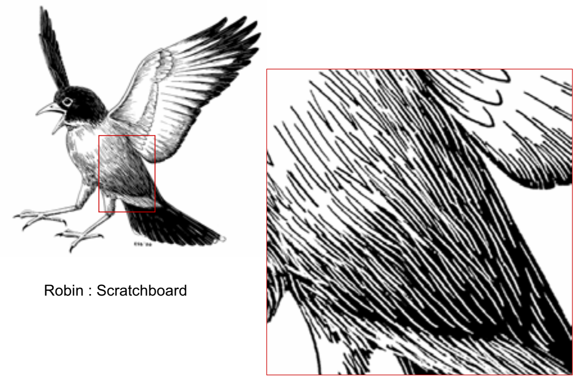
SCIENTIST	ILLUSTRATOR	NPR component
Provides material	Requests information	1
description	Records information	1
specimen	Studies specimen	2
-	Makes rough drawing	3, 4, 5.1, 6
-	Prepares scaled drawing	3, 5.2, 6
-	Makes detailed preliminary drawing	3, 4, 5.3, 6
Checks detailed preliminary drawing	-	
-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

Materials and Rendering (1) Traditional

- Line Drawings (Ink)
  - Outline
  - Line Weight
  - Crosshatching
  - Short-lines and Stippling
- Scratch Board
- Pencil Drawings
- Coquille Board
- Watercolor and Wash
- Gouache
- Airbrush

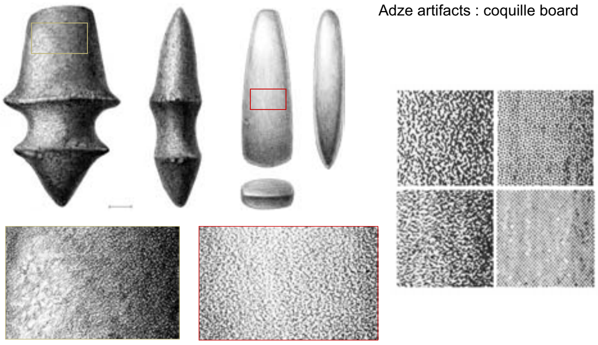


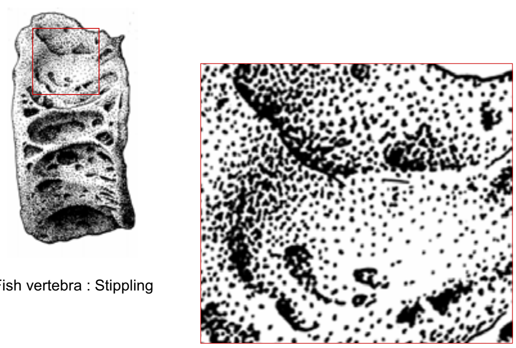
Edmontosaurus : Ink



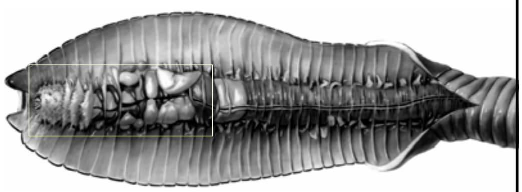
Robin : Scratchboard

Adze artifacts : coquille board

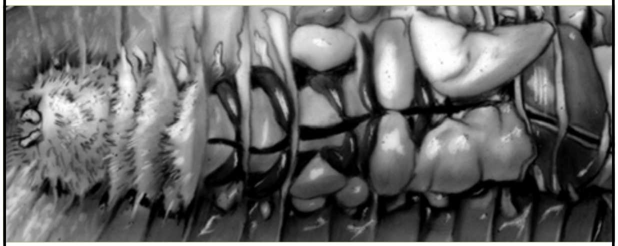




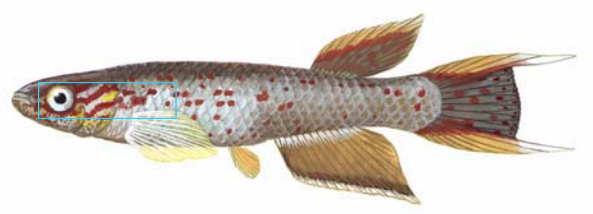
Fish vertebra : Stippling



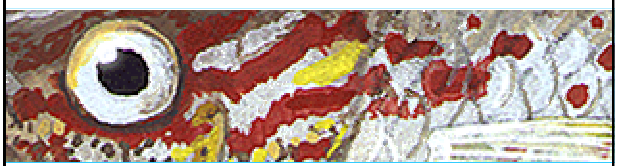
Earthworm dissection



Earthworm dissection

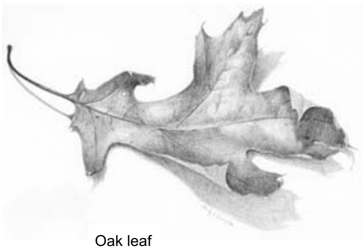


Aphyosemion Australe



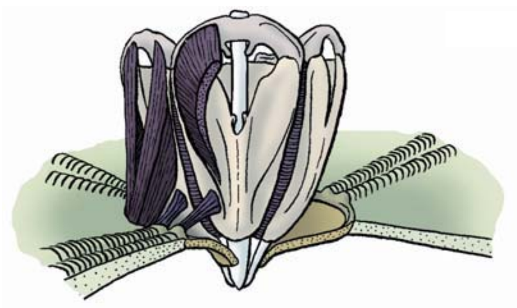
Aphyosemion Australe

Maple leaf



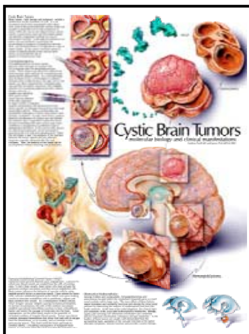
Oak leaf

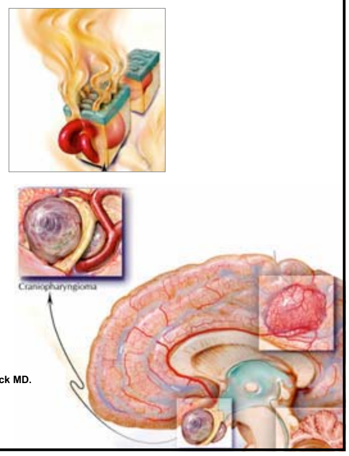
Sea urchin mouthparts



Trilobite : Gouache

Materials and Rendering (2) Digital (1)





Materials and Rendering (2) Digital (2) – NPR

- Technical (design, parts, …)
- Architecture
- Medicine
- Botany
- Cartography
- Archeology
- Zoology

Medicine – Zoology: Scientific Illustration

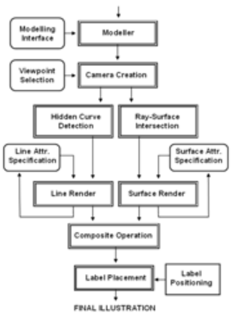
All: Illustrative Visualization

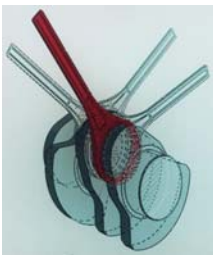
Technical/Architectural Illustration (70s, 80s) Line Drawing of 3D Models

- **1979** Appel et al, **The haloed line effect for hidden line elimination,** SIGGRAPH
- **1982** Roth, **Ray Casting for Modeling Solids,** Computer Graphics and Image Processing
- **1987** Wyvill et al, **Sketches by Ray Tracing,** Computer Graphics International
- **1987** Sasada, **Drawing Natural Scenery by Computer Graphics,** Computer-Aided Design
- **1987** Kamada, T. and Kawai, S., **An Enhanced Treatment of Hidden Lines,** ACM Transactions on Graphics
- **1988** Veenstra and Ahuja, **Line drawings of octree-represented objects,** ACM Transactions on Graphics

Technical Illustration System

[Dooley and Cohen 1990]



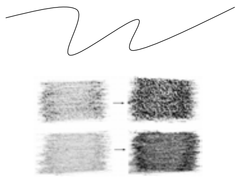


Technical Illustration

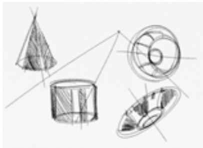
(a) (b) (c) (d)

Technical Illustration
Car Design

[Dias and Jorge 2003]



[Sousa and Buchanan 2000]



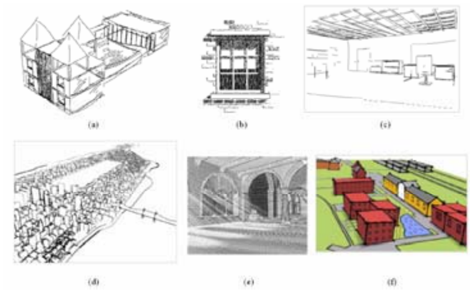
Smart Sketches

Department of Information Systems and Computer Science
INESC-ID/IST/Technical University of Lisbon

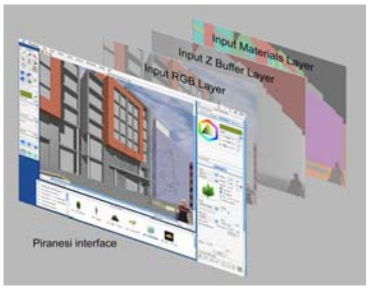
Technical Illustration

- [Agrawala et al 2003] Agrawala, M., Phan, D., Heiser, J., Haymaker, J., Klingner, J., Hanrahan, P., and Tversky, B. 2003. **Designing effective step-by-step assembly instructions**. ACM Transactions on Graphics (Proc. of SIGGRAPH 03) 22, 3, 828–837.
- [Deussen et al. 2000] Deussen, O., Hiller, S., van Overveld, C., and Strothotte, T. 2000. **Floating points: A method for computing stipple drawings**. Computer Graphics Forum (Proc. of Eurographics '00), 40–51.
- [Dias and Jorge 2003] Dias, F.R.M, Jorge, J.A. **Task Analysis and Scenario-Based Design of Calligraphic Interfaces** Proceedings of 12th Portuguese Meeting on Computer Graphics (2003)
- [Gooch et al 1998] Gooch, A., Gooch, B., Shirley, P., and Cohen, E. 1998. **A non-photorealistic lighting model for automatic technical illustration**. In Proc. of SIGGRAPH '98, 447–452.
- [Nienhaus and Dollner 2004] Nienhaus, M., and Dollner, J. 2004. **Blueprints illustrating architecture and technical parts using hardware-accelerated non-photorealistic rendering**. In Proc. of Graphics Interface '04
- [Sousa and Buchanan 2000] Sousa, M.C., Buchanan, J. **Observational Models of Graphite Pencil Materials**, Computer Graphics Forum,19(1) (2000), 27 -- 49

Architectural Illustration



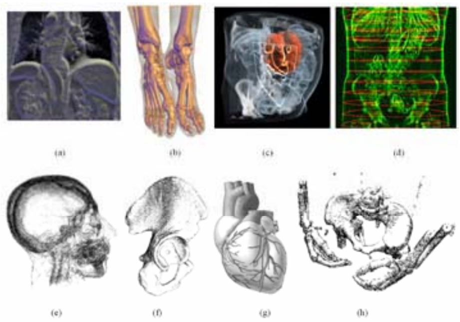
Piranesi System
[Schofield 1994]



Architectural Illustration

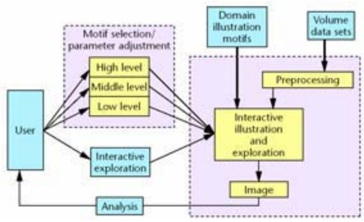
- [Dollner and Walther 2003] Dollner, J., and Walther, M. 2003. **Real-Time Expressive Rendering of City Models**. In Proc. of the 7th International Conference on Information Visualization, 245–251.
- [Hamel 2000] Hamel, J. 2000. **Alternative Lighting Methods for Computer Generated Line Drawings**. PhD thesis, University of Magdeburg.
- [Schumann et al. 1996] Schumann, J., Strothotte, T., Raab, A., and Laser, S. 1996. **Assessing the effect of non-photorealistic rendered images in CAD**. In Proc. of CHI '96 Conference on Human Factors in Computing Systems, 35–42.
- [Winkenbach and Salesin 1994] Winkenbach, G., and Salesin, D. H. 1994. **Computer-generated pen-and-ink illustration**. In Proc. of SIGGRAPH '94, 91–100.
- [Strothotte et al. 1994] Strothotte, T., Preim, B., Raab, A., Schumann, J., and Forsey, D. R. 1994. **How to render frames and influence people**. Computer Graphics Forum (Proc. of Eurographics '94) 13, 3, 455–466.
- [Sousa et al. 2003] Sousa, M., Foster, K., Wyvill, B., and Samavati, F. 2003. **Precise ink drawing of 3d models**. Computer Graphics Forum (Proc. of Eurographics '03) 22, 3, 369–379.

Medical Illustration



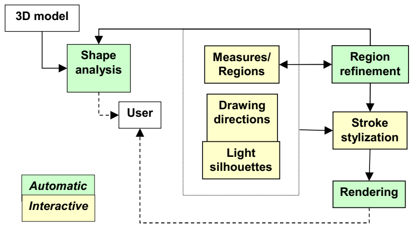
Volume Illustration System

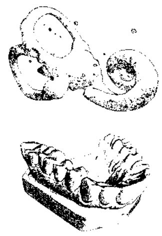
[Svakhine et al 2005]



Precise Ink Drawing System

[Sousa et al 2003, 2004, Pakdel and Samavati 2004]





Medical Illustration

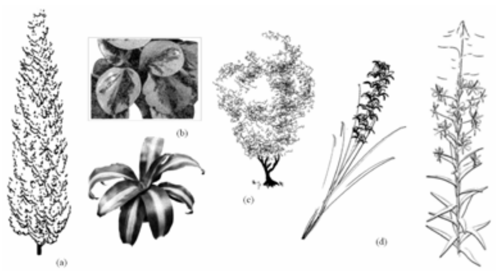
- [Ebert and Rheingans 2000] Ebert, D., and Rheingans, P. 2000. **Volume illustration: Non-photorealistic rendering of volume models**. In Proc. of IEEE Visualization '00, 195–202.
- [Lum and Ma 2002] Lum, E., and Ma, K.-L. 2002. **Hardware-accelerated parallel non-photorealistic volume rendering**. In Proc. of NPAR '02, 67–74.
- [Svakhine et al 2005] Svakhine, N., Ebert, D.S., Stredney, D., **Illustration Motifs for Effective Medical Volume Illustration**, IEEE Computer Graphics and Applications, May/June 2005 (Vol. 25, No. 3).
- [Csebfalvi et al. 2001] Csebfalvi, B., Knig, A., Grller, E., Mroz, L., and Hauser, H. 2001. **Fast visualization of object contours by nonphotorealistic volume rendering**. Computer Graphics Forum (Proc. of Eurographics '01) 20, 3, 452–460.

Medical Illustration

- [Lu et al. 2002] Lu, A., Morris, C., Ebert, D., Rheingans, P., and Hansen, C. 2002. **Non-photorealistic volume rendering using stippling techniques**. In Proc. of IEEE Visualization '02, 211–218.
- [Sousa et al. 2003] Sousa, M., Foster, K., Wyvill, B., and Samavati, F. 2003. **Precise ink drawing of 3d models**. Computer Graphics Forum (Proc. of Eurographics '03) 22, 3, 369–379.
- [Hamel 2000] Hamel, J. 2000. **Alternative Lighting Methods for Computer Generated Line Drawings**. PhD thesis, University of Magdeburg.
- [Sousa et al 2004] Sousa, M., Samavati, F., and Brunn, M. 2004. **Depicting shape features with directional strokes and spotlighting**. In Proc. of Computer Graphics International '04, 214–221.

Botanical Illustration

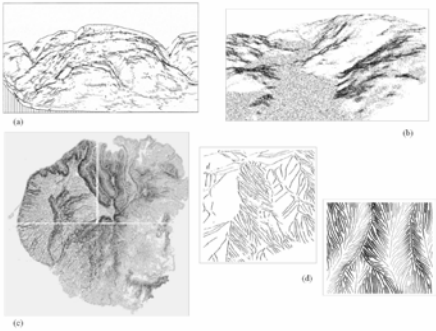
Selection of NPR results for botanical illustration
Copyright
(a) 2000 Oliver Deussen [Deussen and Strothotte 2000],
(b) 2002 Adrian Secord [Secord 2002],
(c) 1997 Mike Salisbury, Michael Wong, John Hughes, and David Salesin [Salisbury et al. 1997],
(d) 2003 Mario Costa Sousa and Przemyslaw Prusinkiewicz [Sousa and Prusinkiewicz 2003].
Used by Permission.



Botanical Illustration

- [Deussen and Strothotte 2000] Deussen, O., and Strothotte, T. 2000. **Computer-generated pen-and-ink illustration of trees**. In Proc. of SIGGRAPH '00, 13–18.
- [Sousa and Prusinkiewicz 2003] Sousa, M., and Prusinkiewicz, P. 2003. **A few good lines: Suggestive drawing of 3d models**. Computer Graphics Forum (Proc. of Eurographics '03) 22, 3, 327–340.
- [Secord 2002] Secord, A. 2002. **Weighted voronoi stippling**. In Proc. of NPAR '02, 37–43.
- [Salisbury et al. 1997] Salisbury, M. P., Wong, M. T., Hughes, J. F., and Salesin, D. H. 1997. **Orientable textures for image-based pen-and-ink illustration**. In Proc. of SIGGRAPH '97, 401–406.

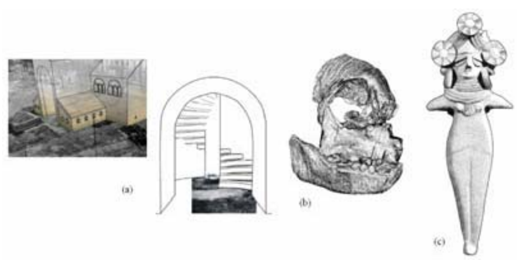
Cartographical Illustration



Cartographical Illustration

- [Visvalingam and Dowson 1998] Visvalingam, M., and Dowson, K. 1998. **Algorithms for sketching surfaces**. Computers and Graphics 22, 2-3, 269–280.
- [Brosz et al. 2004] Brosz, J., Samavati, F., and Sousa, M. C. 2004. **Silhouette rendering based on stability measurement**. In Proc. of the 20th Spring Conference on Computer Graphics (SCCG '04), 157—167.
- [Buchin 2003] Buchin, K. 2003. **Design and Implementation of Real-Time Rendering Techniques for the Non-Realistic Illustration of Digital Terrain Models**. Master's thesis, Hasso Plattner Institute for Software Engineering, Potsdam, Germany.
- [Buchin et al. 2004] Buchin, K., Sousa, M. C., Dollner, J., Samavati, F., and Walther, M. 2004. **Illustrating terrains using direction of slope and lighting**. In Proc. of the 4th ICA Mountain Cartography Workshop.

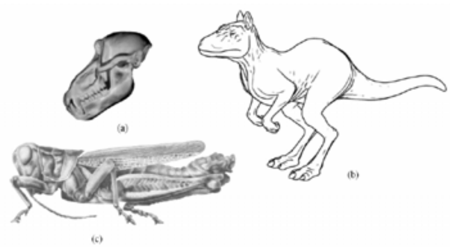
Archeological Illustration



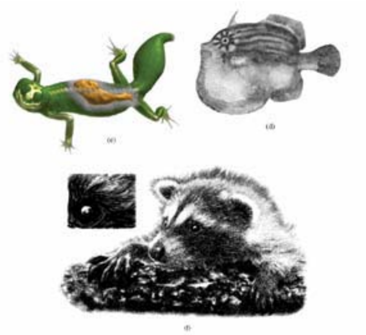
Archeological Illustration

- [Strothotte et al. 1999] Strothotte, T., Masuch, M., and Isenberg, T. 1999. **Visualizing knowledge about virtual reconstructions of ancient architecture**. Proc. of Computer Graphics International '99) 18, 3, 36–43.
- [Sousa et al. 2003] Sousa, M., Foster, K., Wyvill, B., and Samavati, F. 2003. **Precise ink drawing of 3d models**. Computer Graphics Forum (Proc. of Eurographics '03) 22, 3, 369–379.
- [Deussen et al. 2000] Deussen, O., Hiller, S., van Overveld, C., and Strothotte, T. 2000. **Floating points: A method for computing stipple drawings**. Computer Graphics Forum (Proc. of Eurographics '00), 40–51.

Zoological Illustration



Zoological Illustration



Zoological Illustration

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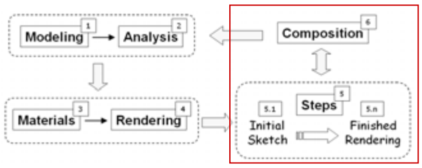
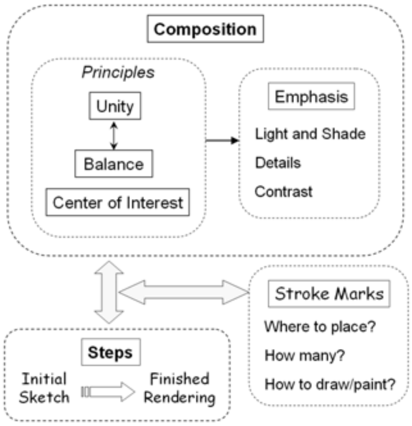
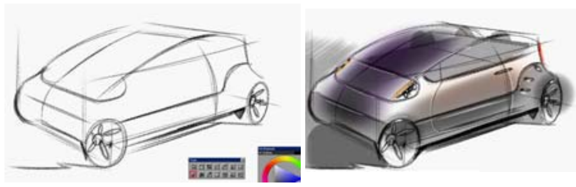


SCIENTIST	ILLUSTRATOR	NPR component
Provides material	Requests information	1
description	Records information	1
specimen	Studies specimen	2
-	Makes rough drawing	3, 4, 5.1, 6
-	Prepares scaled drawing	3, 5.2, 6
-	Makes detailed preliminary drawing	3, 4, 5.3, 6
Checks detailed preliminary drawing	-	
-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



Technical Illustration
Car Design [Dias and Jorge 2003]



Video

Salvatore Cacciatore, Fiat Centro Stile (FIAT Advanced Styling Center)

Smart Sketches

Department of Information Systems and Computer Science
INESC-ID/IST/Technical University of Lisbon

Medical Illustration

Revealing anatomical structures — Spatial Relationships — Multimode Insulin

I V I S GROUP

The Interpretive Visualization Group
Division of Biomedical Communication
University of Toronto

Medical Illustration

http://www.medvisuals.com/medvisuals/headstart/

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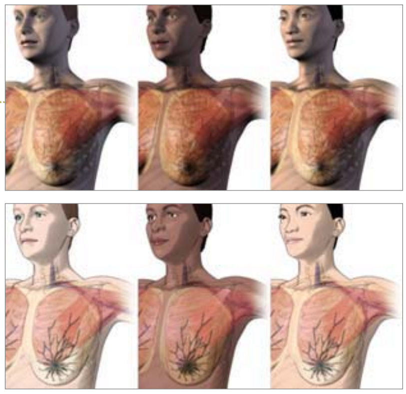
University of Toronto



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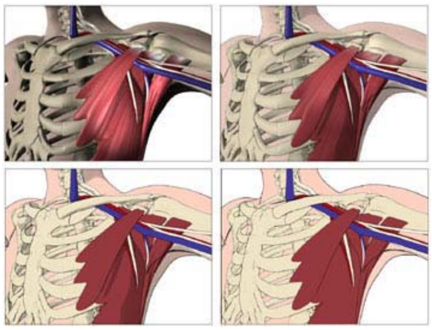

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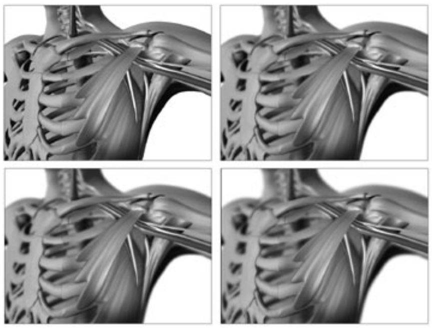
Visual complexity in anatomical relationships



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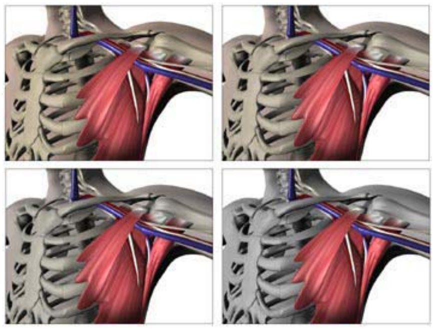
Depth of field in anatomical relationships



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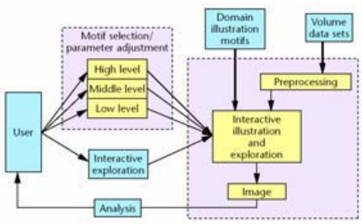
Selective color saturation in anatomical relationships

Volume Illustration System

[Svakhine et al 2005]



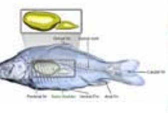
Illustrative Visualization

[Taerum et al 2006]

[Svakhine et al 2005]

[Tietjen et al 2005]

[Viola et al 2004]



[Bruckner et al 2005]

Illustrative Visualization

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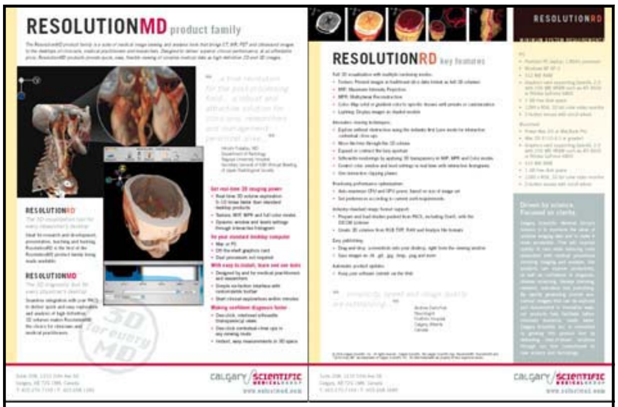
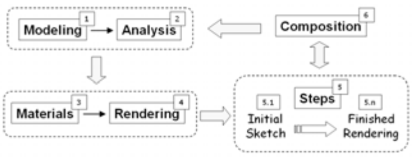


[Taerum et al 2006]
Integrated into the ResolutionMD product family™ from Calgary Scientific, Inc.
http://www.calgaryscientific.com/calscimed/products.htm



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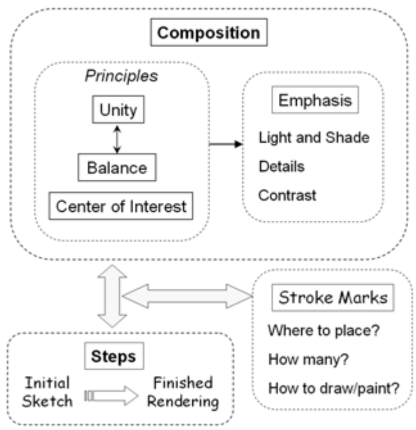

Computational Aesthetics in Graphics, Visualization and Imaging (2005)
L. Neumann, M. Sbert, B. Gooch, W. Purgathofer (Editors)

Illustrative Visualization for Medical Training

Mario Costa Sousa[1] David S. Ebert[2] Don Stredney[3] Nikolai A. Svakhine[2]

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Abstract

A system is presented that produces images that simulate pictorial representations for both scientific and biomedical visualization. It combines traditional and novel volume illustration techniques. We present examples to distill representational techniques for both creative exploration and emphatic presentation for clarity. More specifically, we present adaptations of these techniques for interactive simulation sessions being developed in a concurrent project for resident training in temporal bone dissection simulation. The goal of this effort is to evaluate the use of emphatic rendering to guide the user in an interactive session and to facilitate the learning of complex biomedical information, including structural, functional, and procedural information.

Categories and Subject Descriptors (according to ACM CCS): J.3 [Computer Applications]: Life and Medical Sciences

"Culture is the epidemiology of mental representations: the spread of ideas and practices from person to person. " - Dan Sperber Cultural anthropologist [Pin03]

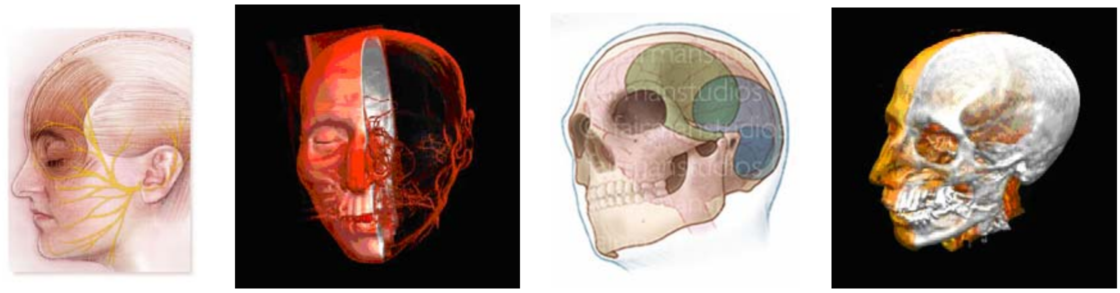
1. Illustrative Medical Visualization

The main goal of medical illustration, as that of visualization and rendering is to *effectively* convey information to the viewer. Computer-generated illustrative medical visualization is a powerful tool that can be applied for education and training of allied, nursing, and medical students, as well as surgical residents. This tool harnesses the power of traditional illustration techniques [Wol58, Hod03] and can be applied to actual patient data, instead of a canonical medical dataset. Patient specific data sets provide actual case studies in pathology and phenotypical variance. They are more relevant to clinical and research pursuits than paragons, and clinically can be exploited to demonstrate diagnosis and treatment options for patients and their families.

The focus of our research in illustrative volume visualization is not to replicate traditional media and techniques of medical illustrators, but to provide a new, extended tool set for the illustrator to effectively create informative illustrations from typical clinical data acquisitions, such as MR, CT, and PET datasets. For instance, the illustrations in Figure 1 show depictions of the human head acquired from CT that employ techniques not easily used in traditional illustration methods. By incorporating these techniques into an interactive visualization system, we can also allow the interactive variation of style and presentation of information during a training or exploration session, adjusting the complexity of the presentation to the expertise and experience of the user [BSSW01, SDS*05].

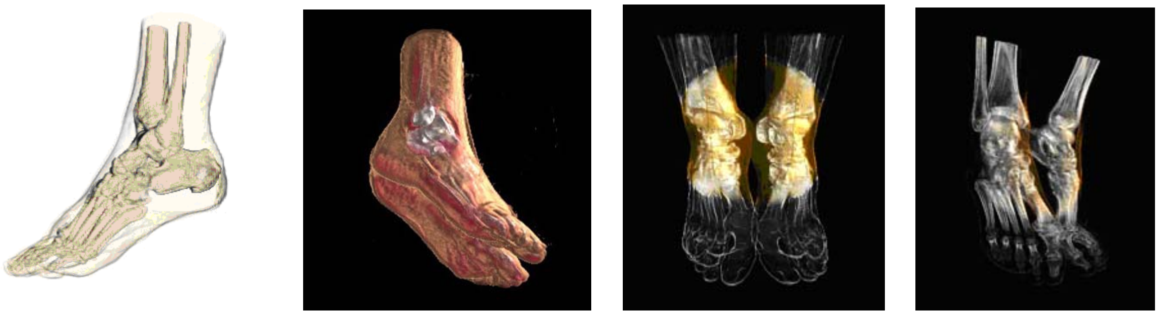
2. User Variance

We have developed an interactive illustrative volume visualization system that utilizes principles from perception and illustration to facilitate the emphasis and de-emphasis of information from a medical dataset based on the application and the user's expertise and perceptual preferences [SE03, SES05]. Our system easily allows one to focus or highlight information, through lighting, color, complexity, and subjugate contextual detail. Examples are shown in Figure 2. Sketching and silhouetting are used in the contextual regions to provide references that facilitate the orientation of the viewer. We utilize variances in multiple attributes and distributed regions to emphasize or de-emphasize form, using a repertoire of volume rendering enhancements, such as



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

Figure 1: *Traditional medical illustrations of (a) the various approaches to forehead lifts, facial anatomy and (c) the anatomy of the cranial base with specific locations for cranial base surgery. Illustrations printed with permission: Copyright Fairman Studios, LLC 2005. Two illustrative renderings (b, d) of a CT head dataset showing the variety of new illustrative techniques that are possible with illustrative volume visualization. (b) Shows the sinuses and skin outlined on the right portion of the image, while (d) shows the skin rendered on the left half and the bone rendered on the right half of the head.*



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

Figure 2: *Illustrative renderings for anatomical explanation and surgery simulation: (a) shows a more traditional anatomy illustration of a foot CT dataset, while (b) shows a subjective surgical view of the tarsal joint, with (c) and (d) highlighting the same dataset through the use of focus of attention and illustrative sketching.*

stipples, lines, continuous shading, as well as illumination and contrast.

This variance of presentation is a key advantage of our interactive illustrative visualization system. The appropriate presentation of information varies based on the expertise of the user and their preference for processing information (e.g., form dominant). Perceptually, we are not all wired the same. Some people are form dominant, some color dominant, some movement dominant, some with high proficiencies in all three, say, and some with low in all three, and every infinite possibility in-between. The issue is relevant to aesthetics. If we are hard wired for color dominance, then it is highly probable that we will find imagery that is focused in color pleasing. That is not to say we cannot appreciate form. Therefore, this approach uses the trainee's level of expertise as a basis for the level of representation, also referred to in this paper as motif classification. Figure 4 shows three levels of representation of micro CT data used in our temporal bone surgery simulator for novice (left two images), intermediate (middle image), and expert training (right image).

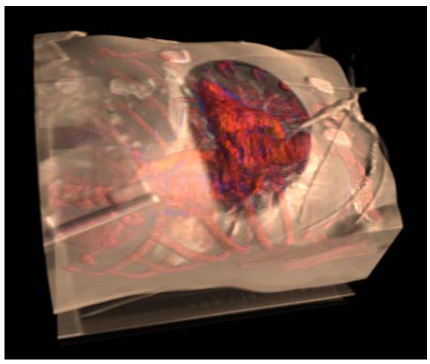


Figure 3: *Illustrative renderings for anatomical explanation and surgery simulation for a cardiac surgical view of an abdominal CT dataset.*

Figure 4: Left to right*: one novice, one intermediate, and one expert visualization for temporal bone surgery simulation.*

Novices are frequently overwhelmed by the quantity and complexity of data presented. Therefore, for novice surgery simulation, a zone of interest is placed in the surgery target area (Figure 5). We use a silhouetted context for subjugation of details outside of the zone, while an illustrative rendering with color cues is used inside the zone, as shown in Figure 2. In contrast, an expert has the necessary experience to subjugate the data details that provide context and can quickly focus on the specific portion of the data and relevant structures. Thus, for expert surgery simulation, we provide more detailed rendering with the selective choice of color and illumination enhancements for structure identification (Figures 3, 4, 6). However, even if an expert is introduced to new information (outside of their own expertise), they may need to start at either the schematic or intermediate level to facilitate integration into their mental representation of the regional anatomy. Therefore, we also need the ability to switch from novice to intermediate to expert levels of representation (Figure 6).

3. Some Guiding Principles for Designing A Useful System

In addition to accommodating user variance into the system design, good aesthetics and design are crucial for creating a system that is effective and that people will use. As Norman [Nor93] points out, “Attractive things work better.” To make something attractive, Wooldridge and Jenkinson [WJ04] suggest that reducing the information presented leads to clarity, that visual complexity should be limited, when appropriate, and that visual elegance is achieved from iterative development and refinement.

Creating an effective system with a natural user interface can be achieved by following principles for effective visual communication based on cognitive psychology and human visual perception. Several useful principles proposed by Norman [Nor93] and Tversky [TMB02] that we have used in designing our system for medical training include the following:

- **Appropriateness principle** [Nor93] - The visual representation should provide neither more nor less information than what is needed for the task at hand. This is in agreement with the views of Wooldridge and Jenkinson that additional information may be distracting and make the user’s task more difficult.
- **Naturalness principle** [Nor93] - Experiential cognition is most effective when the properties of the visual representation most closely match the information being represented. This principle supports the idea that new visual metaphors and representations are only useful when

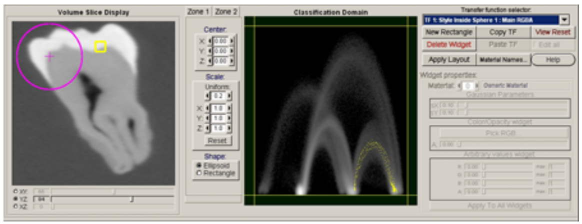


Figure 5: *Part of the expert-level system interface- Left side shows the cross-section window with the zone of interest (purple circle) and a probe (yellow square). Right side shows the low-level interface with transfer function editor with a map of the classification domain and widget controls. The classification domain map shows the probing result (yellow dots).*

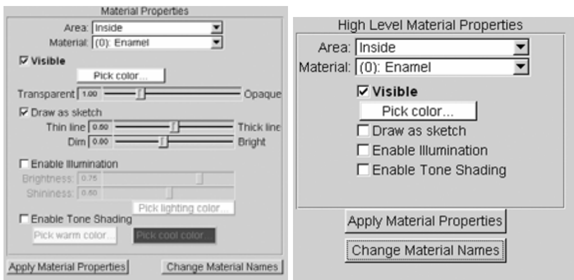


Figure 6: *The mid-level (left) and high-level (right) system interfaces.*

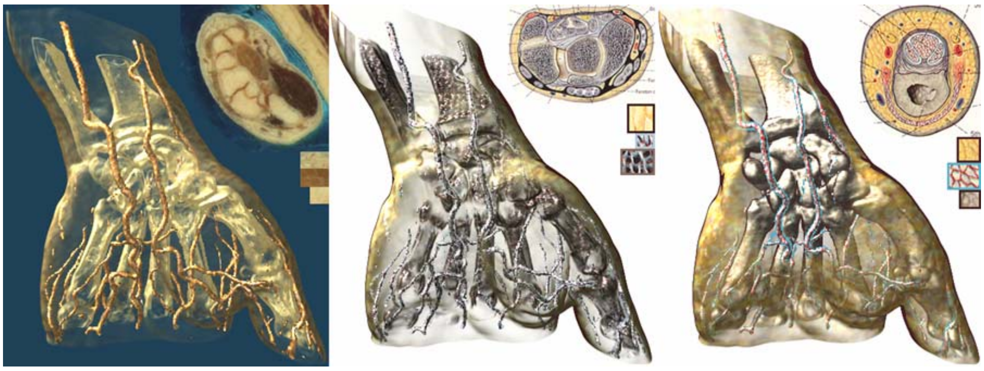


Figure 7: *Example-based volume illustration of a hand CT dataset, where the color and texture examples are shown in the upper right portion of each image. (a) used a photographic slice of the visible man as the input texture, whereas (b) and (c) use two different medical illustrations as their source for color and texture.*

they match the user's cognitive model of the information. Purely artificial visual metaphors can actually hinder understanding, making the system difficult to use. As described in the next section, we have found that even the choice of labels on menus affect the naturalness of the system to various users, which is why we have developed different interfaces and menus for different classes of users.

- **Matching principle** [Nor93] - Representations of information are most effective when they match the task to be performed by the user. Effective visual representations should present affordances suggestive of the appropriate action. This very basic principle of user interaction greatly improves the acceptance and use of the system.
- **Principle of Congruence** [TMB02]- The structure and content of a visualization should correspond to the structure and content of the desired mental representation. Therefore, in our system we try to ensure that the visual representation of the data represents the important medical domain and task information.
- **Principle of Apprehension** [TMB02]- The structure and content of a visualization should be readily and accurately perceived and comprehended. We have used this principle to guide our adaptable system design to vary the visual representation based on the user's expertise and task.

4. Interface Requirements

For adoption and use of a visualization and training system, it is crucial that the system is interactive and easy to use. For our applications, the system needs to generate images at 5 (anatomical education and explanation) to 60 frames per second (stereoscopic surgical simulation) to maintain the interactivity requirements of the task.

For actual deployment of our system, we also need to provide appropriate interfaces for three classes of users. Therefore, the interface incorporates three levels of interaction: an expert level, a mid-level, and a high-level. The expert user-level is for the software developers, experienced illustrators, and system builders. This level allows access to all controls used to generate the styles of the visual rendering in terms of data characteristics (values, gradients, second directional derivatives) and spatial characteristics (orientation, specification of focus region). This level (and the mid-level) also allows creation of illustration motifs and adjustment to the high-level interface. The mid-level interface is for illustrators and experienced end-users that want to make adjustments once they understand the controls. This interface provides higher-level, more conceptual menus with labels that are more appropriate for an illustrator or technically-adept medical professional. The high-level interface is designed for the end user, and in our current application focus, it would be for medical students, surgeons, and surgical residents. This interface mainly allows the change of simple sliders to adjust for inter-patient dataset variation and user personal preferences in depiction. Finally, for the simplest specification, the user can simply load predefined motifs (e.g., expert temporal bone surgical style).

5. Task and User Adaptation

Our illustration motifs are designed to allow the variation in presentation based on both the user and the task. For anatomical education (e.g., Figure 2 (a-c)), we provide the traditional subjective view of the data and allow the rendering style to simulate traditional anatomical text renderings (Figure 2(a)) or to provide illustrative renderings that focus on the primary element of interest (e.g., the tarsal joint in Figure 2 (b) and (c)) using focus plus context techniques where we change the rendering style to capture the viewer's attentive focus to the appropriate location, while providing enough anatomical context for understanding. Figure 2(d) shows an example of a surgical motif for the same foot dataset, where a subjective "surgeon's eye" view of the data is used and the rendering style is more realistic, although enhancements such as making the skin semi-transparent can help in surgical training, as in Figures 2 and 3. This task adaptability is crucial to provide the most effective presentation of information.

As mentioned previously, we also provide variance in rendering to accommodate for the user's visual dominance and experience level, as illustrated in Figure 3. The addition of structural cognitive aids into the rendering to clarify confusing structures, as shown in Figures 2 and 4 for novices can increase their learning. Removing visual clutter and enhancing the rendering to focus visual attention is also useful for novice users. In our system, we allow the setting of various rendering styles according to the user expertise to be used in the training process and will allow the blending between levels to provide a seamless training process.

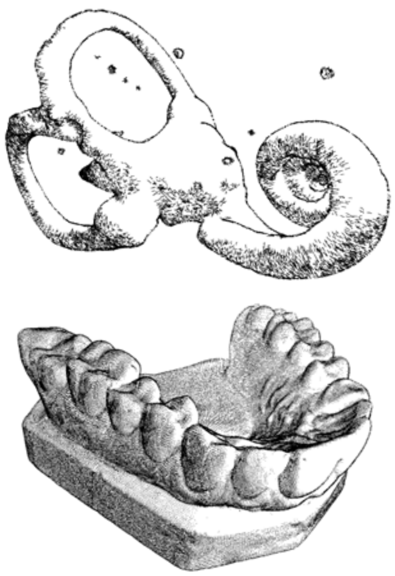


Figure 8: *Inner ear and dental arcade rendered with line and stipple marks, respectively [SFWS03, SSB04].*

6. Our Illustration Goals

One goal of our work is not to simply replicate the techniques used by medical illustrators but to create a new toolkit for illustrators to easily and effectively use for visual communication. By incorporating general illustration principles and styles and interfaces that are designed to be used by illustrators, we can provide a powerful new tool that has unique advantages compared to other illustration media. Our system's goal is not to just replicate their styles but to also incorporate their aesthetic and their techniques into an appropriate, usable system.

We are continuing to extend our system capabilities and have recently explored developing techniques to semi-automatically adapt the colors/textures of a traditional illustration to patient datasets (e.g., MR and CT) [LE05]. Figure 7 shows an example of applying colors and textures from the Visible Human photographic dataset (a) and two different medical illustrations of a hand (b and c) to a segmented hand dataset. These examples show that some basic characteristics of illustrations can be semi-automatically transferred to volume datasets to increase the richness and set the style of the data presentation.

7. Implications and Challenges: From Universal to Conventional to Personal Aesthetics

In addressing the question of whether or not aesthetics are personal or universal [Ren88], we would claim that they are both. Natural settings, such as sunsets are universally appealing due to subtle cues of detailed form, coloration, and movement. We all share, for the most part, similar circuitry that allows us to appreciate the beauty of a sunset. More conventional aesthetics, such as images created with stipple or line, were driven by collective techniques designed for print media (see Figure 8). And then there are our own personal aesthetics, such as how we decorate our bodies, offices, and dwellings, especially with belongings that have personal or "sentimental" value. Most importantly, our personal aesthetics encompass imagery that we are drawn to, that we seek out, and that we create. Our use of imagery, appropriated or self-made, helps express our identity, including how we see the world. These personal aesthetics can be "adopted" by others, and emerge again as conventional aesthetics.

Albeit our primary interest is the pragmatic issue of whether or not information is clearly communicated to the user, obviously the quality of our images is also important. Images that are not interesting to look at do not engage the viewer, and thus are antithetical to learning. By adopting approaches that follow basic principles of human perception, such as selective use of contrast, symmetry (see Figure 2), along with cueing the user's focus with brightness, color, complexity, we can follow a more general, or universal aesthetic. However, by allowing titration of the image qualities in subtle ways to the viewer, we allow a more precise, personal aesthetic to evolve.

These personal aesthetics have subtle variances from both genetic and environmental influences that are manifest in perceptual levels such as form dominance and color dominance. Furthermore, genetics and experience play a modulating role on the conceptual processes. Where basic perceptional systems elucidate what and where, conceptual systems modulate these systems and impart who, how and why. For instance, a religious drawing, albeit a simple line sketch, may hold immense meaning and context for an individual of that faith. Context, imparted from associative processing is essential to how representations are used.

As the techniques for manipulation of NPR images evolve, ultimately, our goal is to allow the user control over how the information is presented that makes the most sense to them at the time they are learning the information. Clearly our “tastes” or “aesthetics” change over time with context, especially as associative cortical regions impart subtle emphases as the user moves from perceptual learning (what and where); to the integration of what is there, where it is; towards the more conceptual, towards what does the structure do, what is its role in the system, and how does its configuration affect its function. Ultimately it would be advantageous to employ NPR techniques to allow user’s to synthesize information, such as creating multimedia, into presentations that demonstrate their comprehension of subject matter. By allowing the user to manipulate the emphasis and deemphasis of information, it would provide a window on how the user is assimilating the information and allow us a better window to judge the more subtle levels of comprehension as they increase their expertise. This would serve two purposes: 1) to identify advanced comprehension, and thus challenge the individual, or 2) more precisely define where the individual is confused, and thus more appropriately intercede to bring them to their full potential.

8. Conclusion

As reality is a construct of the brain, the shared reality we experience is the result of equivalencies in genetic makeup, and shared conventional schema for representations. In our shared perceptions and conceptualizations, the way we “see” the world represents the brain’s way of creating representations from our existence that are meaningful and assist in sense making, and most importantly, are useful in communication. By creating imagery that mimics the way we see, we may augment the assimilation of new information. By developing referents that build on natural representations and shared perceptual experiences, we may be facilitating the sharing of information across disciplines, in a time where interdisciplinary research and investigations are critical to understanding rich and complex phenomena.

However, genetic makeup and experience is congruent only to a degree. Diversity is a powerful instrument of change, a mechanism for both collective and individual growth. By supporting and nurturing cognitive diversity through more advanced visualization techniques, we support the ability to see the world in new ways, not in how we perceive the world, but more importantly, in the way in which we think about the world. Emerging techniques in NPR provide methods by which to communicate information both efficiently and effectively, as well as supporting and nurturing cognitive diversity.

9. Future Directions

There are numerous issues directly related to our research that should be explored further to understand the value of applying illustrative visualization techniques in medicine.

9.1. Traditional illustration

Various levels of representation, from abstract to schematic to realistic, have been exploited for millennia to facilitate the transfer of information from one individual to another. Artists, from the earliest representations that emerged in the Aurignacian period [Whi89] to today, have exploited perceptual phenomenon through their astute applications in various media that elicit cues similar to those found in direct observation of nature.

The real power in the traditional arts and illustration came from their subtle understanding of how to effectively manipulate the media to create subtle cues to represent (abstract or realistic) and include ways to emphasize or de-emphasize information to effectively communicate various messages to their viewer.

9.2. Computer-generated medical illustration

The value of computer generated medical illustration is manifold. Through direct volume-volume rendering of patient specific data, actual case examples of phenotypical variation in anatomy as well as pathological variations can be presented. These data are more salient and relevant to clinical research and medical education. The value in patient education when employed to convey diagnostic and treatment plans to patients and/or their families is self-evident. Though the integration of NPR techniques, complexity inherent in multimodal image acquisitions, i.e., CT, MT, PET, etc, is easily reduced. This complexity would be extremely difficult to reduce through traditional illustrative techniques.

The combination of direct volume rendering and NPR techniques provide a rich and varied repertoire of traditional illustration techniques for use in various biomedical simulation and training scenarios.

9.3. Limitations of NPR systems

Most NPR systems are not flexible enough to allow informed presentation to the appropriate audience. These systems must support rapid iteration, so that various imaging representations can be tried: (a) rapid selection of region of interests, Euclidean, and irregular, (b) rapid lighting, (c) importing segmented systems. This is happening both through the development and maturation of “Interactive NPR” systems [Sch94] (traditional renderings produced partly by the system and partly by the user), as well as by technological developments such as the expansive capabilities of GPU’s.

We do not advocate that an illustrator is the sole arbitrator of visual literacy and aesthetics. We would like to see the systems allow for a selection of styles and rapidly allow one to say “Take my data and make it look like this example”. Our goal isn’t to replicate what traditional media can be used for, but to provide a new tool for the illustrator with its own features and advantages.

9.4. Aesthetic challenges

Replicating the look of traditional illustration techniques and incorporating standard illustration conventions obviously can have an aesthetic quality since these techniques exist in our collective psyche, i.e., chalk drawings and the work of the Renaissance masters, stipple and engraving techniques borrowed from print techniques. However, simply replicating techniques previously developed for other media is not enough. The final question remains: Does the representation clearly convey the information to be depicted? And if it does, does the image also embody an aesthetic quality?

Most traditional techniques evolved by constraints with the media, i.e., early printing techniques could not reproduce continuous tone properly, so stipple and hatching, which evolved out of engraving techniques, became popular, because the engraving plates used for mass production reproduced the images with high fidelity.

We see a strong intermediate use by individuals who would like to select pictorial motifs from images that show various treatments. This would allow for a quick way to draw upon previous motifs that one finds both useful and aesthetically pleasing.

Again, the "prime directive" is to convey the information. However, we are forging into some new territory, because the titration of representations to an individual is counter-intuitive to the notion of a "universal aesthetic". We would posit that this is simply a level of degree. That most of representation falls into the "universal aesthetic" in that perceptual cues (developed) and expected by humans are provided (i.e. content "what") However, individual preferences, in our case, is closely associated with subtle variations in genetic and experiential makeup that are manifest in subtle aspects of form, color, or motion dominance and preference, as well as "associative components", i.e, contextual (level of experience, appreciation, etc.) as opposed to content.

9.5. Variance of expertise (novice, intermediate, expert)

Lintern has shown that simple graphics may be more helpful to novice pilots when using simulation to depict flying, and that simple representations for novices may actually reduce practice time by 15 percent [Lin92]. This work suggests that overly realistic displays may be too overwhelming for novices, because they do not have the mental representation to subjugate noise and process the most salient information in the scene, as would an expert. Experts, based upon extensive experience, use nuances subtlety and intuitively to effectively assess and interact with their environment. At one time consciously sought out and contextualized, as in initial learning, these cues are now subjugated and unconsciously processed. Again, this is mostly due to levels of association. Does the individual have the knowledge to associate aspects that provide a sense of aesthetics, i.e., an appreciation for a subtle variation, or novel attribute?

Within even an expert population, variations in types of learning may exist. These may include visual (imagery) dominant, verbal dominant (written, auditory), and kinaesthetic (touch movement) dominant. We will attempt to study these types of learners to see if there is any correlation in how they utilize the simulation. This will allow us to evaluate if they rate themselves focusing on visual, haptic, or auditory cues.

9.6. Long-term collaboration

An important question is how can we promote long-term collaboration between the medical illustration and computer graphics/NPR communities? A first step here would be to provide complete, user-friendly tools with an interface that is natural and useful for an illustrator. Most existing systems are research prototypes and not products ready to be used. We can create environments to promote this and nurture the possibility of interaction, or like us, find researchers with common ground and see how it goes. We would like to see illustrators get actively involved in promoting visual literacy. Incorporating standard illustration conventions into our systems should be a priority. We have identified three crucial factors on how to automate user adaptable presentation and guide a user to the most appropriate representation: (1) the interface (2) the use of appropriate terminology and (3) task adaptability.

9.7. Interactive simulation

Learning complex information, such as found in biomedicine, proves specifically problematic to many, and often requires incremental step-wise and multiple depictions of the information to clarify structural, functional, and procedural relationships. Spiro and Feltovich have demonstrated that generating alternate views of the same information under different organizational schemes and representations may reduce and prevent reductive biases and oversimplification which often occur in learning complex material [SFCA89]. Although the gradual increase in variability of task complexity and representation initially decrease a learnerŠs performance in training, it has been demonstrated to ultimately increase learning and transfer [FH84, PMJCG73]. Multiple depictions have been shown to facilitate self-evaluation and validation of oneŠs comprehension. However, even with extensive learning through text, images, and lectures, initial interaction to determine proficiency with either cadaver or live patients is often accompanied by high levels of anxiety.

The simulation of procedural relationships, especially those that involve user queries demand interaction. Emerging visualization techniques, such as non-photorealistic representations, coupled with advances in computational speeds, especially new graphical processing units, provides unique capabilities to explore the use and variation of representations in interactive learning sessions.

We are developing a surgical simulation environment that is being exploited to investigate the use of volumetric data to provide interactive levels of representation titrated to the level of proficiency of the user (see Figures 2, 3, 4). Our intention is to run controlled studies that compare traditional methods of learning anatomy, lecture, drawings, etc with simulations studies.

For the purposes of this study, we are employing a basic exploratory pre-test and post-test comparison of improvement in understanding temporal bone anatomy. The metrics to be collected will be based upon proper identification of structures and times to task. Our experimental design will measure a percent change in user's score regarding the use of the simulator as a supplemental learning tool compared to additional time in the anatomy lab.

Acknowledgments

The authors would like to thank nVidia for their support in providing the graphics hardware. We also thank the anonymous reviewers for their valuable comments and suggestions, and to Patricia Rebolo Medici for proofreading the paper. This paper is based upon work supported by the National Science Foundation (Grant Nos. 0222675, 0081581, 0121288, 0196351, and 0328984) and by a grant from the National Institute on Deafness and Other Communication Disorders, of the National Institutes of Health, 1 R01 DC06458-01A1. Parts of this research were also supported by Discovery Grants from the Natural Sciences and Engineering Research Council of Canada.

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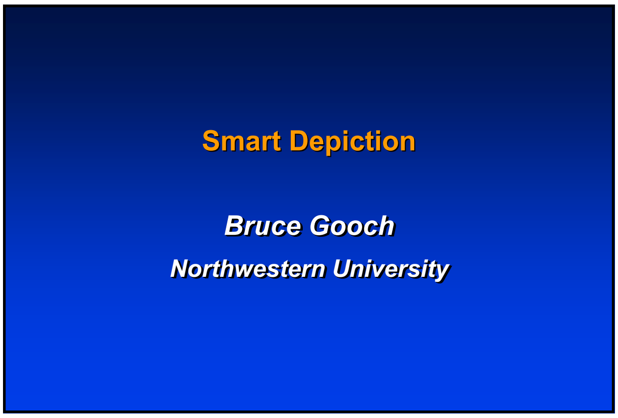
Eurographics 2006 Tutorial

Illustrative Visualization for Medicine and Science

Perception and Evaluation: Optimizing Computer Imagery for Communication

Bruce Gooch, Northwestern University

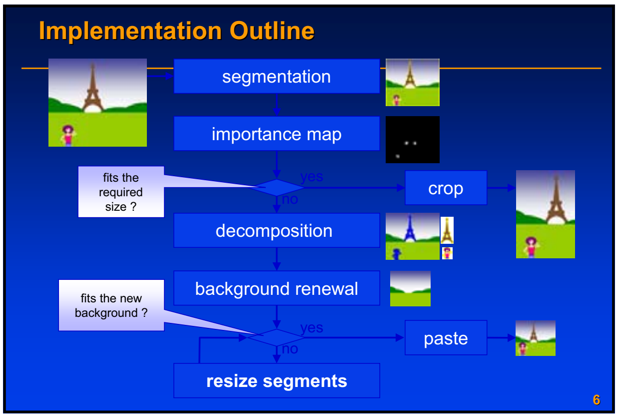

Smart Depiction
Bruce Gooch
Northwestern University

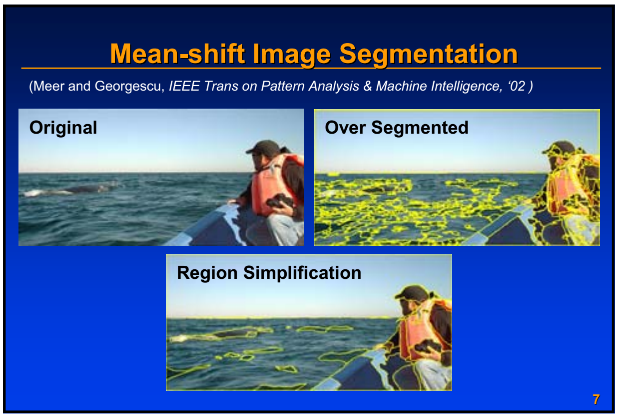

2

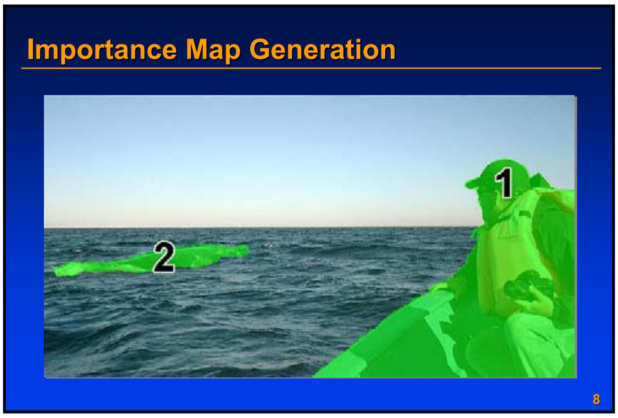

3


Retargeting Image to a Cell Phone
Crop
Scale
Our Result
4


Background
Photoshop, Gimp
Suh et al. UIST 2003
Liu et al. ACM Multimedia 2003
5

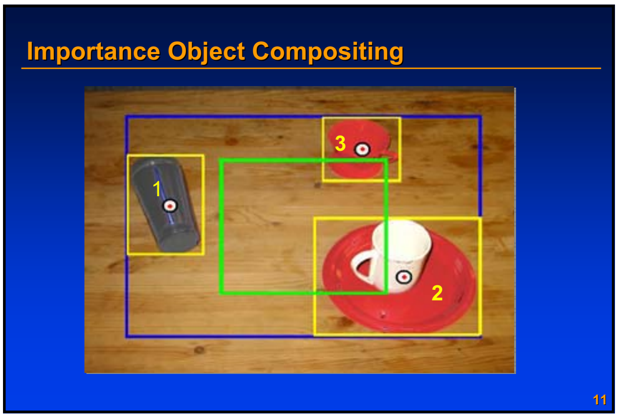

Implementation Outline
segmentation
importance map
fits the required size ?
yes
no
crop
decomposition
background renewal
fits the new background ?
yes
no
paste
resize segments
6

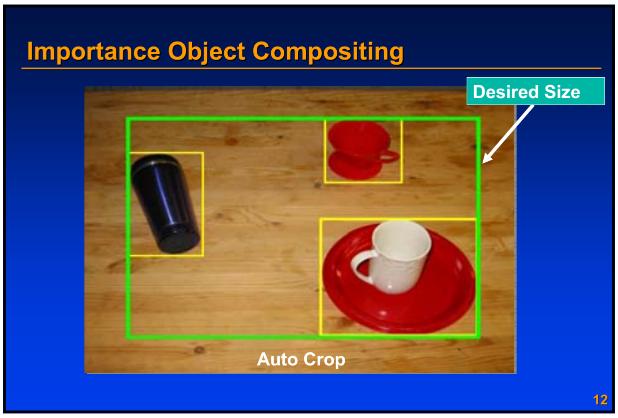

Mean-shift Image Segmentation
(Meer and Georgescu, IEEE Trans on Pattern Analysis & Machine Intelligence, '02)
Original
Over Segmented
Region Simplification
7

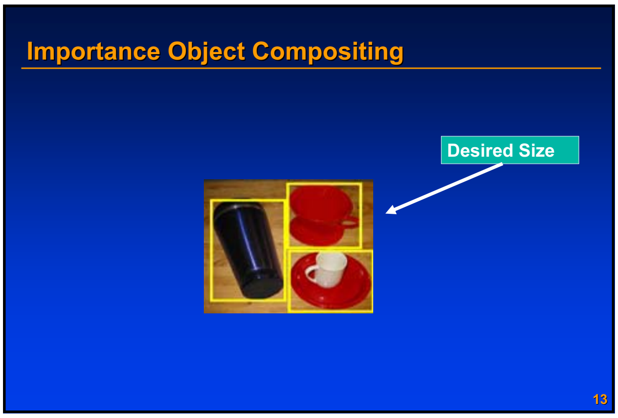

Importance Map Generation
1
2
8


Background Renewal (Harrison WSCG '01)
9


Importance Object Compositing
Original
10


Importance Object Compositing
3
1
2
11


Importance Object Compositing
Desired Size
Auto Crop
12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Desired Size
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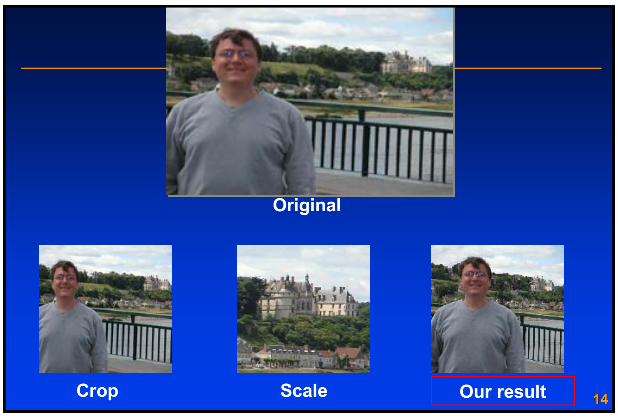
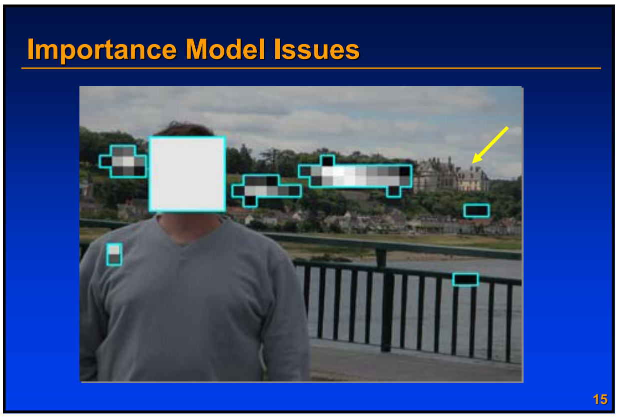
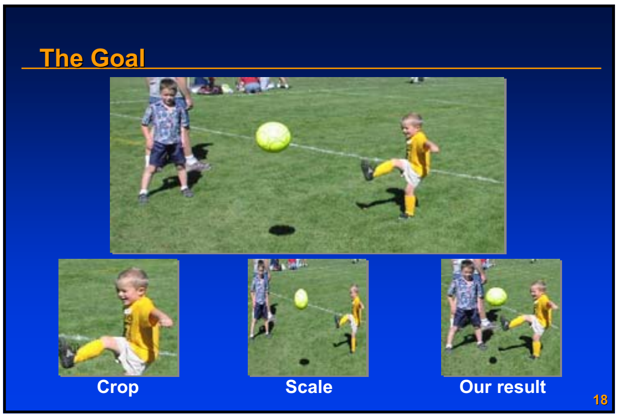

Original
Crop
Scale
Our result
14


Importance Model Issues
15


Original
Crop
Scale
Our result
16


Original
Crop
Scale
Our result
17


The Goal
Crop
Scale
Our result
18

Automatic Image Retargeting

Vidya Setlur[1] Saeko Takagi[2]
Michael Gleicher[3] Ramesh Raskar[4] Bruce Gooch[1]
University of Wisconsin[3] Mitsubishi Electric Research Labs[4]

Semanticons

Creating Context

Parse
- Filename
- Path
- Contents

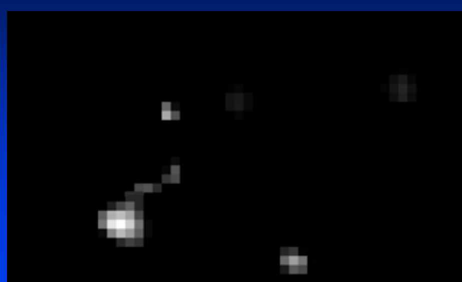
Find Similar Words
- LexNet

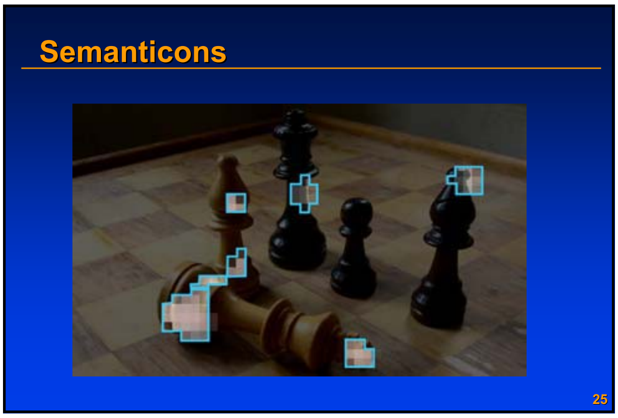
Find Photos

Content Search

Semanticons

Semanticons




Semanticons
25

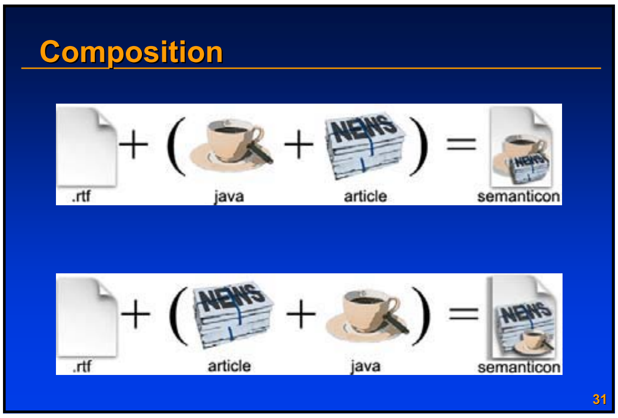

Semanticons
26

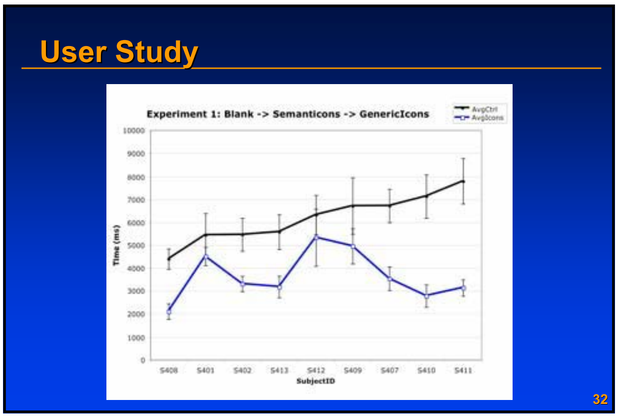

Semanticons
27


Semanticons
HTML
strategicObjs.html
28


Cartooning
29


Cartooning
30


Composition
.rtf
java
article
semanticon
.rtf
article
java
semanticon
31


User Study
Experiment 1: Blank -> Semanticons -> GenericIcons
AvgCtrl
AvgIcons
Time (ms)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
S408
S401
S402
S413
S412
S409
S407
S410
S411
SubjectID
32

Eurographics 2006 Tutorial

Illustrative Visualization for Medicine and Science

Volume Illustration for Medicine and Flows

David Ebert, Purdue University
Nikolai Svakhine, Purdue University

Volume Illustration for Medicine and Flow

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Nikolai Svakhine
Electrical & Computer Engineering
Purdue University
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Talk Overview

Volume illustration approach
- Toolbox of techniques

Common techniques

Domain specific techniques
- Medical illustration
- Flow illustration

Interactive volume stippling and example-based illustration

Interactive volume illustration system

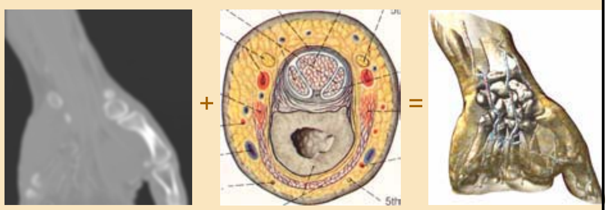
Talk Overview – Interactive Illustration System

Use for medical illustration

Use for surgical simulation

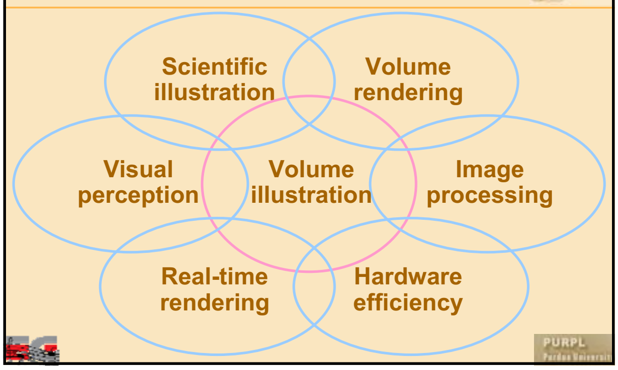
Conclusions

Interactive Volume Illustration



Patient data + Traditional Illustrations = Volume Illustration

Bases of Volume Illustration



Approach to Effective Visual Representations (ala Bertin)

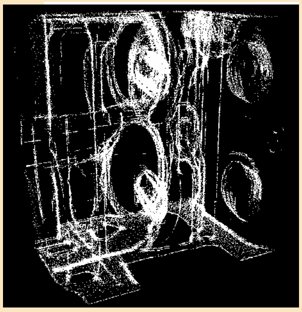
Understand the problem or question

Determine data needed for solution and its characteristics

Determine effective visual representation
- Utilize perception, design, illustration, and advanced rendering techniques
- Interactivity, accuracy, and reproducibility are vital

Volume Illustration: Overview

Abstract away unimportant details



Volume Illustration: Overview

Utilize attentive focus to emphasize data

Volume Illustration: Overview

Utilize illustration principles and techniques

Volume Illustration

Approach

- Apply expressive-level NPR techniques to volume models to improve comprehensibility

Issues

- What to show?
- How to show it?
- How to implement it?

Volume Illustration Approach

What to show?

- Incorporate principles from technical illustration

How to show it?

- Develop a toolbox of illustrative techniques

How to implement it?

- Adapt volume rendering pipeline to volume illustration

Toolbox of Techniques

Feature enhancement

- Boundary enhancement
- Silhouette enhancement

Depth and orientation techniques

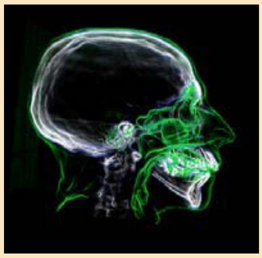
- Aerial perspective
- Intensity depth cueing
- Oriented fading
- Halos
- Tone shading

Illustrative Enhancements

- *Boundary enhancement*
- *Sketching*
- *Edge coloring*
- *Tone shading / illumination*
- *Distance color blending*
- *Feature halos*

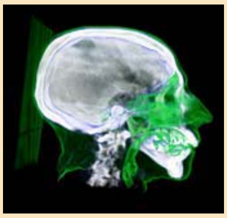
Silhouette Enhancement

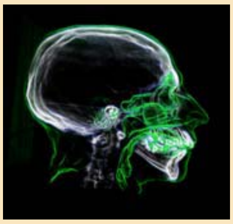
- *Strongest where view vector orthogonal to surface normal vector*
- *Modify the opacity according to (view-vector, gradient-vector) dot product*



Sketch Example

Lower opacity if silhouette term is small





Goal of Illustrative Visualization Process

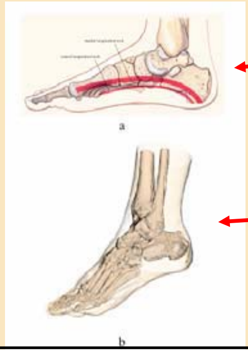
Common Medical Illustration Components

- *Organ/tissue boundary emphasis*
  - Strong use of silhouetting techniques
- *Variation of level of representation*
  - Focus + context techniques
- *Common representation vocabulary*
  - Colors
  - Styles

Medical Motifs

- ***Motifs** are settings upon which illustrator can quickly build styles specification*
- *Example:*
  - Anatomical illustration
  - Surgical simulation
  - Different levels of expertise for intended users

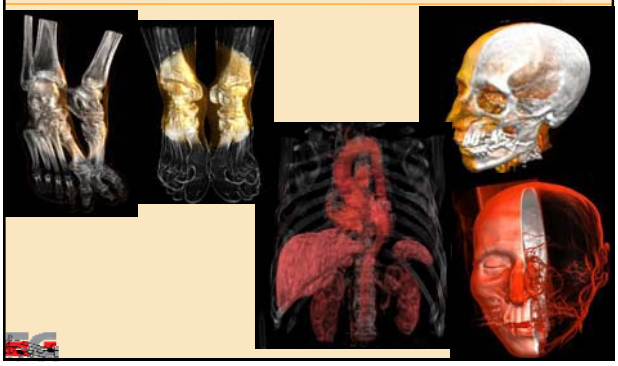
Medical illustrations



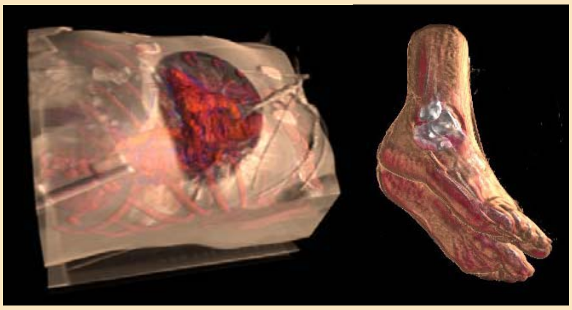
Foot bone structure from anatomy textbook

Same structure shown by IVIS with Visible Human foot dataset

Anatomical Illustration

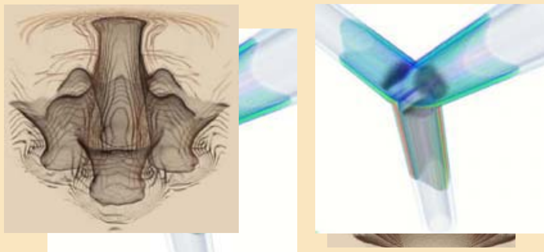


Surgical Training



Images by Nikolai Svakhine

Flow Illustration



Work by Nikolai Svakhine, Yun Jang, David Ebert and Kelly Gaither

Flow Illustration

- *Inspired by work of Leonardo da Vinci*
- *Main feature conveyed with a few simple strokes*
- *Easy to understand 3D turbulent flow*

Flow Data Characteristics: Why Is It Different?

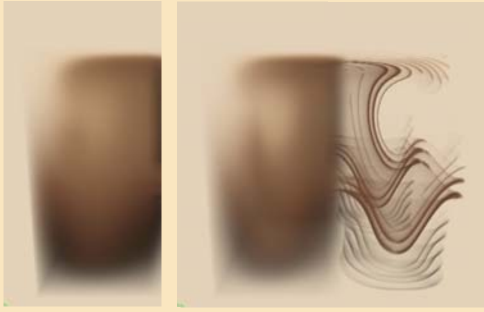
- *Data doesn't often have high gradients – boundaries are not the main concern*
- *Flow features are important (critical points, shocks, vortices, sinks, sources, separation)*
- *Multiple scalar and vector quantities often define features of interest*

Flow Illustration: What Works?

Silhouettes – projected 2D gradients remove visual clutter and detail and show major structures

Contouring transfer function – shows flow contours and structures

Flow Contours



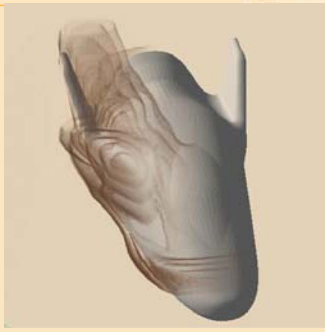
No enhancement

Left – boundary & silhouette
Right – add contours

Flow Illustration: Examples

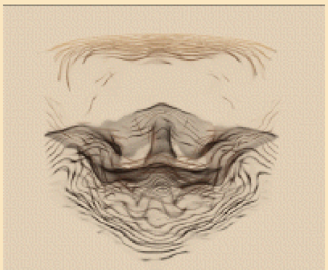
Found cause of vortices from illustration

- Had always assumed wrong source!

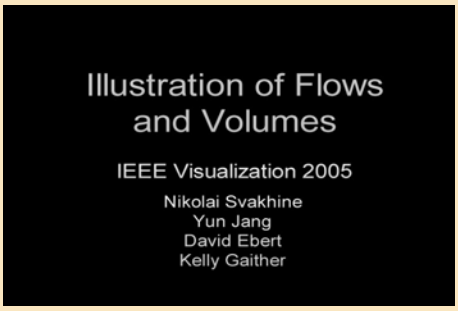


Vortex origin and progression for X38

Flow Illustration: Convection in a Box

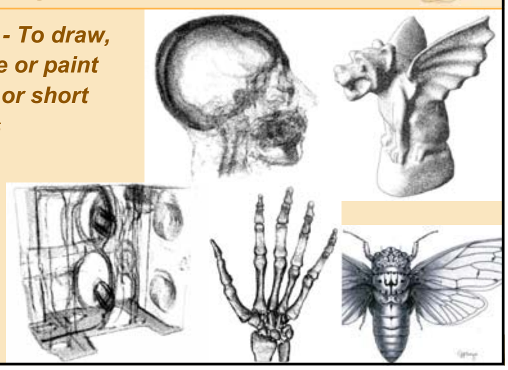


Flow Illustration Movie



Stippling

Stipple - To draw, engrave or paint in dots or short strokes



Two Approaches

Object Space

- Determine stipples to render each geometric primitive (triangle, voxel, etc.)

Image Space

- Compute image
- Determine grey level values
- Generate new image with points using a Poisson distribution

Illustrative Interactive Stipple Rendering

Lu et al., IEEE TVCG 2003

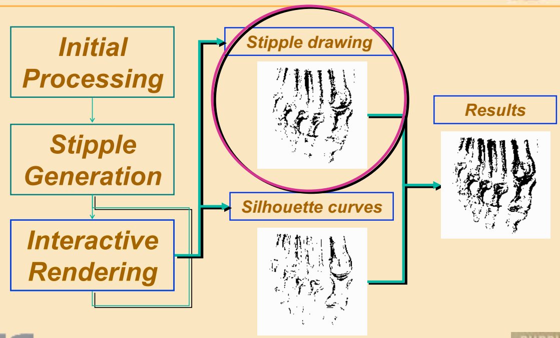
Works for both volumes and surfaces

The Stipple Volume Renderer

Initial Processing → *Stipple Generation* → *Interactive Rendering*

- ***Normalized voxel data***
- ***Voxel positions***
- ***Normalized gradient magnitudes***
- ***Gradient directions***
- ***An edge field: generated by LoG with the voxel data***

The Stipple Volume Renderer

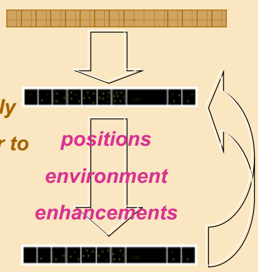


Stipple Drawing

Pre-generate list of stipples & locations

For each voxel / poly

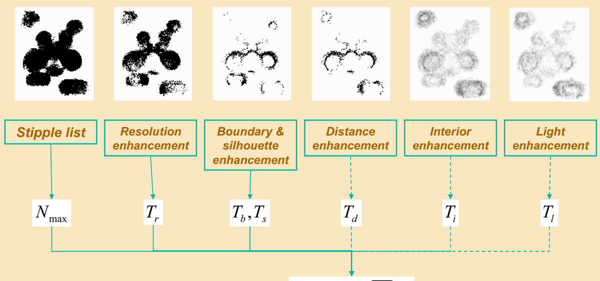
calculate number to draw based on:



Rendering for each frame

Draw points

Feature Enhancements



$$N_i = N_{max} \cdot \prod T_n$$

Resolution Enhancement

For each frame:

Maximum density for the volume position

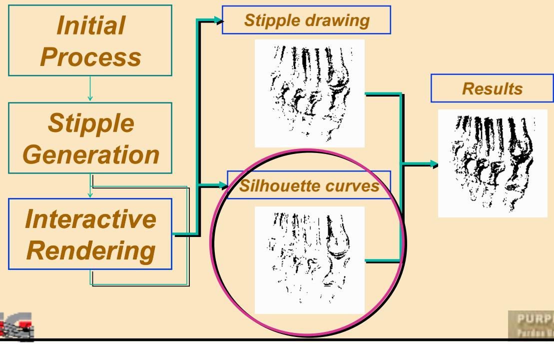
For each voxel:

Maximum density for current voxel

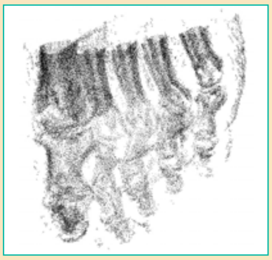
$$T_r = \left[\frac{D_{near} + d_i}{D_{near} + d_0}\right]^{k_{re}} \cdot \left(\nabla \vec{v}_i \cdot E\right)^{k_{nz}}$$

Leg

The Stipple Volume Renderer



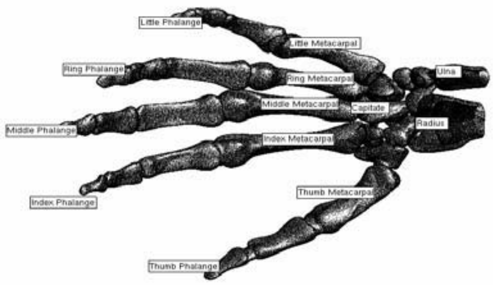
Silhouette Curves



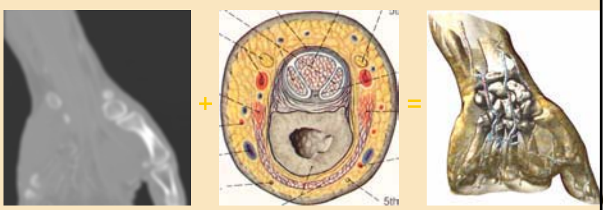
Without

With

Polygonal Results



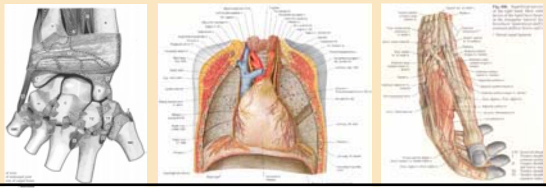
Example-BasedVolume Illustration



Objective: Multiple styles

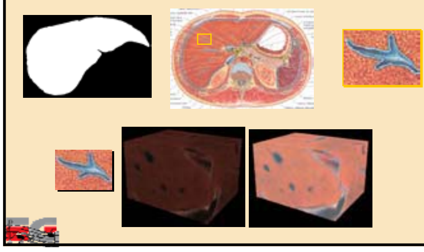
Multiple styles are used in illustrations

- pen and ink, pencil, carbon dust, watercolor and wash, acrylics, airbrush, …
- Suitable approaches to convey object properties



Example-based Illustrative Visualization

Simulate style of professional illustrators & simplify user interaction



Color Transfer

Current approaches

- "Color transfer between images", E. Reinhard et al. 2001
- "Transferring color to greyscale images", W. Welse et al. 2002

Automatic transferring process

Two assumptions:

- Simpler representation & similar object distributions

Example-based Rendering

For each object – one set of textured cubes

Segmented datasets: object ID – one cube set

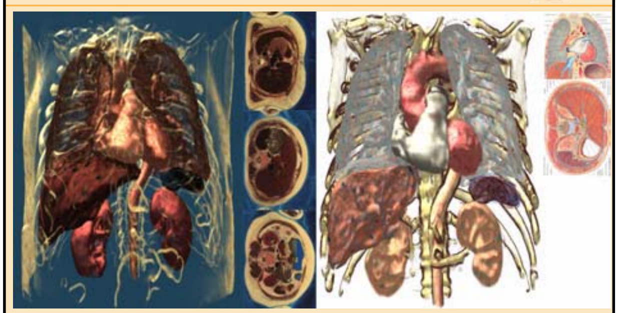
Un-segmented datasets: opacity – cube sets

Only two user interactions: sample & illustration examples

Example-based Rendering - Hand

Gross Anatomy in the practice of medicine. Slaby, F.J., McCune, S.K., and Summers, R.W. 1994. Lea and Febiger.

Example-based Rendering - Abdomen



Sobotta Atlas of human anatomy. Staubesand, J. 1990. Urban and Schwarzenberg Baltimore-Munich.

Talk Overview

Volume illustration approach
- Toolbox of techniques

Common techniques

Domain specific techniques
- Medical illustration
- Flow illustration

Interactive volume stippling and example-based illustration

Interactive volume illustration system

Talk Overview – Interactive Illustration System

Implementation details

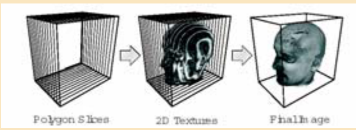
Use for medical illustration

Use for surgical simulation

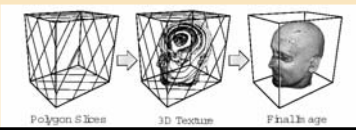
Conclusions

Texture-Based Volume Rendering

Object-aligned (2D textures)

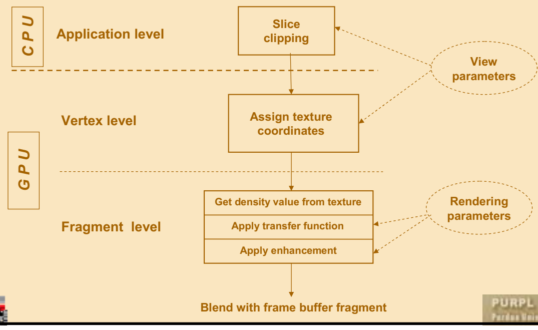


View-aligned (3D-texture)



Rendering Diagram

For each slice:



Simple Transfer Function

Mapping T:
- Scalar values *d* → *RGBA* values

Basic volume exploration tool
- Highlight/color areas of the volume based on the scalar value (e.g., density)

Easily applied at fragment program level

Implementation Details: Advanced Transfer Functions

Multi-dimensional transfer functions
- Use more than one value for transfer function domain

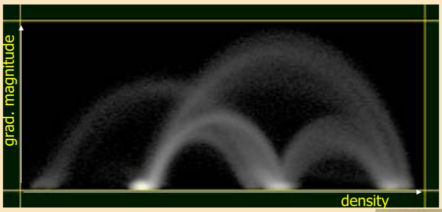
Hierarchical transfer functions
- Use transfer functions not only for (color, opacity), but for illustration effect application

2D Histogram Analysis

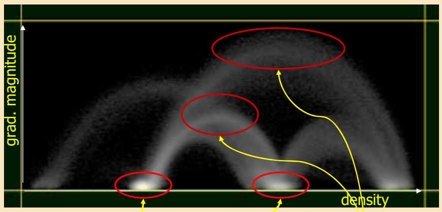
Consider 2D volume histogram

- X for density, Y for gradient magnitude, brightness for sample frequency

CT Tooth Dataset



2D Histogram Analysis



These spots represent **homogeneous materials**

These arcs represent **material boundaries**

Histogram of CT Tooth Dataset

Probe Tool Demo

Use 'probe' to sample multiple points in dataset

See where the points lie in histogram

Identify the material

AVI Demo

Probing Demo

Hierarchical Transfer Functions

Usually transfer functions control (color, opacity)

They can also be used to control **parameters/contribution** ***of the effects***

Design multiple transfer functions to control:

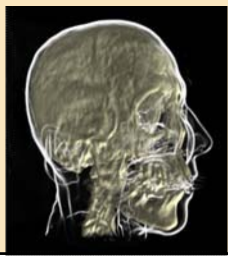
- Sketch
- Illumination
- etc.

This allows applying different combinations of effects to different materials

Example

Sketch applied to 'skin' material

Illumination applied to 'bone' material



Styles

In our system, every transfer function can be modified independently

***Style** is defined as a set of transfer functions, controlling rendering appearance (per material)*

Example style description

- "Apply white sketch to everything except bone and brain, bone is pale yellow and illuminated, brain is invisible"

Next Step: Zones

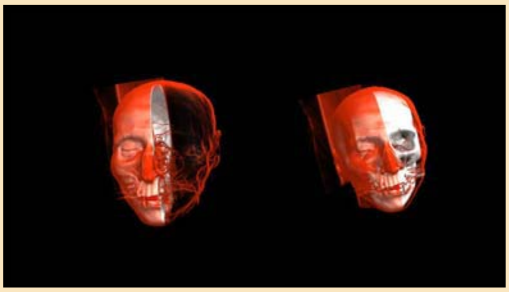
***Zones** are regions of the volume space*

*Zones can have different applied **styles***

Zones can be either ellipsoids or rectangles

This allows large set of possible effects

Zones With Different Styles



Interactive Volume Illustration System Interface and Use in Medicine

Multi-level Interface

Transfer functions are used to parameterize everything

- Color/opacity
- Effect blending
- Enhancement parameters

As with most visualization systems, number of parameters is very large

Multi-level Interface

Transfer function editor is

- Hard to master
- For some tasks, tedious to manage

Solutions

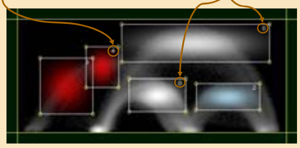
- Multi-level Interface
- Illustration Motifs

Defining Materials

Materials are regions of the transfer domain

Each widget has material ID associated with it

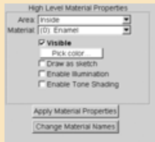
There can me more than one widget with same material ID



Higher Levels

Materials are assigned meaningful names

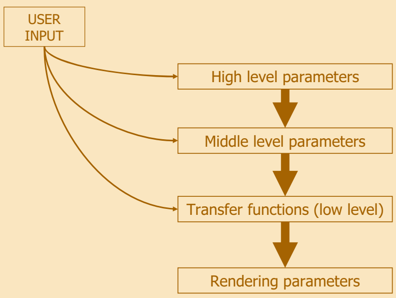
Settings formulated in common language terms



High level

Middle level

Parameter Pipeline



Levels of Expertise

Novice

- Frequently overwhelmed by the quantity and complexity of data presented during training
- Must learn to develop their attentive focus and unconsciously orient the structures in the data for reference

Expert

- Has necessary experience to subjugate data details that provide context
- Can quickly focus on the specific portion of the data and relevant structures

Levels of Representation

Motifs are designed with help/feedback from professional medical illustrator

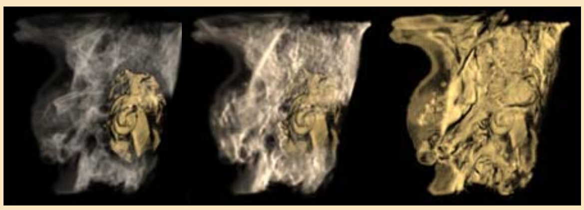
Temporal bone microCT

Schematic/simplistic representation of the cochlea and semicircular canals

A more complex representation of the same area, with more detail on surrounding bone

Almost 'realistic' representation

Levels of Representation

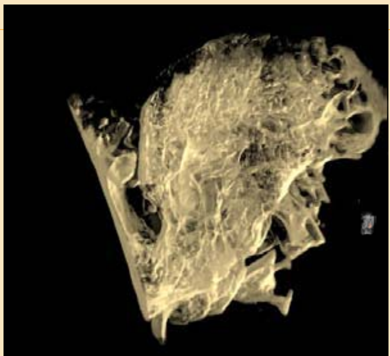


Temporal bone microCT

Even without segmentation, structures are visible

Different levels of enhancement

Surgical Training



Images by Nik Svakhine

Utility of Volume Illustration

Enhancing presentation

- Teaching
- Explaining
- Convincing

Reinforcing unreality

Emphasizing important features

Conclusions

Volume illustration is an effective, powerful tool !

- Effective enhancement / extraction of information
- Perception research
- Art / illustration techniques
- Interactive

Conclusions

Visualization is most powerful when combined with

- Effective enhancement / extraction of information
- Perception research
- Advanced illumination and shading
- Art / illustration techniques
- Improved interaction
- A larger solution

Acknowledgments

Collaborators:

- Aidong Lu, Nikolai Svakhine, Chuck Hansen, Chris Morris, Penny Rheingans, Elliot Fishman, Bill Oliver, Joe Taylor, Mark Hartner, Tim Thirion, Ross Maciejewski, Don Stredney, Mario Costa Sousa, Amy Gooch, Kelly Gaither, Yun Jang

Funding:

- National Science Foundation:
  NSF ACI-0081581, NSF ACI-0121288, NSFIIS-0098443,
  NSF ACI-9978032, NSF MRI-9977218, NSF ACR-9978099
- DOE VIEWS program
- Adobe
- Nvidia

Eurographics 2006 Tutorial

Illustrative Visualization for Medicine and Science

Smart Visibility in Visualization and Focus of Attention

Ivan Viola, Vienna University of Technology

Smart Visibility in Visualization and Focus of Attention

Ivan Viola

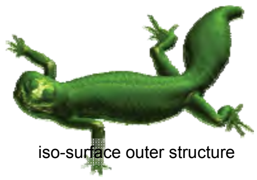
Institute of Computer Graphics and Algorithms

Vienna University of Technology

Smart Visibility Techniques

- Modifications of visual representation and spatial arrangement according to feature relevance
- High-level abstractions exploiting human understanding
- Expressive illustration techniques
  - Visual modifications
    - Section views
    - Cut-away and ghosted views
  - Spatial deformations
    - Deformations
    - Exploded views

Motivation



iso-surface outer structure

iso-surface inner structure

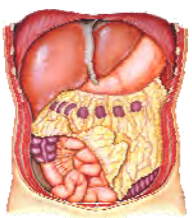
semi-transparent outer structure

ghosted view - outer and inner structure

Outline

- Cut-away and Ghosted Views
  - Importance-Driven Volume Visualization
  - VolumeShop: Interactive Direct Volume Illustration
- Exploded Views and Deformations
- Focus of Attention using Smart Visibility

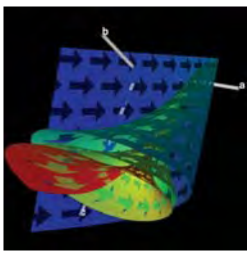
Cut-away and Ghosted Views



http://www.medigraphics.com/
http://www.khulsey.com/

Viewpoint Independent Cut-Away Views

Streamarrows

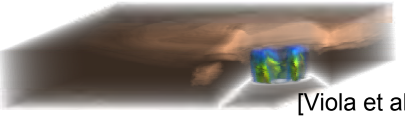


[Löffelmann et al. '97]

Volume Cutting

[Pflesser et al. '02]

Viewpoint–Dependent Cut-Away Views



[Viola et al. '04 '05]

[Bruckner et al. '05 '05] [Straka et al. '04]

Outline

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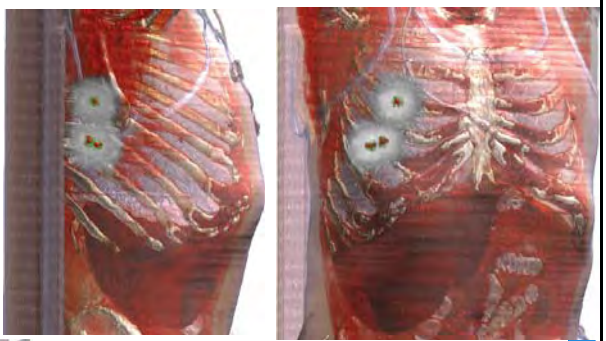
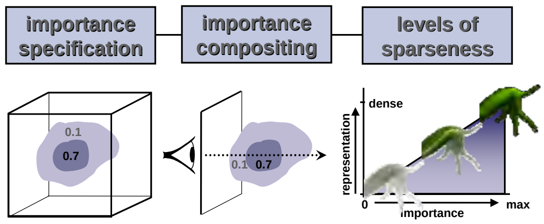
Importance-Driven Volume Visualization

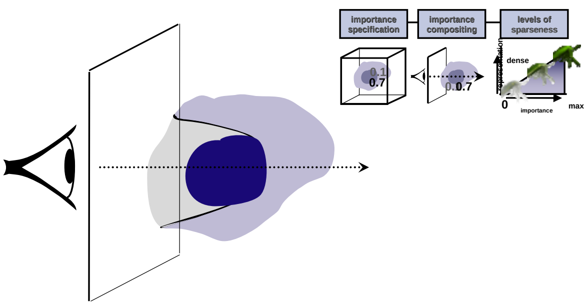
[Viola et al. '04 '05]



Importance-Driven Visualization Model



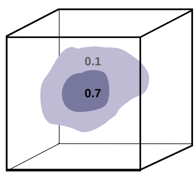
Importance-Driven Visualization Model



importance-driven feature enhancement

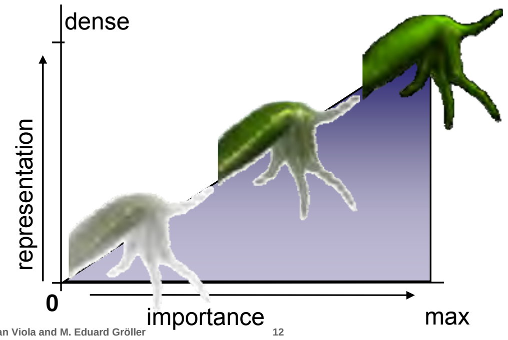
Importance Specification

- Determines the representation
- Automatic specification
  - Feature classification
  - Value range
  - Distance to other feature
  - Distance to focal point
- User-steered assignment to segmented objects



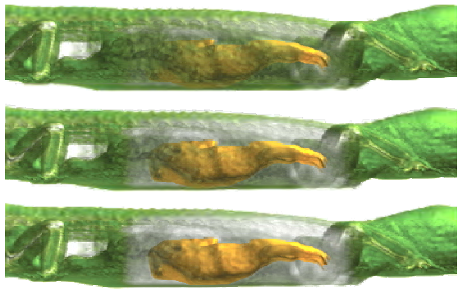
Levels of Sparseness

- Smooth transitions in representation



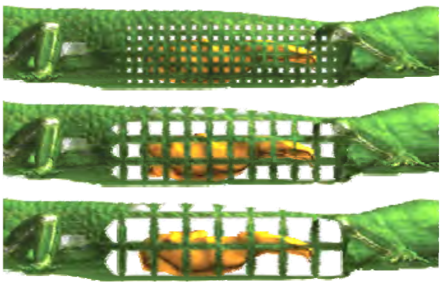
Opacity and Color Modulation

- High importance: opaque, color saturated
- Low importance: transparent, desaturated



Screen-Door Transparency

- High importance: dense, small grid spacing
- Low importance: big grid spacing

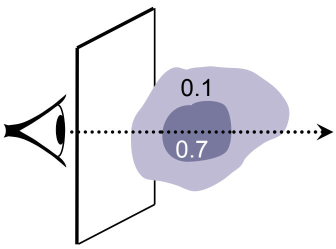


Importance Compositing

- Connects importance to levels of sparseness
- Focus features – dense representation
- Context features
  - If occluding – sparse representation
  - Else – dense representation

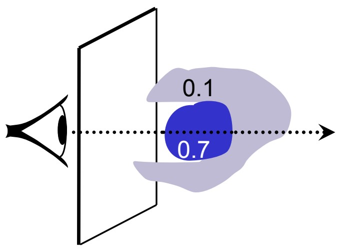
Importance Compositing

- Maximum importance projection
- Average importance compositing



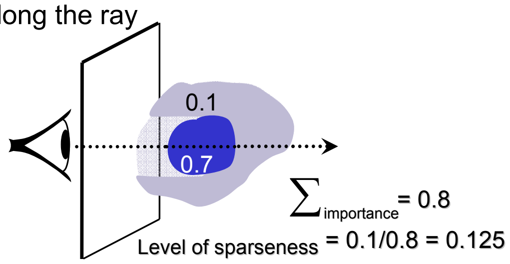
Maximum Importance Projection

- Only feature with highest importance along the ray is rendered

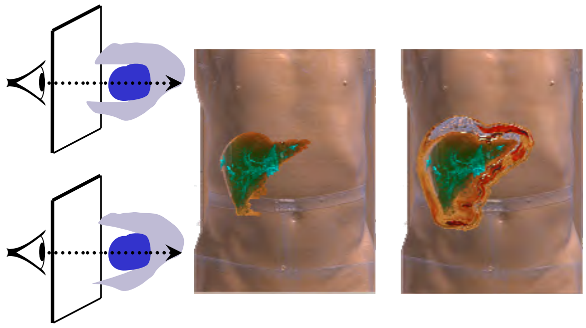


Average Importance Compositing

- Occluding context information is suppressed
- Not entirely removed
- Sum-up importance of intersected features along the ray



Improving the Spatial Arrangement



Examples

maximum importance projection

average importance compositing

Outline

- Cut-away and Ghosted Views
  - Importance-Driven Volume Visualization
  - VolumeShop: Interactive Direct Volume Illustration
- Exploded Views and Deformations
- Focus of Attention using Smart Visibility

VolumeShop

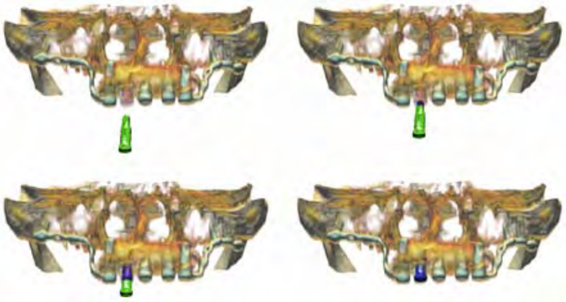
[Bruckner et al. '05]

Goal

- Tool for Direct Volume Illustration
- Supporting:
  - Multi-object Volume Rendering
  - 3D painting segmentation
  - Stylized rendering techniques
  - Smart visibility techniques
  - Labeling and Focus enhancement
  - Interactive Manipulation

Multi-Object Volume Rendering

- Emphasized regions of interpenetration



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Illustrative Enhancement

- Artistic rendering styles are integrated using lighting transfer functions

direct volume rendering | contour enhancement | cartoon-like shading | metal shading

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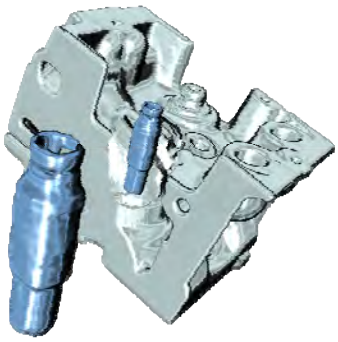
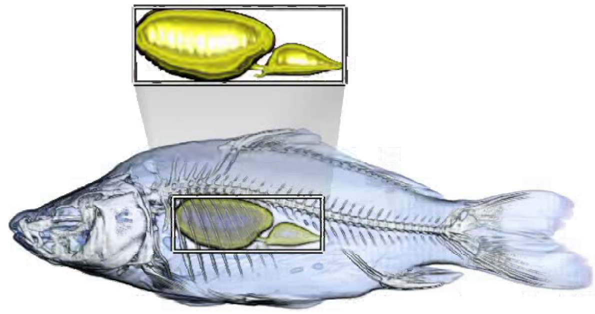
Cut-Away and Ghosted Views



Ivan Viola, Stefan Bruckner and M. Eduard Gröller 26

Ghost and Selection Correspondence



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Labeling

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Availability

www.volumeshop.org

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Outline

- Cut-away and Ghosted Views
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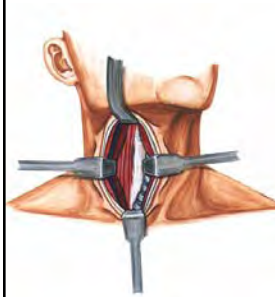
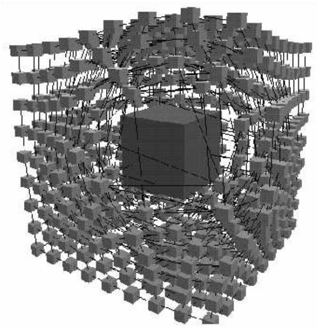
Deformations and Exploded Views




http://www.medigraphics.com/
http://www.khulsey.com/

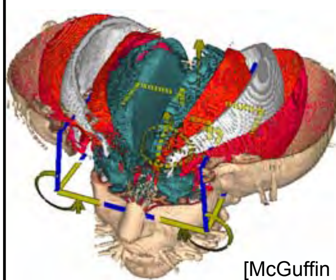
Deformations



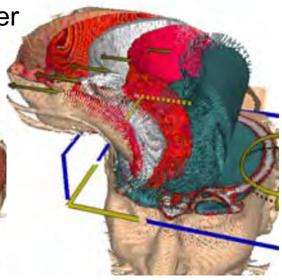
[Carpendale et al. '96]

Browsing Deformations

Leafer



Peeler



[McGuffin et al. '03]

Spatial Exploding

Volume Splitting

[Islam et al. '04]

Dynamic Multi-Volumes

[Grimm et al. '04]

Outline

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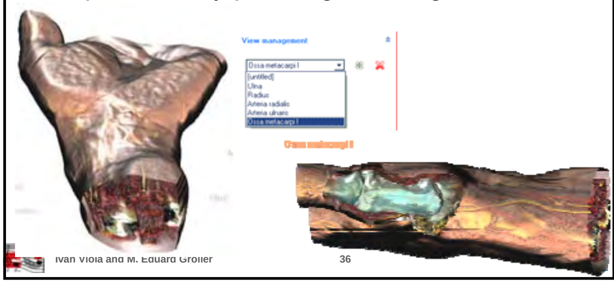
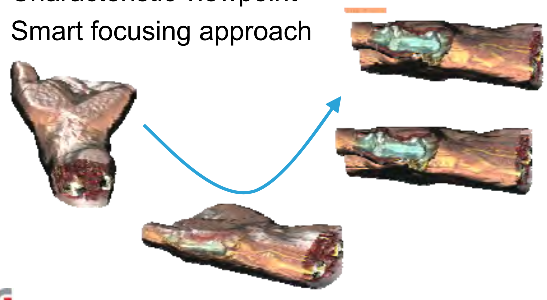
Goal

- Input: known and classified volumetric data
- High level request: show me feature *X*
- Output: visually pleasing focusing at *X*



Focusing Considerations

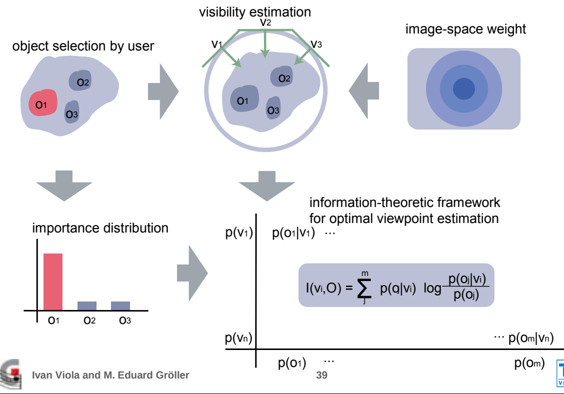
- Focus discrimination
- Characteristic viewpoint
- Smart focusing approach



Visual Focus Discrimination

- Levels of sparseness
  - Dense for focus to visually pop-out
  - Sparse for context visually suppressed
- Cut-aways to unveil internal features

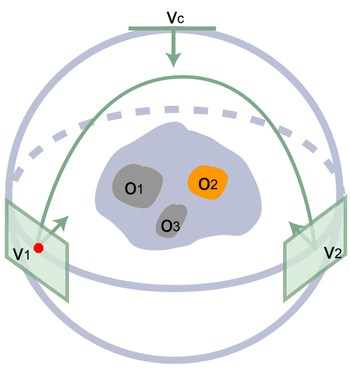
Estimation of Characteristic Viewpoints

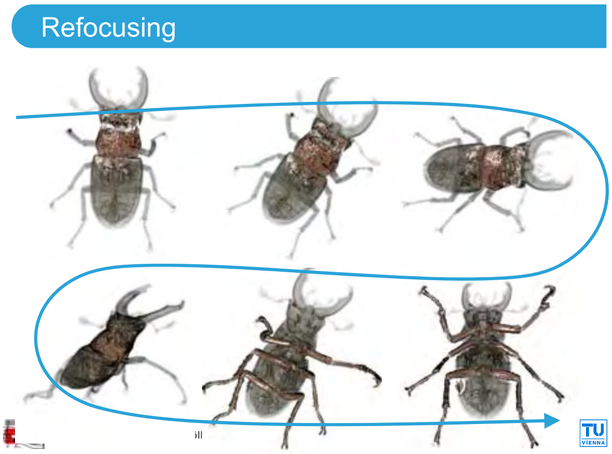


Guided Navigation

- Focusing at feature *X*
  - Discrimination of *X* from context
  - Change to a characteristic viewpoint of *X*
- Refocusing from feature *X* to feature *Y*
  - De-emphasis of feature *X*
  - Emphasis of feature *Y*
  - Change to *general* characteristic viewpoint
  - Change to characteristic viewpoint of *Y*

Refocusing

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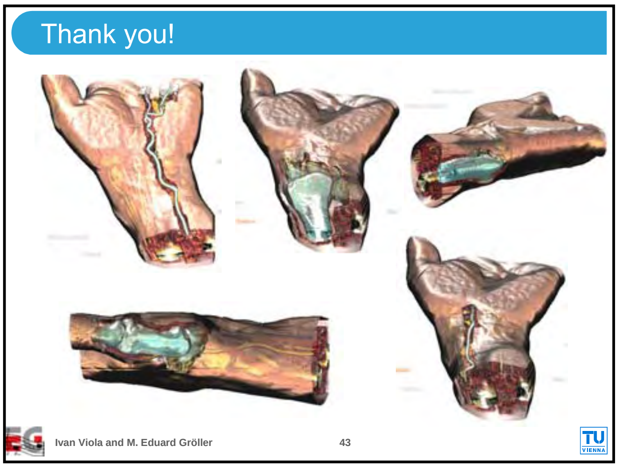
Thank you!
Ivan Viola and M. Eduard Gröller
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Computational Aesthetics in Graphics, Visualization and Imaging (2005)
L. Neumann, M. Sbert, B. Gooch, W. Purgathofer (Editors)

Smart Visibility in Visualization

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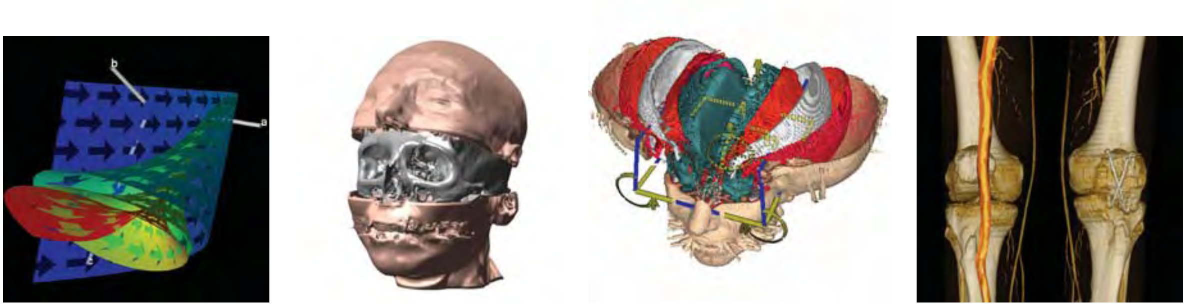


(a) (b) (c) (d)

Figure 1: *Examples of smart visibility visualizations: cut-away view of a complex dynamical system [LMG97] (a), volumetric splitting [IDSC04] (b), feature browsing by leafer deformation [MTB03] (c), and cut-away view of peripheral arteries [SvC*04] (d).*

Abstract

In this paper we discuss expressive visualization techniques that smartly *uncover the most important information in order to maximize the visual information in the resulting images. This is achieved through dynamic changes in visual representations, through deformations, or through spatial modifications of parts of the data. Such techniques originate from technical illustration and are called cut-away views, ghosted views, and exploded views. These illustrative techniques unveil the most important visual information by employing high levels of abstraction. The change in visual representation or spatial position is done easily perceivable and the overall visual harmony is preserved.*

1. Introduction

Illustration has always been an important visual communication medium for humans. The origin of illustration can be found in the Paleolithic period (30000 B.C. to 10000 B.C.) The cave paintings from this period display mostly large wild animals and tracings of human hands. Drawings of humans are rare and are usually schematic rather than the more naturalistic drawings of animals.

Hierogyphs as the visual language developed in ancient Egypt (3200 B.C. to 30 B.C.), depicted religious, political, and daily life. The line is the most important element in Egyptian paintings. All visual elements are delimited by black lines. It is generally accepted that Egyptians did not use perspective. They just used hierarchic perspective in their early profile drawings. Through overlapping they tried to convey the idea of depth. Some scenes with sets of overlapping people depict workers involved in the seeding of the fields.

Like the drawings of the ancient Egyptians, the architectural drawings of the early Greeks (1100 B.C. to 100 B.C.) also lacked perspective. To imitate this kind of art in architecture, the ancient Greek architects even designed their buildings to visually counterbalance the viewer's in-

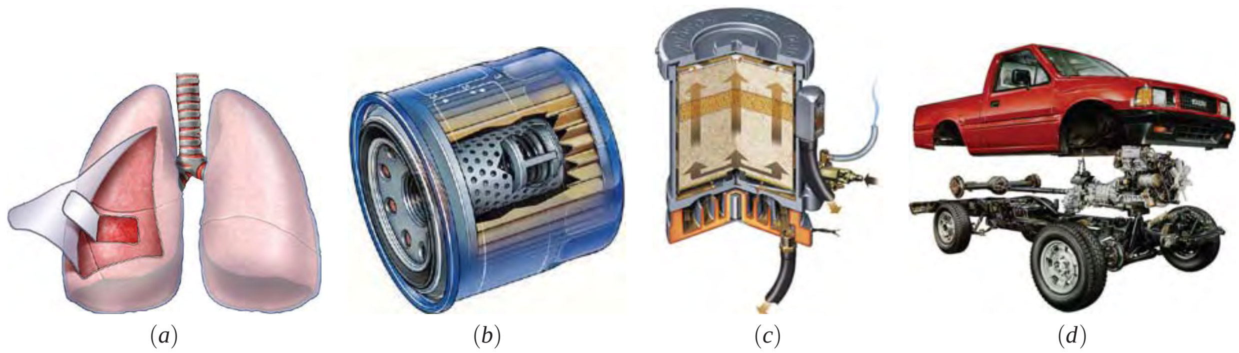


Figure 2: *Different types of hand crafted expressive illustrations: cut-away view (a), ghosted view (b), section view (c), and exploded view (d). Technical illustrations are courtesy of Kevin Hulsey Illustration, Inc [Hul05].*

tuitive understanding of perspective. A typical example is the Parthenon in Athens, which was situated at the top of the Acropolis compound. The Parthenon could only be approached from one access point. The rear of the structure is bigger and wider than the front, and the side columns increase in mass from front to rear. This construction technique gave the Parthenon an appearance through which it approximated the flat or axonometric views the Greeks were used to see in their art.

The principle of perspective was defined in the year 1000 A.D. by the Arabian mathematician and philosopher Alhazen [Oma77]. He explained in his work that light projects conically into the eye. A method for perspectively projecting a scene onto an image was developed approximately 300 years later during the Renaissance period. In this period the beginning of descriptive technical illustrations took place through the work of artists such as Leonardo da Vinci (1452-1519). In da Vinci's personality artistic abilities were combined with a scientific mind, which enabled a merging of visual art with invention. The creation of spatial illusions was another major achievement of this period. The evolution of what is called illusionistic perspective happened at that time.

The flourishing of technical illustrations was a direct result of the industrial revolution. Mass production and outsourcing created the need to adopt conventions and standards in technical illustrations that were universally understood. By the mid 1900s both artistic and technical illustrators had a predictable methodology available for illustrating objects and environments more realistically. Illustrative techniques are often designed in a way that even a person with no technical understanding clearly understands the piece of art. The use of varying line widths to emphasize mass, proximity, and scale helped to make a simple line drawing more understandable to the lay person. Cross hatching, stippling, and other low abstraction techniques gave greater depth and dimension to the subject matter. Technical illustrations were further advanced during the photorealistic art movement around 1960. Photorealists were often working with photographic slide projections onto canvases. The style is very accurate, with an emphasis on details and it often simulates glossy effects such as reflections in specular surfaces.

By merging technical illustration and photorealism, the technical illustrator could now convey highly complex technical information to someone with little understanding of mechanics or drafting. To further increase the expressivity of illustrations, high level abstraction techniques such as cutaway views or exploded views have been established.

The aim of illustration is to generate expressive images that effectively convey certain information via the visual channel to the human observer. Additionally, illustrators and visual artists in general create images that follow principles of visual harmony such as color combinations, scene composition, contrast, dynamics or other *aesthetical* aspects. Breaking some of these principles may evoke misunderstanding and confusion. Thus, not only expressivity but also the overall visual harmony and aesthetics play a very important role in illustrations. In the next sections we will address high level abstraction techniques and expressive visualization techniques in more detail.

2. Smart Visibility

A typical problem in the visualization of three-dimensional or higher-dimensional data is that the most interesting features are not easily perceivable, because they are occluded by other, less important features. Traditional visualization techniques classify the visual representation of features independently from the viewpoint. The global setting limits viewpoint positions and viewing angles to a range, where the important structures are not occluded by other objects.

An effective way to visualize three-dimensional data and resolve the occlusion of the most prominent information is to take approaches used in technical and medical illustrations [GMS*02, Hod03]. Illustration challenges are very similar in these cases. Illustration techniques such as cut-away views, ghosted views, or exploded views effectively uncover the most important information. This is achieved by changing the level of visual abstraction or modifying the spatial arrangement of features. Figure 2 shows examples of expressive illustrations that enable to see interesting structures. Further excellent illustrations featuring expressive techniques can be found on the referenced websites [How05, Hul05].

Illustration techniques such as cut-aways or exploded views are realized in scientific visualization through *Smart Visibility Techniques*. As done in illustrations, Smart Visibility Techniques use high-level abstractions to capitalize on characteristics of the human cognition. Approaches include local modifications of visual representations (e.g., artificial cuts) or changes in spatial arrangements (e.g., deformations) in order to emphasize the most relevant data. We utilize the term Smart Visibility in two meanings:

- Smart Visibility goes beyond simple visibility calculation. Typically visibility is determined due to the light propagation in a scene. Depending on the spatial arrangement of objects with respect to the viewer the light reflected from certain objects might be (partially) prevented from reaching the viewer. Some of the objects are occluded. Smart Visibility considers more than just light propagation. For example also the relevance of the individual objects is taken into account. An important object might shine through an otherwise occluding object closer to the viewer. In this sense the augmented visibility determination can be called ”smart”.
- Smart Visibility exploits the expertise of the human observer. Let us assume that the viewer already has a preknowledge on the shape of an object. In this case part of the shape can be left away to reveal more interesting inner structures. Due to the viewer’s prior experience with the object he still can mentally complete the object from the partial information he is shown. A prominent example are cut-aways along symmetry axes of highly symmetrical objects. The viewer can easily perceive the entire object by actually just seeing parts of if. In this sense Smart Visibility makes use of the present mental models in ”smart” viewers.

3. Cut-Away Views, Section Views, and Ghosted Views

The popularity of cut-away and ghosted views is demonstrated by the fact that they can be found in all books on technical or medical illustrations [GMS*02, Hod03]. An automatic generation of cut-away and ghosted views for polygonal data was introduced by Feiner and Seligmann [FS92]. They propose a family of algorithms that automatically identify potentially obscuring objects and display them in a ghosted or cut-away view. The proposed algorithms exploit z-buffer rendering. They are suitable for real-time interaction achieved by hardware acceleration. Interactive semi-transparent views, section views, and cut-away views for polygonal data have been recently revised by Diepstraten et al. [DWE02, DWE03]. Semi-transparent views unveil interesting objects obscured by context information through increasing the transparency of the context. Diepstraten et al. propose to adhere to an effective set of rules for the automatic generation of the discussed illustrative techniques. For semi-transparent illustrative views the following three rules should be taken into consideration:

- faces of transparent objects never shine through
- objects occluded by two transparent objects do not shine through
- transparency falls-off close to the edges of transparent objects

For section views and cut-away views they propose to follow seven other rules:

- inside and outside objects have to be distinguished from each other
- a section view is represented by the intersection of two half spaces
- the cut-out of a section view is aligned to the main axis of the outside object
- an optional jittering mechanism is useful for cut-outs
- a mechanism to make the walls visible is needed
- cut-outs consist of a single hole in the outside object
- interior objects should be visible from any given viewing angle

The mentioned algorithms and rules for cut-away views, section views, and ghosted views have been applied to polygonal data and are generally applicable in computer graphics. For an arbitrary clipping of volumetric data Weiskopf et al. [WEE03] propose a number of effective techniques to increase performance and visual quality. The implementation of clipping operations is mapped to commodity graphics hardware to achieve interactive framerates. Additionally to clipping all rendering computations are performed on the graphics hardware. Per-fragment operations estimate on-the-fly the visibility according to the clipping geometry and adjust the shading in areas where clipping occurs. In the following Sections 3.1 and 3.2 we focus more on visualization related tasks. First we will discuss an approach for automatic cut-away and ghosted views from volumetric data [VKG05]. This technique employs additional information about the importance of a particular feature. Afterwards we will show the potential of such expressive views with a set of applications.

3.1. Importance-Driven Feature Enhancement

Traditionally features within a volume dataset are classified by optical properties like color and opacity. With

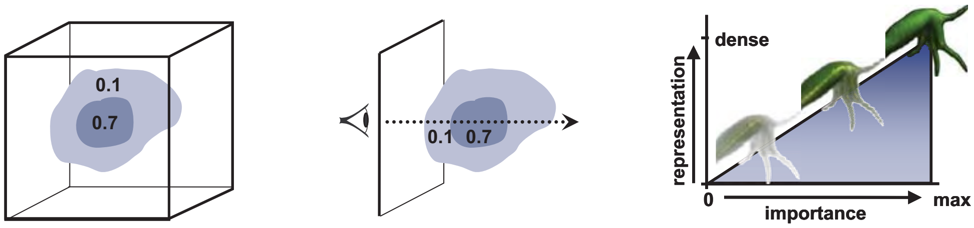


Figure 3: *Stages in the pipeline of importance-driven volume rendering: Volumetric features are assigned importance values (left image). The volume is traversed (center) in the importance compositing stage to estimate levels of sparseness (right). These levels are used to enhance or suppress particular parts of the volume. The resulting images then emphasize important features.*

importance-driven feature enhancement we additionally assign one more dimension to features, which describes their importance. Importance encodes which features are the most interesting ones and have the highest priority to be clearly visible. Prior to the final image synthesis, the visibility of important features is estimated. If less important objects are occluding features that are more interesting, the less important ones are rendered more sparsely, e.g., more transparently. If the same object does not cause any unwanted occlusions in other regions of the image, it is rendered more densely, e.g., opaque, in order to see its features more clearly. This allows to see all interesting structures irrespective if they are interior or not, and the less important parts are still visible as much as possible. Instead of using constant optical characteristics, which are independent from the viewpoint, we use several levels of sparseness for each feature. Levels of sparseness correspond to levels of abstraction. We do not assign a single optical characteristic, but several characteristics with smooth transitions in between. These multiple levels of sparseness allow the object to continuously change its visual appearance from a very dense representation to a very sparse one. Which level of sparseness will be chosen, is dependent on the importance of the particular object and the importance of objects in front and behind. The level of sparseness thus may continuously vary within a single feature. For different viewpoints the same part of a feature may be represented with different levels of sparseness. To determine the sparseness level for each object or parts thereof the rendering pipeline requires an additional step, which we call importance compositing. This step evaluates the occlusion according to the viewpoint settings, takes the importance factor of each feature into account and assigns to each feature a particular level of sparseness. The final synthesis results in images with maximal visual information with respect to the predefined object importance. The interrelationship between object importance, importance compositing, and levels of sparseness is depicted in Figure 3. Importance compositing traverses the whole volume to identify object occlusions and assigns the corresponding level of sparseness to each object. Object importance translates to object visibility in the result image. This causes different rendering settings for the context object (with importance *0.1*) in the area of the image which is covered by the focus object (importance *0.7*).

Figure 4 shows a cut-away view of the multi-dimensional volumetric data of hurricane Isabel using importance-driven feature enhancement. The important feature was the hurricane eye selected through a cylindrical proxy geometry. Inside the cylinder the total precipitation mixing ratio is visualized. Thanks to the cut-away view it is possible to have a clear view at this property close to the eye of the hurricane. Outside the cylinder is the context area where the total cloud moisture is visualized.

Figure 4: *Cut-away visualization of a multidimensional volumetric data of hurricane Isabel.*

Figure 5 illustrates a ghosted view of the scalar volumetric data of a Leopard gecko. The small internal structure (in yellow) of the Leopard gecko dataset is the most interesting information and has been pre-segmented. The body is considered as context information. In the area of occlusion the visual representation of the gecko body is reduced to contours to have a clear view on the interesting internal organ.

3.2. Applications of Expressive Visualizations

Expressive visualizations inspired by illustration techniques are useful for various visualization tasks. Straka et al. [SvC*04] are applying a cut-away technique for CT-angiography of peripheral arteries in human legs. The goal is to have a clear view on the vessels, which are partially segmented by their centerline. For a clear understanding of the spatial arrangement it is necessary to visualize also bones and skin contours. To have an unobstructed view on the vessel for each viewpoint it is sometimes necessary to perform

Figure 5: *Ghosted visualization using contours in a CT scan of a Leopard gecko.*

(*a*) (*b*)

Figure 7: *Medical illustration of a human hand (a) compared to the visualization of a human hand using a dynamic opacity approach as a function of the specular highlight [BGKG05] (b).*

a cut in the bone. To avoid potential misinterpretations, the cut is clearly depicted as an artificial and sharp change in the data. This is illustrated in Figure 1 (d).

Krueger et al. [KTH*05] incorporate smart visibility to improve the spatial perception of feature arrangement for surgical planning. They present a system for neck dissection planning, where the lymph nodes are emphasized using ghosted views to easily convey their spatial position. Other features such as muscles or bones are suppressed either locally or globally. They are represented in a sparse way to support the understanding of the feature arrangement. The neck dissection planning system is designed for interactive path-planning in minimal invasive interventions. Figure 6 clearly shows all lymph nodes in the neck to enable optimal path planning for the neck dissection.

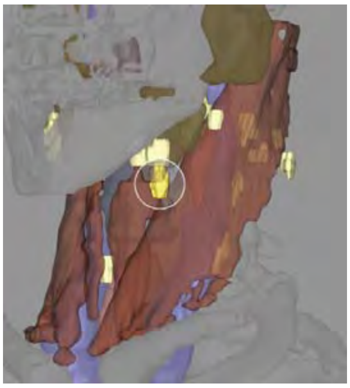


Figure 6: *Smart visibility of lymph nodes in the neck. All lymph nodes are clearly visible, the currently analyzed one is additionally emphasized by a circle around it.*

An extension to direct volume rendering that focuses on implicitly increasing the visibility of features has been proposed by Bruckner et al. [BGKG05]. This technique is known as illustrative context-preserving volume rendering. The approach maps transparency to the strength of specular highlights. This allows to see *inside* the volume in the areas of highlights. The human visual system can easily complete the shape of partially transparent parts and therefore additional information can be shown there. One parameter tunes the ratio between specularity and transparency. A depth parameter determines how far one can look inside a volumetric object (fuzzy clipping). Certain data-value ranges can be excluded from the transparency modulation to allow a clear view on specific (inner) structures. In Figure 7 Their approach is compared to a medical illustration of a human hand.

An interactive tool for cut-away and ghosting visualizations has been recently proposed by Bruckner et al. [BG05]. The tool denoted as VolumeShop is an interactive system which features advanced manipulation techniques and illustrative rendering techniques to generate interactive illustrations directly from volumetric data. The system is using latest-generation texture-mapping hardware to perform interactive rendering applying various kinds of rendering styles. It implements a multi-volume concept to enable individual manipulations of each volume part. The segmentation of the volumetric objects can be done directly via 3D painting. Apart from importance-driven visualization resulting into cut-away and ghosted views, VolumeShop includes a label management to introduce basic descriptions for the visualized data. To focus on a particular feature, it can be moved from its original spatial position. To indicate its original spatial position it is possible to display a *ghost* there, or add additional markers such as *fanning* or arrows. Some ghosted visualizations generated using VolumeShop are shown in Figure 8.

Previous applications of cut-away views are viewpoint-dependent, i.e., the shape and location of the cut is directly dependent on the viewpoint information. Volume cutting is another medical visualization technique that is related to cut-away views, but the cut shape is not influenced by viewpoint settings. Pflesser et al. [PPT*02] present an interac-

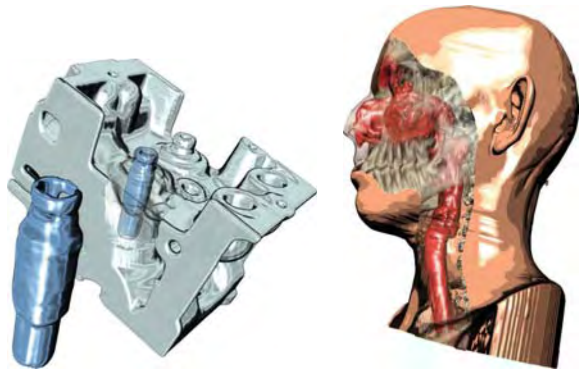


Figure 8: *Interactive ghosted visualizations of the engine block and human head datasets [BG05].*

tive drill-like tool for surgical training, which is based on a multi-volume concept. Owada et al. [ONOI04] extend volume cutting by incorporating two-dimensional textures that are mapped on the cut surface. This enhances the visualization with additional information of the internal arrangement of bones or muscles. Such a concept can be very useful for anatomy education for example. Both volume cutting techniques are illustrated in Figure 9.

Visualization of complex dynamical systems can also be enhanced by applying cuts to stream surfaces. Streamarrows proposed by Löffelmann et al. [LMG97] exploit cutting for enhancing the visual information. They use arrows as a basic element for cutting away part of the stream surface. This allows to see through the surface and perceive other surfaces or structures behind. Animating streamarrows along the stream surface enables to see beyond the front stream surfaces and perceive the flow direction. Streamarrows belong to the category of view-point independent cut-away techniques and are shown in Figure 1 (a).

Figure 9: *Volume cutting featuring two-dimensional textures for anatomy education [ONOI04] (left) and volume cutting with a drill-like tool for surgical education [PPT*02] (right).*

4. Exploded Views and Deformations

Exploded views and deformations modify the spatial arrangement of features to uncover the most prominent ones. It is also a very effective way to present assembly instructions. Exploded views enable a clear view on individual features and convey the information about the original spatial location by helpers such as lines or arrows. Agrawala et al. [APH*03] proposed design principles for creating effective assembly instructions based on exploded views. They additionally present a system for the automatic design of assembly instructions and a system that semi-automatically generates exploded views from two-dimensional images [LAS04]. The rules for assembly instructions are based on cognitive psychology and experiments:

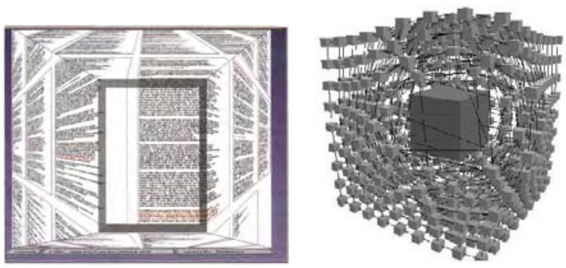
- assembling is decomposed into a hierarchy of operations and parts
- parts in the same hierarchy (e.g., legs of a chair) have to be added at the same time-step, or in sequence one after another
- step-by-step instructions are better understandable than a single diagram showing all the operations
- diagrams presenting the final assembly are necessary to understand the step-by-step action diagrams
- parts added in the current assembly step must be clearly visible
- objects have to be presented in their clearest orientation

Smart-visibility visualizations are using some of the above mentioned rules for other tasks than assembly instructions. In the following visualization approaches are presented that have been inspired by the exploded views concept. They implicitly use some of the rules for assembly instructions.

4.1. Applications of Expressive Visualization

Information visualization is a field where deformations in visual data representation are rather wide spread. Information visualization is often concerned with the display of large, multi-dimensional, abstract data. In this area focus+context techniques are crucial to emphasize the small amount of relevant information among the typically very large overall data with multiple dimensions.

There are a lot of techniques that incorporate a kind of distortion for important feature emphasis. Typical representatives are magic lenses, fish-eye views, or perspective wall displays. These techniques allow to *zoom* into the data and to discriminate the focus data from the context data. An example of a magic lens applied to a document is shown in Figure 10 (a).



(a) (b)

Figure 10: *Information visualization examples using the smart visibility concept: lens metaphor for easier document browsing [RM93] (a) and viewpoint-dependent distortions of three-dimensional graphs [CCF96] (b).*

One technique that relates especially to smart visibility performs viewpoint-dependent distortion of three-dimensional data. This technique highlights data by dedicating more display space to it [CCF96]. Distortions are applied to abstract graphs in order to clearly see interesting graph nodes. All nodes originally occluding the focus node are moved away to uncover the most relevant information as shown in Figure 10 (b). Similar concept has also been recently proposed for exploration of scalar volumetric data [WZMK05].

Volume splitting is a scientific visualization technique that is closely related to exploded views [IDSC04, GBKG04]. This technique is intended for displaying multiple enclosed iso-surfaces within the volumetric data. Each iso-surface, except the innermost one, is split into two parts and moved apart. Such splitting is denoted as logical splitting. Another type is geometrical splitting which moves apart the two halves of the entire volume. Logical splitting is illustrated in Figure 1 (b).

McGuffin et al. [MTB03] propose an elaborate framework with a set of advanced deformations for an understandable visual presentation of complex three-dimensional information. Browsing is investigated as the operation for investigating the interior of a volume. Browsing is realized on pre-segmented data decomposed into several semantic layers (e.g., skin, muscle, skull, brain). The user can cut into and open up, spread apart, or peel away parts of the volume in real time. This makes the interior visible while still retaining surrounding context. Additionally they present a set of interaction techniques based on various metaphors. Interaction techniques are controlled by pop-up menus and three-dimensional widgets. The interaction technique using leafing deformation is shown in Figure 1 (c).

Another interesting visualization technique inspired by exploded views is called fanning in time [GBKG04]. It is a temporal exploded view analogous to temporal exploded views from illustration or multiple exposure photographs. In photography and digital image processing this technique is known as computer enhanced multiple exposure numerical technique (CEMENT). It is useful for the visualization of time-series with a relatively small number of time-steps. The main goal is to show all time-steps in one image similar to illustrative photographs of for example a skateboarder performing a certain motion sequence. Figure 11 illustrates the idea of fanning in time and the correspondence to illustrative photography.

Figure 11: *Illustrative photography of a snowboarder performing a jump (top). Photography expressively displays the principle of a particular motion sequence (Image is courtesy of snowboarder Matúš Hubka). Fanning in time (bottom) shows all time steps of a time-varying dataset of a beating heard [GBKG04].*

5. Conclusions

In this paper we have presented smart visibility visualization techniques inspired by strategies from high level abstraction approaches in traditional illustration. We have shown that many challenging visualization tasks can be solved by adopting existing techniques from visual arts. Computer generated visualization still needs improvement to compete with hand crafted illustrations in terms of expressivity, harmony, or aesthetics. Therefore the aesthetical aspect of scientific visualizations will be an intensively researched area in the scope of illustrative visualization in the future.

A considerable advantage of scientific visualization as compared to traditional illustration is the possibility of real-time interaction and manipulation. The effective combination of expressive visualization techniques with appropriate interaction tools conveys the information from complex scientific data much better than a static image.

6. Acknowledgments

The work presented in this publication is carried out as part of the ex**vis**ation project (`www.cg.tuwien.ac.at/research/vis/exvisation`) supported by the Austrian Science Fund (FWF) grant no. P18322.

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Importance-Driven Feature Enhancement in Volume Visualization

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(Invited Paper)

Abstract— **This paper presents importance-driven feature enhancement as a technique for the automatic generation of cut-away and ghosted views out of volumetric data. The presented focus+context approach removes or suppresses less important parts of a scene to reveal more important underlying information. However, less important parts are fully visible in those regions, where important visual information is not lost, i.e., more relevant features are not occluded.**

Features within the volumetric data are first classified according to a new dimension denoted as *object importance*. This property determines which structures should be readily discernible and which structures are less important. Next, for each feature various representations (*levels of sparseness*) from a dense to a sparse depiction are defined. Levels of sparseness define a spectrum of optical properties or rendering styles. The resulting image is generated by ray-casting and combining the intersected features proportional to their importance (*importance compositing*).

The paper includes an extended discussion on several possible schemes for *levels of sparseness* specification. Furthermore different approaches to *importance compositing* are treated.

Index Terms— **view-dependent visualization, volume rendering, focus+context techniques, level-of-detail techniques, illustrative techniques**

I. Introduction

THE relevance of volume visualization in medical applications has been increasing over the last years. Three-dimensional visualization is becoming an essential tool for medical diagnosis and operation planning. Due to the rapid development of high-precision imaging modalities the amount of data is steadily increasing. The amount of relevant information is often relatively small as compared to the overall amount of acquired data. Therefore these small, interesting features have to be visually emphasized. Examples are tumors in the kidneys, lesions inside the liver, and lung nodules. Diagnostic examinations are complex tasks, where properties of the anatomical tissues have to be taken into account. In addition to the size and shape of pathologies also their spatial position and vicinity to other anatomical structures is of interest. Hence, from a computer science point of view it is a focus+context task.

The detection of liver lesions illustrates the medical requirements on the applied visualization method. Medical experts need to see the tumor from several directions in order to estimate the shape of the lesion. Furthermore the spatial position of arteries in close vicinity is very important in order to determine which liver segments must be removed in a possible subsequent surgical treatment. The visualization task is to display three different structures: the tumor, the vessel tree of the liver, and the liver parenchyma. However, displaying these structures simultaneously results in objects occluding each other. Traditional techniques classify objects within the dataset independently from the viewpoint. The global setting limits viewpoint positions and viewing angles to a range, where the important structures are not occluded by other objects. One possibility is to use clipping planes. Such an approach eliminates less important objects also in those viewing situations, where it would not be necessary. Different optical properties and rendering techniques (i.e., silhouette rendering) ease the problem only to a certain degree and these settings are applied globally. Beside this the fine-tuning of rendering parameters is a time consuming process not suitable for rapid clinical use.

Medical tasks such as visualizing liver lesions can be resolved by *importance-driven volume rendering* (IDVR) [28]. The tumor and the vascular tree in close vicinity are the most important features, the liver tissue and the surrounding anatomy (bones, aorta, skin) are of lower importance but still helpful for orientation purposes. With IDVR the interesting structures are clearly visible from different viewing angles. Occluding objects are rendered more sparsely or suppressed entirely.

The main contribution of this paper is importance-driven feature enhancement as an approach to automatic focus+context volume rendering. The proposed method overcomes the problem of occlusions within the volume,

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which happens when using any kind of view-independent classification. As opposed to previous approaches, the optical properties of the proposed technique are not constant for an entire object. Depending on the viewing situation, the estimated *level of sparseness* varies dynamically. In order to visually emphasize features with the highest importance, occluding objects between these features and the viewpoint are rendered sparsely. Interesting objects are represented more densely to see most of the details. If no occlusion occurs, even the less important features can be rendered densely. This enables an automatic generation of images with maximal visual information.

In Figure 1 an anatomical illustration of the human abdomen [12] and a result of our technique is presented. In this case the internal structures are classified with a high importance value so that structures between the viewpoint and the important features are simply cut away automatically.

The paper is organized as follows: Section II describes previous work related to importance-driven volume rendering. Section III explains the basic idea of the proposed model. Sections IV and V discuss the principal components of the model, i.e., *importance compositing* and *levels of sparseness*, and depict their impact on the resulting visualizations. In Section VI we describe the test datasets and show various rendering results applicable for medical and flow visualization. Finally we draw conclusions, summarize the paper in Section VII and propose future work in Section VIII.

II. Related Work

Scientific work related to our model can be divided into several categories. First, methods that use advanced and semi-automatic transfer function specification for feature enhancement are discussed. Our work enables automatic focus+context visualization, where the viewpoint information is taken into account. We therefore point out some previous focus+context approaches. Then, various rendering techniques for *levels of sparseness* specification are reviewed. Finally former work on incorporating cut-away concepts in visualization is mentioned.

Feature Classification: A typical feature classification in volume visualization is done through *transfer function* specification [18]. The transfer function with density as single input parameter is also denoted as one-dimensional transfer function. In recent years the idea of multi-dimensional transfer functions has been introduced. The multi-dimensional concept incorporates first and second derivatives of the density into the transfer function design [11], [17]. It is possible to assign optical

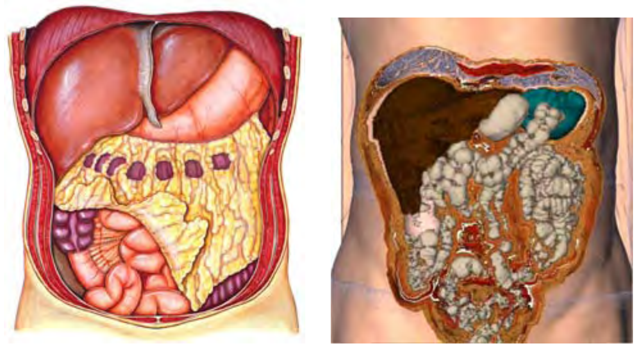

Fig. 1. Comparison between an artistic medical illustration of the abdomen (left) and our method (right).

properties based on gradient and curvature values, so for example object boundaries are classified differently than homogeneous regions. Taking into consideration first and second derivatives enables the semi-automatic generation of transfer functions [16]. An interesting approach was presented by Hauser and Mlejnek [9] for multi-dimensional 3D flow data. They use the *degree-of-interest* function that maps the user interest to optical properties. These concepts, however, define the representation globally, i.e., the visibility of important features is not guaranteed. The lack of adaptation of optical properties to the viewpoint settings is the main drawback of view-independent classifications.

Focus+Context Rendering: Visualization tasks frequently use the focus+context metaphor to clearly differentiate very relevant information from the context. Viewpoint-dependent distortion of three-dimensional data [3], for example, highlights data by dedicating more display space to it. Distortions are applied to abstract graphs in order to clearly see interesting graph nodes. An interesting idea is also to include the *distance to focal point* into the volume rendering pipeline [29]. The optical properties are changing according to the distance to the focal point. Using this technique several expressive focus+context effects can be achieved. Focus+context approaches use viewpoint-independent classification and therefore they have the same limitations as the feature classification methods discussed above.

Gaze-directed volume rendering [19] was an early approach in volume visualization, where the observer's viewing direction was taken into consideration. The motivation in this case was to increase the rendering performance instead of increasing the visual information. The volume dataset is rendered in different resolutions. According to the viewing direction only the focal region is represented in full resolution, and the other parts are rendered in lower resolution.

Sparse Representation: The graphics community has been inspired by artists to represent features sparsely in order to exploit the human imagination. The display of contours is a popular method to thinly represent context information in volume visualization [4], [24]. Outlines are often sufficient to roughly understand the shape and can be combined with other rendering techniques such as direct volume rendering or maximum intensity projection [10]. To make a contour representation more expressive *suggestive contours* can be used [5]. The suggestive contours technique combines contours rendered from a particular viewpoint with contours from other viewpoints close to the current view. Also *pen-and-ink* techniques convey good shape information. Pen-and-ink styles in combination with traditional volume rendering have already been applied for focus+context rendering in volume visualization [26]. This is up to a certain degree similar to the combination of curvature-directed strokes with iso-surface rendering [14]. This approach was proposed for rendering structures that are nested within other objects. The interior structures are rendered fully opaque, while the enclosing objects are represented by a set of curvature-directed lines. Using stippling techniques for volume visualization is another example of inspiration from traditional illustration [21]. The visibility of interior structures can also be modified by dynamic changes in transparency of the outer shape. Recent work proposes to map transparency to the level of specular highlight [2]. This allows to see *inside* the volume in the areas of highlights. Dynamic transparency is also used in the user interface design [8].

Cut-Away Views: Cut-away illustrations are another way to represent nested objects. The popularity of this technique is demonstrated by the fact that it can be found in almost all books with technical or medical illustrations [13]. In volume visualization this technique is also known as *volume cutting* [23]. Automatic generation of cut-away images has been already researched in computer graphics [6], [7]. Straka et al. [25] are applying a cut-away technique for CT-Angiography. For visualizing complex dynamical systems, streamarrows were proposed by Löffelmann et al. [20]. They use arrows as a basic element for cutting away part of the stream surface. This allows to see through the surface and perceive other surfaces or structures behind.

Importance-driven volume rendering (IDVR) has been firstly introduced in our previous work [28]. We have presented a generalized model for view-dependent focus+context tasks in volume visualization. This paper extends the discussion on the key elements of the model: *object importance*, *levels of sparseness*, and *importance compositing*. Furthermore suggestions on feature definition are discussed to overcome the limited applicability to pre-segmented data. IDVR turns out to be helpful not only for changing viewpoints, but also in case of dynamic features.

III. Importance-Driven Volume Rendering

In volume visualization we are often dealing with the problem that interesting structures are partly or completely occluded by surrounding tissue. This is hard to resolve by traditional view-independent approaches, such as transfer function specification. We propose a viewpoint-dependent model that removes unwanted occlusions automatically and maximizes the information content in the final image.

Interesting structures within the volumetric data are denoted as *features* respectively *objects*. The specification can be done in many different ways, also depending on the type of the data. In medical visualization features are often classified as particular organs. Such objects are defined by a segmentation process. Another way of feature classification can be through a spatial relationship within the volume or eventually through the location with respect to another *feature*. In such a way it is for example possible to classify the vortex core of a hurricane. In the case of multi-dimensional volumetric data, features can be defined by specifying interesting ranges of values for each data dimension. There are many other ways to determine features. A detailed treatment of feature definition is outside the scope of this paper.

Traditionally features within the volume dataset are classified by optical properties such as color and opacity. We additionally assign another dimension to features, which describes their *importance*. Importance encodes which features are most interesting and have the highest priority to be clearly visible. Each feature is therefore weighted by a positive scalar value called ***object importance***. During the rendering stage, the model evaluates the visibility of each feature according to its importance. If less important structures are occluding features that are more interesting, the less important ones are rendered more sparsely, e.g., more transparently. If the same object does not cause any unwanted occlusions in other regions of the image, it is rendered more densely, e.g., opaque, in order to see its features more clearly. All interesting structures are visible irrespective if they are covered or not, and the less important parts are still visible as much as possible.

Instead of using constant optical characteristics, which are independent from the viewpoint, we use several ***levels of sparseness*** for each object. We do not assign a single optical characteristic, but several characteristics

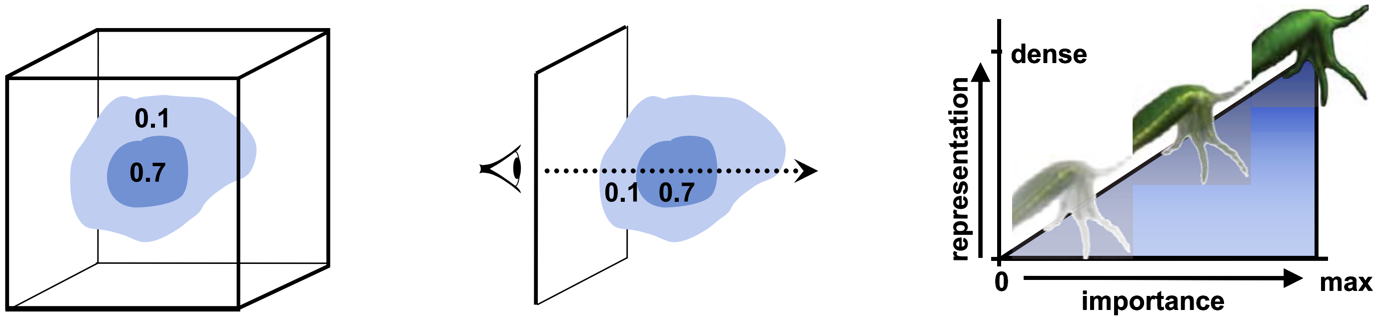

Fig. 2. Basic elements of importance-driven volume rendering: Volumetric features are classified by *importance* values (left). The volume is traversed in the *importance compositing* step (middle). Then *levels of sparseness* are chosen to enhance or suppress particular parts of the volume (right).

with smooth transitions inbetween. These multiple levels of sparseness allow the object to continuously change its visual appearance from a very dense representation to a very sparse one. Which level of sparseness will be chosen is dependent on the importance of the particular object and the importance of objects behind it. The level of sparseness thus may continuously vary within a single object. Also depending on the viewpoint the same part of an object may be represented with different levels of sparseness.

To determine the sparseness level for each object or parts thereof, the rendering pipeline requires an additional step, denoted as ***importance compositing***. This step evaluates the occlusion, takes the importance factor of each object into account and assigns to all objects particular *levels of sparseness*. The final synthesis results in images with maximal visual information with respect to the predefined object importance.

The relationship between the above mentioned components is depicted in Figure 2. *Importance compositing* is done similar to the direct volume rendering (DVR) approach. For each ray the compositing step evaluates object occlusions and assigns the corresponding *level of sparseness* to each object. Object importance is preserved in the sense that it is mapped to object visibility in the resulting image. This causes different rendering settings for the context object (importance value 0.1 in Figure 2) in the area of the image which is covered by the focus object (importance 0.7).

The difference between traditional volume rendering and importance-driven volume rendering is clearly visible in Figure 3. The goal is to emphasize the inner organ as focus object. In the traditional approach it is necessary to reduce the opacity of occluding objects globally. Importance-driven rendering assigns a higher sparseness factor only to the area where occlusion occurs.

IV. Importance Compositing

Importance compositing is an additional pass added to the traditional volume-rendering pipeline. It determines the level of sparseness for each object or a part thereof in order to preserve important features. There are many possibilities conceivable how to perform importance compositing. In the following we will discuss three methods of importance compositing, which are inspired by compositing optical properties through ray casting of volume data.

A. Maximum Importance Projection

Maximum intensity projection (MIP) [22] is a simple and fast volume rendering approach. It is applicable for sparse data where important information has high intensity values such as contrast-media enhanced blood vessels. With MIP compositing reduces to selecting the highest intensity value along a ray. Intensities are encoded as gray values to produce the final image.

Analogous to MIP we propose maximum importance projection (MImP). For each ray the object with highest importance along the ray is determined. This object is displayed densely. All the remaining objects along the ray are displayed with the highest level of sparseness,

Fig. 3. Comparison between traditional volume rendering (top) and importance-driven volume rendering (bottom).

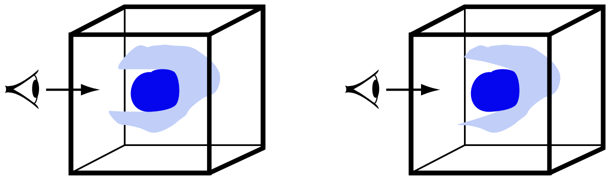

Fig. 4. Maximum Importance Projection. Illustration of cylindrical (left) and conical countersink (right).

i.e., fully transparent. With MImP structures are either rendered using the most dense representation or they are not rendered at all.

With MIP the spatial arrangement of structures is not readily apparent. MImP has a similar problem which we alleviate as follows: The image area, where the most important object is projected onto, is denoted as object *footprint*. With MImP the footprint is exactly the image region where only the focus object is visible. One can consider MImP as a cut-away view, where the space in front of the most important object is simply clipped. The clipping region is a translational sweep with the footprint as cross section (general cylinder). One can now modify this cylinder to obtain a clipping frustum. This is achieved by scaling up the footprint during the translational sweep towards the viewer. This produces a countersink clipping geometry. Figure 4 illustrates the difference between the cylindrical and conical MImP in 2D. The conical MImP is easily realized during ray traversal by changing the starting point for those rays that intersect the side faces of the clipping frustum. Figure 5 shows images to compare both approaches. The cylindrical MImP does not clearly show the spatial relationship between focus and context objects, i.e., the focus object appears in front of the context object. Conical MImP corrects this visual artifact.

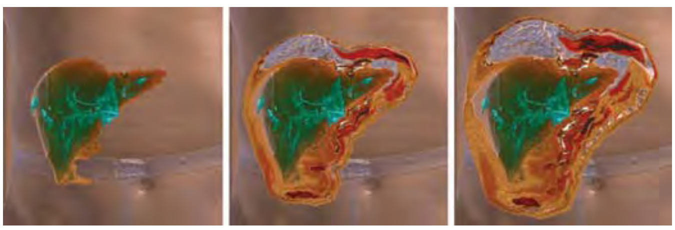

Fig. 5. Maximum importance projection (MImP). Cylindrical MImP (left) and conical MImP with different slope factors (middle and right).

The countersink geometry, respectively the ray starting points are computed from the footprint of the focus object. The footprint contains depth information of the focus object's *last hit* for each ray along the viewing direction. This information is used for performing the cut-out. For cylindrical MImP we simply skip ray samples that belong to the context object, until the focus object's last hit depth is reached. For the conical MImP we need to enlarge the footprint to build the conical shape. This is realized using image processing operators on the depth image, where the intensity encodes the depth of the entry point. The depth-footprint is processed by a 2D chamfer distance transform [1]. First e_{max} the highest depth value of the footprint is calculated. The starting points e_i of the rays that pierce the countersink are calculated from e_{max}, the slope s_c of the countersink, and distance d_i as shown in Equation 1:

$$e_i = e_{max} - d_i * s_c \quad (1)$$

d_i denotes the image space distance from pixel i to the footprint.

To correctly simulate the cut-out it is necessary to change the gradient vector of the ray entry points at the countersink geometry. Two components of the gradient are estimated from the gradient information of the 2D distance field. The z component is constant, i.e, the *slope* s_c of the countersink frustum.

B. Average Importance Compositing

The second approach of importance compositing takes into account all the objects along a ray. The influence of an individual object is hereby independent from the number of ray samples within the object. An object o has an importance value I_o. Ray r intersects n_r objects. The level of sparseness S_o of a particular object o at ray r is equal to the fraction of its own importance and the sum of the importance of all the intersected objects:

$$S_o = \frac{I_o}{\sum_{i=1}^{n_r} I_i} \quad (2)$$

Average importance compositing (AImC) does not completely remove the less important objects as with MImP. The sparseness factors are estimated according to the given importance. This allows a very sparse representation of the occluding object to see a rough structure of the shape and to clearly see the important object behind it. The importance compositing stage computes the levels of sparseness of all objects for every pixel in the final image. Levels of sparseness are computed using the object footprints. At each pixel position we perform a lookup to each object footprint. Object importance values of all objects that cover the current pixel position are summed up. The sparseness factor of each of these objects is estimated through division of their object importance by the evaluated sum (Equation 2).

The final image synthesis using AImC is an extension to traditional DVR. At each sample location during ray traversal the level of sparseness additionally modulates the visibility of the sample. Similar to cylindrical MImP, AImC generates images where the spatial arrangement of structures is not readily apparent. In order to improve spatial perception we propose two methods to perform final importance-driven image synthesis using AImC, i.e., an image-space and an object-space approach.

Image-Space AImC: The object footprints introduce sharp transitions in levels of sparseness, which might reduce spatial perception. To improve the spatial perception we generate smooth transitions between different levels of sparseness. Before the levels of sparseness are computed for each object, we apply image processing operators to every footprint, i.e., dilation and averaging. As pixels in the footprint have a weight of one, the weights in the generated transition zone are smoothly decreasing to zero. The levels of sparseness estimation is analogous to Equation 2. For each pixel we compute the footprint-weighted importance sum of all contributing objects. The object importance is in this case always multiplied by the footprint value in the range of $[0, 1]$. Footprint values below one are part of the *transition* area between different levels of sparseness.

The image-space approach does not evaluate whether the sample of a suppressed context object is in front or behind the important object. The level of sparseness is constant for all samples of an object along a particular ray. This means that also part of the context object *behind* the focus object is suppressed.

Object-space AImC: To avoid suppression of context behind the focus object, we propose a more costly object-space approach. Using this approach only those samples of the context object are suppressed that are *in front* of the focus. In this case the level of sparseness is not constant for an object along a particular ray. The difference between the image-space and the object space approach is illustrated in Figure 6. The Figure shows that image-space AImC suppresses all context samples along a ray. The object space approach suppresses only the part of the context object that occludes the focus object.

The image synthesis of the object space approach is analogous to the conical MImP. In the case of the conical MImP the countersink geometry is used to estimate the starting position of the ray in order to perform the cut-out. In object-space AImC the countersink geometry defines the border between different levels of sparseness. The starting position of the ray is not changed. During the ray traversal in the final image synthesis, each sample location is evaluated whether it *belongs* to the countersink region or not. The context outside the countersink is depicted with a more dense representation and inside a more sparse form is chosen.

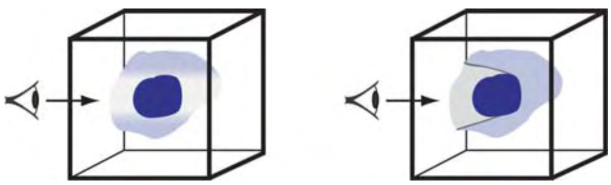

Fig. 6. Average importance compositing (AImC). The illustration depicts the difference between the image-space (left) and object space approach (right).

Results of each approach are shown in Figure 7. The images show the same dataset under different viewing angles. The top row illustrates the image-space approach and the bottom row the object-space approach.

The AImC approach preserves the *thickness* of the occluding part of the context object. This leads to different visibilities of the focus object under different viewing conditions. If the occluding context area is too thick, the focus object is not visible enough. In order to see the focus object properly the level of sparseness function has to be changed for the context object or the importance of the focus object has to be increased. The following Sub-section describes how to automatically overcome the problem a of varying thickness of the occluding object.

C. Visibility Preserving Importance Compositing

Visibility preserving importance compositing (VPImC) guarantees constant visibility of the focus object. Independent from the thickness of the context in front of the focus a constant fraction of visibility is reserved for the focus object. For example under some viewing angle the context object may be *thin* and samples can be represented more densely. Under a different viewing angle the context object may be *thicker* in front of the focus object. Therefore samples that belong to this area should be more transparent. This is illustrated in Figure 8. The suppression of the context varies according to the *thickness* of the context, therefore the visibility of the focus remains constant.

The values for levels of sparseness using VPImC are estimated in the same way as with AImC (Equation 2). In AImC the levels of sparseness are selected for each sample during ray-traversal. With VPImC we select an appropriate level of sparseness *after* the ray-traversal stage. The level of sparseness is determined as follows: The level of sparseness for the context object in front of the focus object shall be S_o. In VPImC the goal is to adjust the *average* accumulated opacity of the occluding region to be equal to the value S_o. Therefore the context part in front of the focus is rendered separately. All ray opacities of the occluding part are summed together to

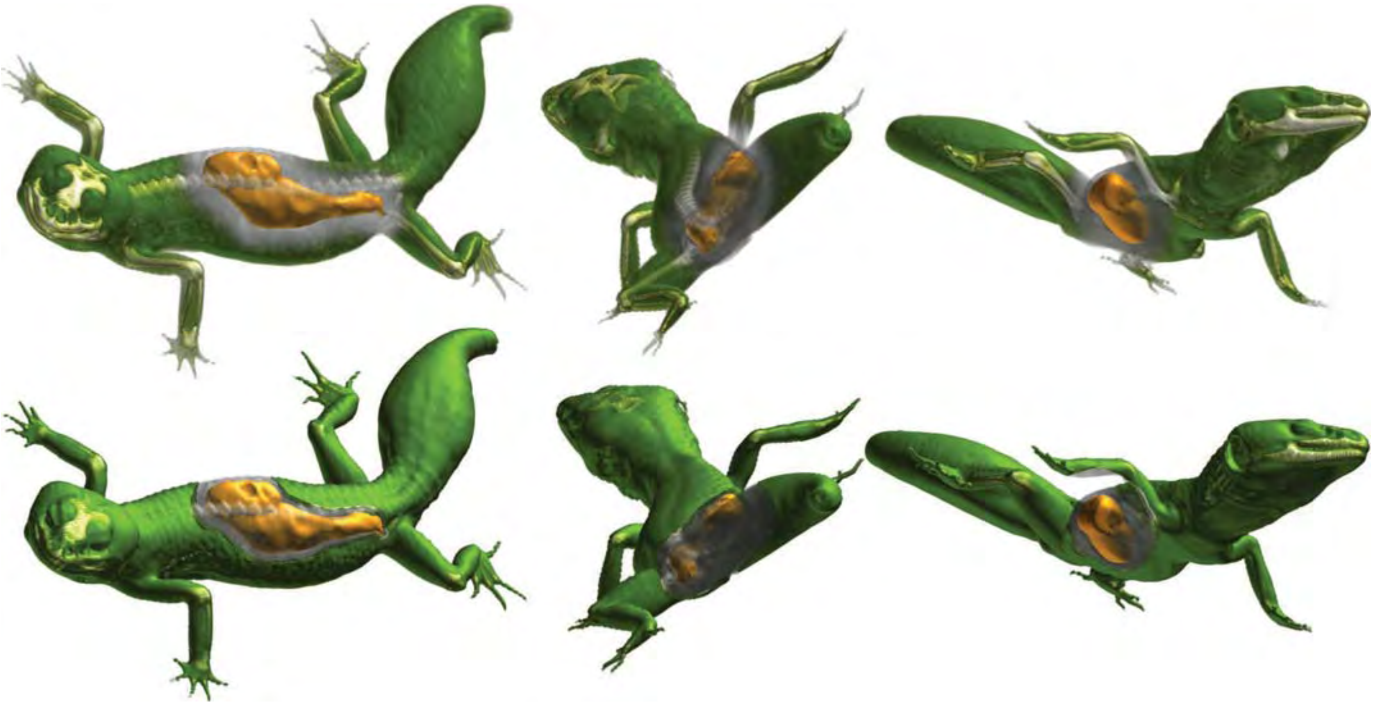

Fig. 7. Average importance compositing (AImC) is shown under different viewpoint settings in combination with modulating optical properties. The upper row shows image based AImC. The bottom row shows the object space approach with the same viewpoint settings.

compute the average per-ray opacity α_{avg}. To preserve the constant visibility of the focus object the average per-ray opacity has to be equal to S_o. Therefore for each ray, the accumulated opacity value is corrected. This is expressed by the Equation 3:

$$\alpha_{accum\_new}(x) = \alpha_{accum}(x)\frac{S_o}{\alpha_{avg}} \qquad (3)$$

where α_{accum_new} is the modified accumulated opacity of the suppressed context part, α_{accum} is the original accumulated opacity value, S_o is the level of sparseness value of the context object and α_{avg} is the average accumulated opacity value of the entire suppressed context part.

The separate rendering of the occluding part is done using two level volume rendering [10] (2lVR). Every object or a part thereof (as in the case of the context object) is rendered separately in a *local compositing step*. Then the *visibility correction* is done for the occluding part. Finally a combination of both context parts takes place in the *global compositing step*. A more detailed discussion on 2lVR follows in Sub-section V-D.

Figure 9 shows the results of the compositing under different viewpoint settings. It offers a comparison to the importance compositing technique shown in Figure 7 (described in Section IV-B). Especially in the middle images of Figure 7 a large occluding context region considerably reduces the visibility of the focus object. This is not the case in Figure 9 (middle image.)

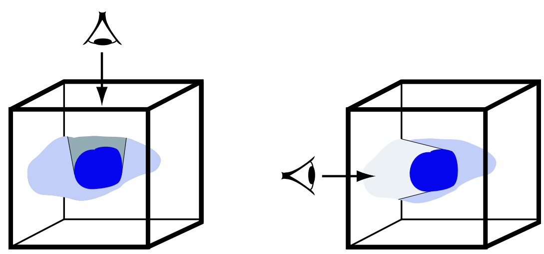

Fig. 8. Principle of visibility preserving importance compositing. Constant visibility allows a denser thin context (left) and requires a sparser thick context (right).

V. Levels of Sparseness

Importance compositing determines for each part of an object its visibility in the rendered image. This is achieved by determining the appropriate level of sparseness. In the following four types of levels of sparseness are described. Three of those are depicted in Figure 10. The series of images illustrates how the context area in front of the focus object smoothly varies from a dense to a sparse representation.

A. Color and Opacity Modulation

A direct control of optical properties is the first approach to modify the visual prominence of a particular

Fig. 9. Visibility preserving importance compositing (VPImC). The dataset is shown under different viewpoint settings with constant visibility of the focus object. Focus visibility is independent from the thickness of the occluding context part.

feature. With increasing sparseness the object becomes more transparent in order to show the more important underlying data. This approach is widely used in transfer function specification.

Interesting results can be achieved by controlling color saturation through the level of sparseness. In general color is a very important visual cue in visualization. Highly saturated colors attract the observer's attention more than colors close to gray. The level of sparseness can therefore be expressed also in the saturation of the color. Changing only the saturation, however, does not increase the visibility of occluded objects. It is necessary to change the color and opacity values at the same time. Different visual appearances within the same object can cause misinterpretations. Therefore smooth transitions between different levels of sparseness have to be applied. A smooth modulation of the optical properties is shown in Figure 10 (top).

B. Screen-Door Transparency

Screen-door transparency is a well-known strategy to simulate transparency. The appearance of an object behind another semi-transparent object is simulated with a screen-door as follows: A screen-door consists of a wire-mesh and holes inbetween. The wires of the mesh depict the first object, while the second object is visible through the holes. From a certain distance holes and wires blend together to produce a semi-transparent impression. We use an analogous idea to define levels of sparseness. The volumetric dataset consists of voxels. The level of sparseness determines which voxels should be rendered and which not. The arrangement of visible voxels is uniform and is forming a 3D wireframe structure. The impact of increasing sparseness is shown in Figure 10 (middle).

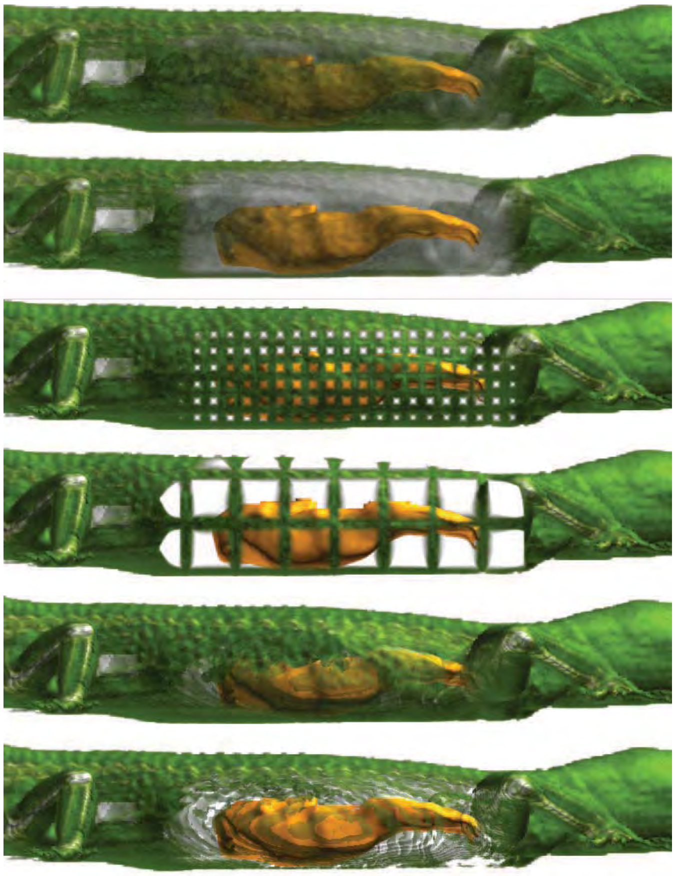

Fig. 10. Changing *levels of sparseness*. Top two rows: opacity modulation and color saturation modulation. Middle two rows: screen-door transparency. Bottom two rows: volume thinning. Images display *levels of sparseness* for the body with factors 0.75 and 0.25.

C. Volume Thinning

Volume thinning proceeds as follows: Voxels of an object are sorted according to two sorting keys. The first sorting key is gradient magnitude, the second sorting key is curvature magnitude of the iso-surface through the voxel. Reducing the sparseness factor according to gradient magnitude has the effect that the volume is con-

Fig. 11. Sparse and dense rendering styles: The occluding context object is rendered using summation (left), illustrative contour enhancement (middle), and maximum intensity projection (right).

tinuously reduced to fewer and fewer strong iso-surfaces. As soon as only few iso-surfaces remain the reduction proceeds according to curvature magnitude. This has the effect that the iso-surfaces gradually dissolve and in the end (most sparse representation) only few high curvature areas on strong iso-surfaces remain. Figure 10 (bottom) illustrates visibility reduction through volume thinning.

D. Sparse and Dense Rendering Styles

The previous levels of sparseness techniques describe how to enhance/suppress the visual representation of a particular object. The sparseness function smoothly varies from the most dense to the most sparse representation.

Another approach is to assign different *rendering techniques* as different levels of sparseness. For example the dense representation is achieved by direct volume rendering and the sparse one by illustrative contour rendering. In the case of object representations, combination is done via compositing. The combination of different rendering techniques is achieved through two level volume rendering [10]. The difference between levels of sparseness based on object representations and rendering styles is shown in Figure 12.

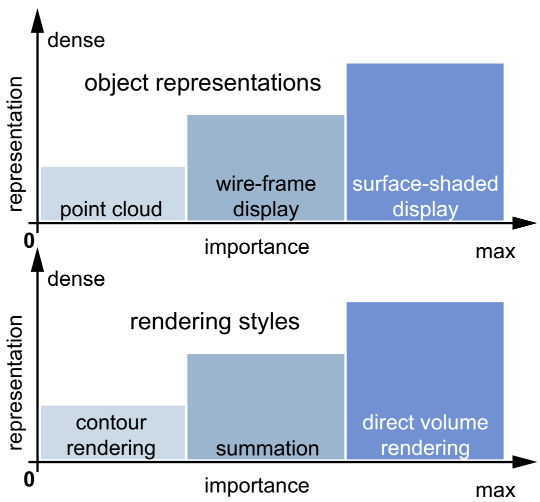

Fig. 12. Two types of *levels of sparseness*: based on object representations (top) and based on different rendering techniques (bottom).

Two level volume rendering (2lVR) is a technique to combine different volume rendering techniques. Well-known rendering techniques are direct volume rendering (DVR), MIP, summation (similar to X-Ray imaging), or illustrative rendering with contour enhancement [4], [24]. 2lVR renders each object within a volume with a different technique and composites the optical properties in a *local compositing step*. Each ray is partitioned by the intersecting objects into sub-rays. Local compositing is done for each sub-ray according to the rendering technique chosen for the respective object. The result of an entire ray is computed in a *global compositing step* which combines the results of the individual sub-rays.

Results of using different rendering techniques as levels of sparseness are shown in Figure 11. Where no occlusion occurs the context information is rendered using standard DVR. In the case of occlusion of the inner structure a different sparse rendering technique is applied. The images show the application of summation, contour enhancement, and maximum intensity projection for the local compositing. Global compositing is done by using again DVR.

VI. RESULTS

We show results of our method on three datasets. The *Leopard Gecko* dataset is of resolution $512 \times 512 \times 87$. The *Monster Study* dataset has been downsampled to the half of its full resolution, i.e., $256 \times 256 \times 610$. Both datasets are using pre-segmented objects. The third dataset is a time-varying simulation of the hurricane Isabel. It is a three-dimensional flow dataset with multiple simulated properties including cloud moisture, precipitation, pressure, and temperature. This dataset is not pre-segmented, only the position of the hurricane eye

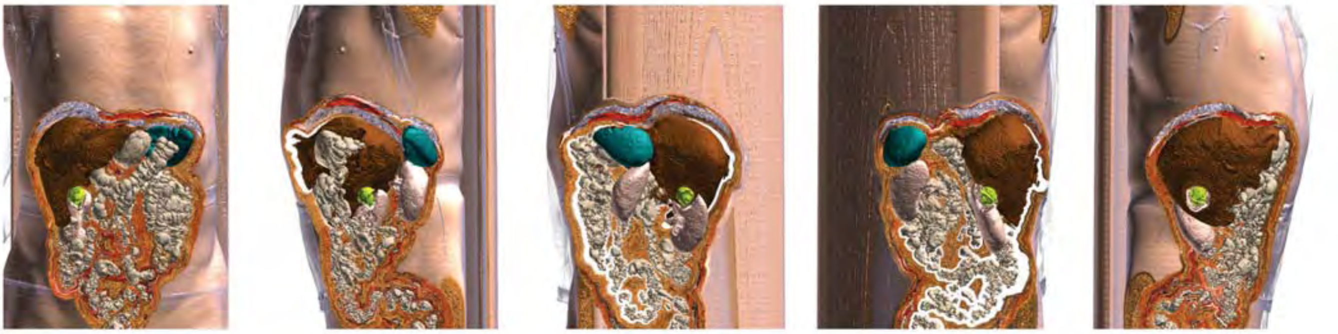

Fig. 13. The Monster Study dataset rendered using conical MImP. The highest importance is assigned to the tumor object (yellow). The organs of the abdomen are assigned a medium importance. The rest of the dataset has the lowest importance.

in object space is predefined. The simulation consists of 48 time steps.

Figure 13 shows the conical MImP of multiple abdomen organs from different viewpoints. The liver, spleen, kidneys, and intestine have the same importance value. The tumor (in yellow), located between kidney and liver, has the highest importance value. The rest of the body is of lower importance than any of the mentioned objects. The organs of the abdomen have the same importance and therefore they do not *cut away* each other. The highest importance value is assigned to the tumor and therefore everything in front of the tumor is cut-away. MImP allows to visualize the most important information, i.e., the tumor, its shape and spatial position in relationship to other objects. In contrast to traditional approaches the occlusion problem is solved automatically.

Another example of a conical MImP is shown in Figure 14. It shows 6 out of 48 time steps of the hurricane Isabel data. In this case a different way of feature classification was chosen. The important feature is the position of the eye of the hurricane. At the eye position a proxy cylinder is placed and everything inside the cylinder has higher importance than the rest of the data. The cylinder footprint is the basis for the countersink geometry.

This example also shows how to combine multiple scalar volumes using importance-driven volume rendering. The focus object is defined as the group of voxels inside the cylinder around the hurricane eye. Inside the cylinder the total precipitation mixing ratio is visualized. Thanks to the cut-away view it is possible to have a clear view at this property close to the eye of the hurricane. Outside the cylinder is the context area where the total cloud moisture is visualized. This time-dependent dataset also shows that the important feature can change its position and shape over time. Importance-driven volume rendering guarantees to visualize the important feature irrespective of viewpoint and feature position and shape.

The performance of the current implementation is not interactive. The goal of the implementation was to do a proof of concept rather than performance optimizations. The model was integrated as a plugin into the J-Vision [15] medical workstation.

To fully appreciate the strengths of importance-driven volume rendering viewpoint changes or dynamic scenes are essential. This is best illustrated with animation sequences, which are available at `http://www.cg.tuwien.ac.at/research/vis/adapt/2004_idvr/`.

VII. Summary and Conclusions

In this paper we have investigated importance-driven volume rendering as a view and feature dependent approach for automatic focus+context volume visualization. A new factor to the traditional volume rendering pipeline is introduced, i.e., the importance dimension. According to the importance and viewpoint settings each object is rendered in order to maximize the visual information. This method allows to see structures within the volume as dense as possible. A sparse representation is chosen only if other, more important structures are occluded.

Importance compositing defines how the occluding context information should be visualized. It can be simply cut away (MImP), or displayed using sparse representations. This approach can preserve either the thickness of the context object (AImC) or the visibility of the focus object (VPImC).

We have discussed four schemes for levels of sparseness. Levels of sparseness control the optical properties or the amount of visible elements of the volume. Smooth opacity changes work well in combination with desaturation. The amount of visible volume elements can be

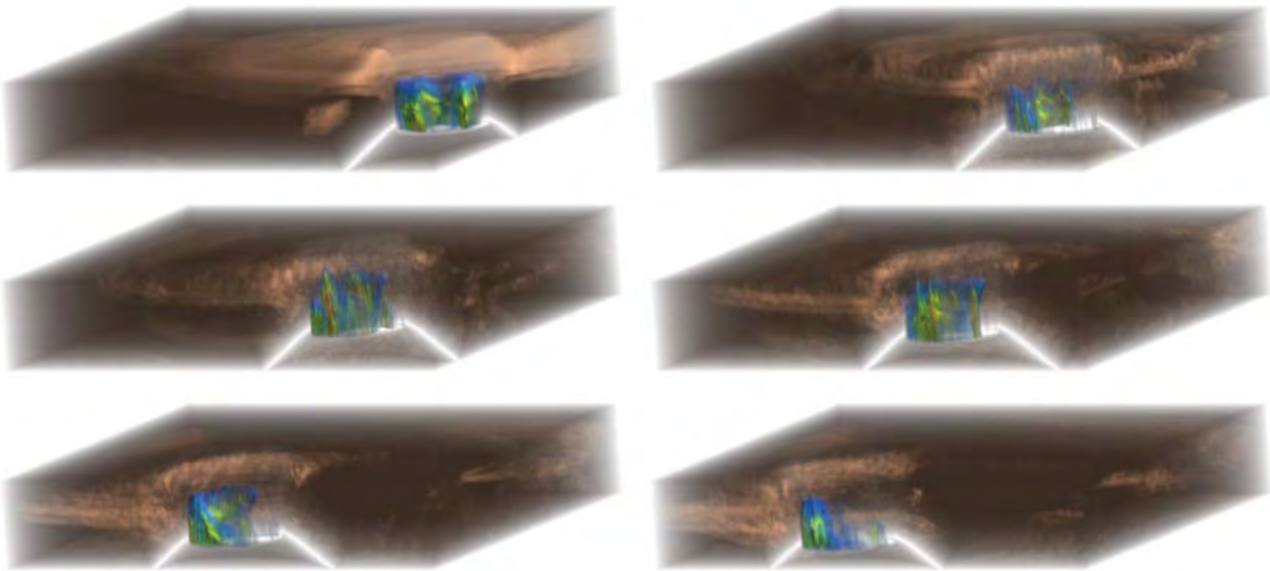

Fig. 14. Visualizing the simulation data of hurricane Isabel. Two different properties are visualized: total cloud and total precipitation mixing ratios. The interesting feature is the precipitation close to the eye of the hurricane. The context feature is the cloud mixing ratio. Images are showing 6 out of 48 time steps from left to right, top to bottom.

distributed uniformly over the whole volume, or the first- and second-order derivatives can be used for visibility distribution.

Levels of sparseness specify transitions of data representation from most dense to most sparse ones. Another approach defines levels of sparseness through different rendering techniques.

VIII. Future Work

The paper opens multiple opportunities for possible research areas. An open issue is, how to do the feature selection and importance assignment automatically. Various automatic feature detection approaches can be integrated into the model to select the important features without additional user interaction.

The paper has presented various levels of sparseness schemes. The continuous transition from dense to sparse representations for volumetric data is a wide area of research. In polygonal rendering levels of sparseness are often used. The most sparse representation is a set of points, another representation is a wireframe display, and the most dense display is a surface representation. Volume graphics does not yet have such a variety, which shows the need for research in this direction.

The third factor of importance-driven volume rendering is importance compositing. The paper presents simple compositing schemes derived from ray-casting approaches. The next step are compositing schemes that incorporate first- and second order derivatives to preserve object boundaries. The parts with high first derivatives values can then be considered as more important and a dense representation is chosen there.

The conical MImP and other object-space importance compositing approaches are implementing the cut-out illustration technique to improve perception of the spatial relationships. More elaborate approaches for intelligent automatic cut-out generations need to be researched. In cut-away views sometimes the borderline of the cut-out regions is emphasized (e.g., through thick lines, or zig-zag lines). Automatically emphasizing these transition zones is also an open problem.

Each viewpoint brings out only a fraction of the entire information contained in the data set. How to estimate viewpoint entropy and how to automatically determine optimal viewpoints [27] is another, not yet researched, area in volume visualization.

IX. Acknowledgments

The work presented in this publication has been funded by the AD**A**PT project (FFF-804544). AD**A**PT is supported by *Tiani Medgraph*, Vienna (`http://www.tiani.com`), and the *Forschungsförderungsfonds für die gewerbliche Wirtschaft*, Austria. See `http://www.cg.tuwien.ac.at/research/vis/adapt` for further information on this project.

The *Monster Study* dataset is courtesy of Tiani Medgraph and the *Leopard Gecko* is courtesy of University of the Veterinary Medicine Vienna. The hurricane Isabel data is courtesy of the National Center for Atmospheric Research in the United States. The medical illustration of the human abdomen is courtesy of Howell MediGraphics [12].

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Eurographics 2006 Tutorial

Illustrative Visualization for Medicine and Science

Illustrative Rendering for Intervention Planning Methods, Applications, Experiences

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University of Magdeburg

Illustrative Rendering for Intervention Planning: Methods, Applications, Experiences

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Keywords: Medical visualization, illustrative rendering, neck dissection, operation planning

1. Introduction

Visualizations are generated for a certain purpose. In medical applications this purpose is often a diagnostic question or a therapy planning scenario. In these scenarios, it is essential to adapt the appearance of objects or regions to their relevance for the specific task. As an example, it is often useful to focus on certain anatomic structures whereas other objects or regions only serve as orientation aid which might be displayed less pronounced. A medical visualization system might “know" what is relevant, after the user selected an object either immediately within the visualization or indirectly via its name in a list. Emphasis techniques modify the selected object or other objects such that its shape can be clearly recognized and its location in the overall model becomes obvious.

Most of the techniques discussed here require segmentation information concerning relevant objects. As a family of visualization techniques suitable for emphasis in medical visualization, we discuss so-called non-photorealistic rendering techniques where points and lines are employed to display and augment objects. These are inspired by traditional illustration techniques in scientific and medical applications. The potential of these techniques is to emphasize important features and to remove extraneous detail [Hod89]. Among the large variety of possible visualization techniques, those are preferred which are recognized at a first glance (*preattentive vision*, [Tre85]). Research in visual perception indicates that there are visualization parameters which are recognized without attention. As an example, objects shown with highly saturated colors are recognized immediately. Another effective focussing technique is blurring where only important objects are rendered sharply whereas others appear blurred, similar to blurred regions in photographies [KMH02].

2. Illustrative Surface Rendering

Computer graphics has been focussing for a long time on photorealistic rendering where the goal is to compute an image from a description of the geometry by simulating optical effects such as reflection, absorption and refraction as closely as possible. In 1990, a new direction emerged and meanwhile gained much acceptance—non-photorealistic rendering (NPR). The goal here is to provide a wider range of rendering techniques to express various effects and to simulate styles from traditional scientific and medical illustration. The term “non-photorealistic" is widespread in computer graphics although it is not expressive. Due to the inspiration from traditional illustrations, these methods are also called *illustrative rendering*. According to our experience, illustrative rendering is a better term for the communication between computer scientists and medical doctors.

Directing attention to relevant features, on the one hand, and omitting unimportant details on the other hand may be achieved by rendering strokes an points instead of shading surfaces. Illustrative rendering also provides facilities to expose features which have been obscured which is essential in the context of emphasis techniques.

The pioneering work [ST90] was entitled “Comprehensible rendering of 3D shapes". Silhouette and feature lines were generated to emphasize the shape of objects, and hatchings were employed to highlight the curvature of objects and to convey the texture of objects. Also, discontinuities in the depth-buffer were analyzed and visualized by means of lines. Silhouettes are essential in shape recognition because they provide cues for figure-to-ground distinction. However, since they are view dependent, they need to be determined for every viewing direction [IFH*03].

It is interesting and worth wile to note, that the goals of scientific visualization and illustrative rendering are very similar: to convey information effectively and to emphasize features in the data. Therefore, it is not surprising that Illustrative rendering techniques have adopted in visualization in general and in medical visualization in particular [NSW02].

Shape perception. Psychological studies clearly revealed that silhouette and hatching lines might improve the comprehensibility of images. As an example, Kim et al. investigated the effect of textured lines superimposed on shaded surfaces [KHSI03b] [KHSI03a]. In their study, users had the task to estimate surface normals. It turned out that the 3D shape was better perceived with hatching lines in the direction of maximum curvature. Slightly better results were achieved with hatching lines in two directions. These and other studies reveal that texture may improve shape perception. While illustrative rendering has many subareas and applications, such as artistic applications or games, we focus on techniques to improve the perception of anatomic and pathologic structures which are essential for surgical planning. Illustrative techniques have the potential to convey complex information, such as anatomic and functional information.

2.1. Emphasis and Non Photorealistic Rendering

Illustrative rendering provides a wide range of techniques which might be employed for emphasis purposes . In photorealistic rendering, emphasis might be achieved by adapting the position of the virtual camera or by placing a spot-light source. The rendering process itself, however, regards all edges and faces as similarly important. Nothing is left blank even if it is less relevant. Partial visibility of an outer object to reveal inner structures can only be achieved by semitransparent rendering. This method, however, strongly degrades shape perception.

Illustrative rendering offers more degrees of freedom to emphasize objects or regions. The CSO might be enhanced by silhouette and hatching lines, while others are not. As has been pointed out by [VKG04], Illustrative rendering permits *sparse visual representations* of objects which consume less screen space than shaded surfaces. Outlines or silhouettes are probably the sparsest meaningful visualization which allows to roughly understand the object shape. The addition of prominent *feature lines* or hatching lines leads to a denser representation which reveals more detail on the object shape. Finally, the combination of such illustration techniques with conventional rendering techniques represent a dense representation which depicts an object clearly at the expense of obstructed objects behind. The adjustment of the level of sparseness, is probably the most essential aspect of Illustrative rendering for emphasis of objects.

The negative side of this freedom is that good choices for many parameters are needed. More degrees of freedom make it more difficult to adjust a visualization. While artists may take hours to produce expressive images, medical visualizations are often generated under time-pressure. Also, medical visualizations should be precise and reliable. Our view on Illustrative rendering and its potential is focussed on these aspects. Techniques which require considerable and non-trivial input by the user (for example specification of hatching directions) are not considered. Also, rendering styles which are more artistic than precise are omitted. Browsing through medical illustrations gives an idea about useful rendering styles for medical education and therapy planning. The left image uses silhouettes and points to convey the shape of the liver. The local density of points is adapted to the curvature of the organ and simulates a lighting effect. This rendering style is called *“stippling"*. Small dots of ink are placed onto paper such that their density gives the impression of tone. Besides their expressive power, stippling is attractive since the rendering of points is very fast facilitating interactive exploration.

2.2. Silhouette and Feature Lines from Surface Models

Surface models in medical visualization are generated by thresholding medical volume data or by transforming segmentation information in (polygonal) surfaces. For continuous objects, such as B-Spline surfaces, the silhouette S is defined as the set of points on the object's surface where the surface normal is perpendicular to the vector from the viewpoint [HZ00]. At these points p_i, the dot product of the normal n_i with the view vector is zero (Eq. 1):

$$\{S\} = \{P|n_i\Delta(p_i - c) = 0\} \quad (1)$$

with c being the camera position (for perspective projections).

For polygonal models, the definition above cannot be directly applied because normals are only defined for edges and not for arbitrary points. However, silhouettes can be found along edges in a polygonal model that lie on the border between changes of surface visibility. Thus, silhouette edges of a polygonal model are edges that share a front- and a back-facing polygon.

Other significant lines are creases, which are defined by comparing the angle between its two adjacent polygons. If this angle is above a certain threshold the common edge represents a crease. Creases on smooth surfaces are also called *crest lines*. They represent ridges as well as valleys on such surfaces. Together with some other lines considered as important, creases are also referred to as *feature lines*.

Silhouette algorithms solve two tasks: They determine silhouette edges and determine the visible subset of them. In general, *image*- and *object-space* and methods are available for these tasks (see [IFH*03] for a recent survey).

Image-space methods operate on image buffers which contain per pixel information. In particular, the z-buffer and the normal-buffer (representing the z-coordinate and the normal of the polygon rendered at each pixel) are useful to find silhouette edges. Strong discontinuities in these buffers indicate the borders between objects and thus silhouettes. Edge detection methods from conventional image processing are employed for this purpose (recall [HZ00]). Image-space methods efficiently compute silhouettes because graphics hardware may be exploited.

Object-space methods, on the other hand, analyze the 3D model and produce an analytical description of the silhouette which is essential if silhouette lines should be flexibly parameterized. The ability to adjust parameters, such as line width as a function of the local silhouette orientation, is crucial for artistic renderings. For medical visualization, however, it is less relevant. Fig. 1 illustrates the use of images-space silhouettes and feature lines to convey the shape of context objects.

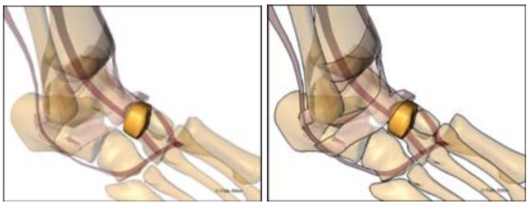


Figure 1: *An anatomic illustration with emphasis on a user-selected bone. The context objects are rendered strongly transparent (left). On the right, transparent objects are enhanced with silhouette and feature lines to better convey their shape. (Courtesy of Felix Ritter, MeVis Bremen).*

Subpolygon silhouettes. In medical visualization (flat) polygonal meshes usually approximate curved anatomic structures with a smooth appearance. Therefore, silhouettes of polygonal meshes can differ obviously from the silhouette that an algorithm based on polygonal edges yields. Therefore, methods have been developed to determine silhouettes more precisely.

As an example, [HZ00] consider the silhouette of a free-form surface approximated by a polygonal mesh. To find this silhouette, they recompute the normal vectors of the approximated free-form surface in the vertices of the polygonal mesh. Using this normal, they compute its dot product with the respective viewing direction. Then, for every edge where the vertices have opposite polarity, they use linear interpolation along this edge to calculate the point where the surface normal is zero. The connection of these points yields a piecewise linear subpolygon silhouette line which probably has fewer artifacts and is closer to the real silhouette.

Data structures for silhouette and feature line determination. For the efficient extraction of lines and strokes from 3D meshes, it is essential to use a data structure which provides local connectivity information. For conventional surface rendering, it is sufficient to represent the affiliation of vertices to polygons. For silhouette and feature line determination, it is essential to access adjacent polygons (polygons which have a common edge or a common vertex). This information is represented for example in a Winged Edge data structure [Bau72] which is useful for object-oriented rendering methods. As the name suggests, it is based on an (global) edge list and consists of locally linked edges. For every object, the data structure additionally stores a list of polygons and vertices. As an example, the winged-edge data structure allows to select adjacent polygons with strong deviation in the surface normal efficiently. This data structure is created as a preprocessing step.

Suggestive contours. An interesting extension of the more traditional silhouettes are so-called *suggestive contours* introduced by [DFRS03]. They include contours derived from adjacent viewpoints to generate expressive renderings which convey complex shapes with concavities convincingly. Suggestive contours are computed based on Eq. 1. Instead of drawing pixels if the dot product of surface normal and view vector is zero; pixels are drawn if the dot product represents a local minimum.

An essential advantage of suggestive contours is their temporal coherence. While conventional silhouettes may strongly change after small rotations, suggestive contours are more constant [DFR04]). Temporal coherence is an advantage for animations as well as for interactive 3D renderings.

2.3. Hatching Surface Models

Feature lines may effectively convey prominent features of a surface, such as ridges and valleys in the shape of the human brain. In the absence of such prominent features they are not applicable. The surface of organs, for example, has only a very few landmarks which might be emphasized with feature lines. In particular, for such smooth objects, hatching may convey shape information. Hatching techniques support a continuous perception of a surface encompassing rapidly changing as well as relatively constant areas.

Hatching may be utilized in isolation or in combination with surface rendering, in particular with strongly transparent surfaces. Strongly transparent surfaces are often used in medical visualization to show outer structures such as organs and inner structures such as vasculature or pathology simultaneously. The drawback of this strategy is that most of the depth-cues to convey shape have a minimal effect (at best) for transparent surfaces. This is well-known in psychophysics as well as in computer graphics and visualization [IFP96].

The challenge however is to develop algorithms for the optimal placement and scaling of hatching lines and strokes to convey shape information best. While hatching techniques designed for artists rely on many parameters which have to be supplied by the user, in medical visualization, an easy or even automatic parametrization is essential. Artists have recognized that the direction of strokes has a strong influence on our perception of surfaces. A uniform direction is not preferable as shapes tend to be perceived flattened. [IFP96] found that medical illustrators often use the curvature of surfaces to guide hatching: strokes are oriented along the strongest curvature. They described a viable approach for defining principal curvature directions by approximating partial derivatives based on finite differences of voxel values [IFP95]. The driving application for their work is radiation treatment planning where isosurfaces represent equal intensity of radiation dose. For treatment planning, the radiation beams and several of the surfaces are shown as transparent isosurfaces together with the tumor which should be destroyed is rendered opaque. Hatching techniques enhance the interpretation of the transparent isointensity surfaces. This work started in 1990 [LFP*90] and represents the first application of Illustrative rendering techniques in medical visualization.

2.4. Reconstruction of Surfaces for Illustrative Rendering

Medical volume data consists of slice where the in-plane resolution is usually higher than the distance between slices. This is referred to as *anisotropic data*. A typical resolution is $0.5 \times 0.5 \times 4mm$. Segmentation results are usually stored as volume data where the values indicate to which object the corresponding voxel belongs—voxels belong either completely to a certain structure or not at all.

A surface may be generated by the Marching Cubes algorithm or one of its refinements. Marching cubes applies linear interpolation to compute intersections of the surface with the volume data. If Marching Cubes is applied to anisotropic data aliasing effects occur. These effects strongly hamper the expressiveness of illustrative renderings. This is a general problem for any kind of medical visualization, however, it is more serious in case of silhouette and feature line rendering since the artifacts appear pronounced (see Fig. 2, left).

To overcome this problem two strategies are possible:

- Interpolation of additional slices, and
- Smoothing surfaces

On the one hand, higher order interpolation techniques can be employed to compute in-between slices. Ideally, the number of interpolated slices is chosen such that an isotropic resolution arises. Cubic interpolation is an appropriate method to compute these additional slices. The drawback of this strategy is the considerably increase in memory consumption. In our example with a voxel size of $0.5 \times 0.5 \times 4mm$, the number of slices and thus the overall size of the dataset is increased by a factor of 8.

Smoothing segmentation results for illustrative rendering. A large variety of techniques exist to remove high frequency noise in polygonal models. These methods differ in their computational effort and in the quality of the resulting surfaces. Some of the smoothing techniques allow to fulfil certain constraints. For surgical planning, it is often desirable that structures do not shrink after smoothing. Therefore, volume conservation is an essential constraint. Usually, smoothing modifies the position of vertices. Alternatively, surface normals could be modified. Shaded surface visualizations benefit from the modification of surface normals, however illustrative techniques (without shading) do not benefit from shading.

A wide-spread and simple algorithm is Laplacian smoothing where each vertex is moved in the geometric center of its local neighborhood [YOB02]. The filter is applied iteratively and has a smoothness factor and the number of iterations as parameter. Laplacian smoothing cannot prevent shrinkage. Other simple smoothing techniques are Gaussian and Median smoothing [Tau95a], [Tau95b].

Similar to image processing techniques used to reduce noise in 2D data, there are more advanced techniques which reduce noise but preserve features better. A family of these advanced techniques is based on the physical process of diffusion. In particular, anisotropic diffusion leads to excellent results [TWBO02]. Other advanced smoothing techniques which turned out to be useful for smoothing anatomic structures are described in [DMSB99] and [Kob00].

In Fig. 2 and Fig. 3, the effect of smoothing surface to the resulting silhouettes and feature lines is shown. In both cases, the same filter was applied. However, the two parameters had to be selected differently to cope with the peculiarities of these structures.

An essential aspect of smoothing is the assessment of the result. In a qualitative sense, the surface should appear smooth. Quantitatively, the smoothed surface can (and should be) evaluated with respect to the distance to the original surface. Strong differences are not acceptable for clinical applications. The Hausdorff distance provides a worst case approximation of how strongly the smoothed surface differs from the original one. A general problem is that different smoothing techniques are appropriate for different anatomic structures. Smoothing techniques which are appropriate for thin and elongated structures are different compared to those appropriate for compact larger structures, such as organs. In case of thin structures, special care is necessary to avoid topologic changes (separation of a previously

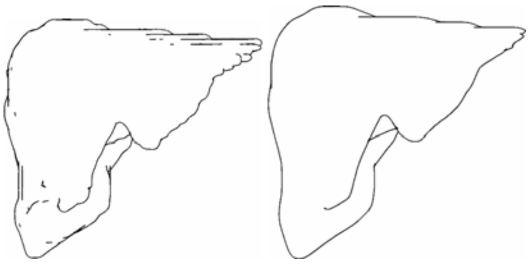


Figure 2: *Silhouette generation of the liver. Left: the isosurface representing the original segmentation result is employed. The resulting staircase artifacts are distracting and confusing since they have no anatomical basis. Right: the triangle mesh of the isosurface was smoothed with a relaxation filter.*

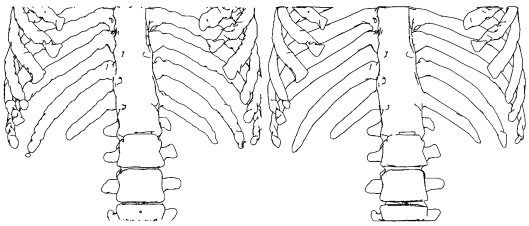


Figure 3: *Silhouette generation of skeletal structures. The unprocessed isosurface leads to noisy artifacts which can be corrected by appropriate smoothing.*

connected structure). Pathologic structures, such as lesion, again require different techniques. For surgical planning, it is essential that for each class of anatomic structure suitable default techniques and parameters are selected to reduce the interaction effort of the user.

3. Combining Line-, Surface-, and Volume Visualization

The combination of different rendering styles is a challenging problem. Hybrid surface and volume renderings can be generated either by converting surface data to volume data (voxelization) and subsequently creating a combined volume rendering. The alternative approach is to apply a two-pass rendering where surfaces and volume data are rendered independently and are combined in a final step considering depth values of surface and volume data. Similarly, there are two different strategies, how line rendering can be integrated with surface and volume rendering.

1. Integration of lines and surfaces in the volume rendering process
2. Apply different rendering passes to render lines, surfaces and volume data.

Integration of lines and surfaces in the volume rendering process. This strategy is computationally faster and easier to implement. An example for this approach is given in [VKG04].

Combining different rendering passes. The second strategy leads to an object-space method where line strips are considered as individual graphics primitives which might be parameterized flexibly. This strategy has been suggested by [NSW02]. This strategy is also realized in [TIP05] where the geometry and appearance of lines, surfaces and volume rendering are integrated in an extended OpenInventor-scenegraph. This object-space approach, however, poses some technical problems to achieve a correct rendering with respect to the depth-order of lines, surfaces and volume data. In a scenegraph representation, the ordering of nodes in the graph is essential for a correct rendering.

For the efficient extraction of lines and strokes from 3D meshes, a Winged Edge data structure is employed (recall Sect. 2.2). In order to render and stylize these objects, each object's mesh data is subsequently used to extract, the lines, and stylize them. The stylization process is divided into several steps represented by nodes in the scene graph. This concept also allows the reuse of certain line stylization pipelines because the respective nodes may be linked into the scene graph at several positions. This ensures a coherent appearance of the objects that use the same pipeline.

In order to use DVR, we integrate this rendering technique into one scene graph. This is achieved by specialized DVR node coupled with a TF node. However, since DVR always renders the whole volume into the z-buffer, it is not possible to add surface shading afterwards. Thus, the sequence in which the modules for the individual rendering techniques are added to the rendering pipeline will be important.

3.1. Hybrid Rendering with Object-Based Methods

In this subsection, we describe the object-space method in more detail. This description is based on [TIP05].

Surface rendering. For surface shading the OpenInventor architecture relies on normal z-buffer rendering. Thus, no special order of nodes is required for a correct rendering of the scene. Due to the nature of the remaining two techniques, the resulting scene graph may get fairly complex. Therefore, we start by discussing the extension of the scene graph for surface shading to include DVR. Then, we will show how line rendering can be added and explain the required individual modifications. Our rendering process is based upon the scene graph architecture of OpenInventor. In addition, we use the OpenNPAR system that extends OpenInventor and adds line extraction and line stylization capabilities.

Direct volume rendering. DVR may be combined with surface rendering by adding the respective nodes to the scene graph. However, the DVR node fills the z-buffer for the entire volume that is rendered regardless of the TF as explained above. Therefore, it has to be added to the scene graph after the surface shading has been completed, i.e., as the last node in the scene graph traversal. Otherwise, the surface objects would not be rendered because all would fail the z-buffer test. Hence, after the DVR, the z-buffer contains no more sensible depth information. Furthermore, DVR may previously be modified according to segmentation results.

Silhouette rendering. The object-space line rendering approach that we employ comprises three steps: geometry data preparation, line extraction and stroke generation, and stroke stylization.

After extracting the significant edges (silhouettes and feature lines), these edges are assembled into strokes and are processed in a stroke pipeline for stylization. As an essential step, this involves that hidden lines are removed. A fast and simple method for hidden line removal might be accomplished in the following way:

1. Objects are rendered into the z-buffer (while the frame buffer remains unchanged).
2. In a second step, all extracted lines are scan-converted individually and stepwise classified as hidden or visible using the previously generated z-buffer data [IHS02].

Then, stylization may be applied such as changing the stroke's width, saturation, and color. The edge extraction and stroke generation is thus independent from the final stroke rendering.

If surface rendering is used in addition to the line graphics, the surface objects have to be rendered into the final image prior to the lines. Silhouettes are located exactly at discontinuities of the z-buffer of the surface objects. One side of each generated and stylized line would otherwise be overwritten by the surface object since they are typically more than one pixel wide. This is also the reason hidden line removal (HLR) has to be carried out for the computed strokes before the final rendering process. In addition, the z-buffer generated for HLR would interfere with a correct rendering of the surface objects.

However, this approach is only applicable for opaque objects because transparent objects do not change the z-buffer. Thus, lines that lie behind a transparent object would not be removed. In order to prevent distant lines are rendered on top of closer transparent model parts, the z-buffer rendering must be carried out for the transparent objects as well.

According to the discussion above, line extraction and visibility classification are accomplished prior to rendering surface objects. Also, DVR has to be performed after all surface objects have been drawn. However, rendering surfaces on top of the stylized lines would potentially overwrite parts of the rendered lines as explained above. Fortunately, line extraction is independent from line rendering as discussed above. Therefore, we use the following procedure for generating the hybrid rendition (see also Fig. 4):

1. generate the z-buffer for surface and line objects (including transparent objects),
2. extract lines from internal mesh representation,
3. determine line visibility according to the z-buffer,
4. clear the z-buffer,
5. render surface objects using z-buffering,
6. render stylized lines with writing z-buffer data but without doing the z-buffer test, and
7. render volume using z-buffering.

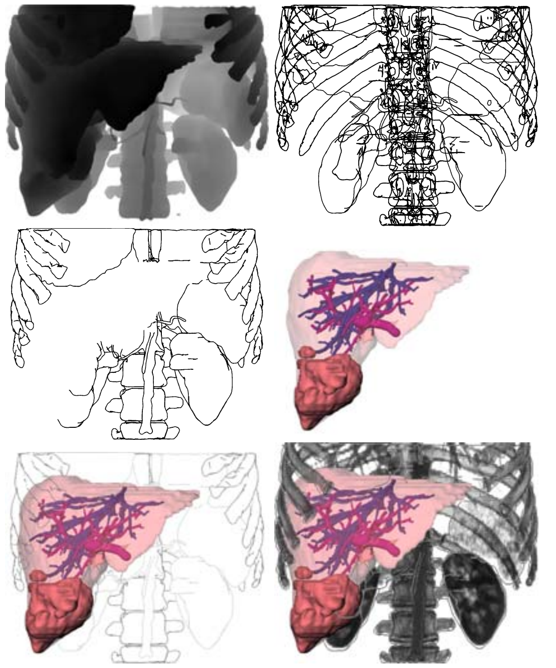


Figure 4: *Sequence for combining all rendering styles. (From: [TIP05]).*

The z-buffer of the surface objects and the line objects are rendered first (Fig. 3.1). The z-buffer is generated for all objects regardless whether they are transparent or opaque. Thereafter, the lines are generated (Fig. 3.1) and HLR is performed using the z-buffer information (Fig. 3.1). Because the line data is stored separately, it is not affected by surface and volume rendering. After the line extraction, the generated z-buffer is not needed anymore because it also contains transparent and line objects and becomes deleted.

Now, the surface rendering is initiated (Fig. 3.1). Since we included transparent objects in the initial z-buffer rendering, there will be no lines that will mistakenly be drawn on top of them. Due to the separate storage of the stroke data, the lines can be displayed with correct depth information. For this purpose, the line rendering is performed without z-buffer test but with writing z-buffer data (Fig. 3.1). DVR is carried out as the last step and after the lines because now the line data is present in the z-buffer as well (Fig. 3.1).

3.2. Emphasis with Hybrid Visualizations

The different rendering styles are not equally well suited to visualize objects. Thus, they will be used to depict different structures according to their relevance for the visualization. With respect to relevance, in the following we will refer to three types of structures or objects:

Focus objects (FO): objects in the center of interest are emphasized in a particular way.
Near focus objects (NFO): important objects for the understanding of the functional interrelation or spatial location. Their visualization depends on the particular problem.
Context objects (CO): all other objects.

The combination of different rendering styles provides facilities to adapt a medical visualization to the importance of anatomic and pathologic structures. Illustrative rendering might be used to depict anatomic context, either as single rendering mode or in combination with strongly transparent surface rendering. As an alternative, volume rendering might be employed for the anatomic context. Surface rendering and high opacity might be used for FOs.

Silhouettes may also be used to discriminate two classes of objects; those which exhibit a certain feature are rendered with silhouettes enabled whereas the remaining objects are drawn without silhouettes. A reasonable use of this strategy is to enable silhouettes for objects which are more "interesting" since silhouettes direct the user's attention. Alternatively, signaling colors such as red can be used to direct the user's focus to the focus object. This is shown if Figure 5, where the (red) colon is the focus object in the left image, and the paranasal sinus is the focus object in the right image.

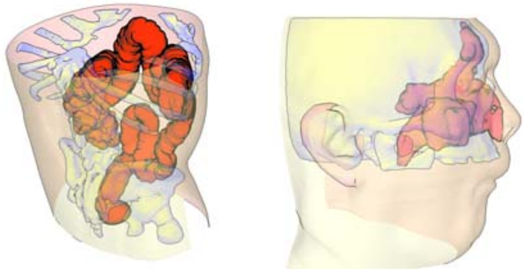


Figure 5: *Mixed rendering styles for multiple objects. Left: Abdominal dataset from CT with colon, skeleton, and skin. Right: Head dataset from CT with paranasal sinus, skull, and skin. (Courtesy of Zein Salah, Universität Tübingen [Sal06].)*

In Fig. 6 and 7, we show some combinations of rendering styles designed for a medical education system. Focus objects are the liver and the intrahepatic structures; the skeleton serves as anatomic context.

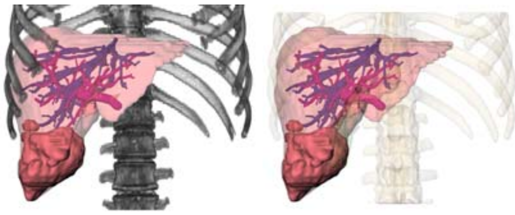


Figure 6: *Important structures as surface rendering. Context shown as direct volume rendering and as strongly transparent surfaces (left) (right). (From: [TIP05]).*

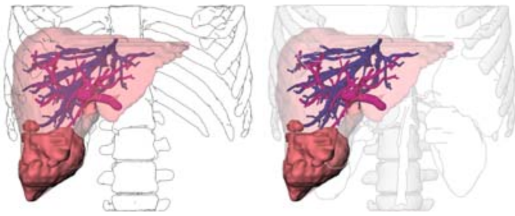


Figure 7: *Important structures as surface rendering. Context displayed exclusively with silhouettes (left) and as strongly transparent surfaces combined with silhouette rendering (right). (From: [TIP05]).*

A relevant yet difficult question concerns the appropriateness of the images in Fig. 6 and 7. Many variants have been discussed with surgeons and the four images in Fig. 6 and 7 have been regarded as suitable. But is there any best image? An encompassing user study might give some hints. Probably, different viewers strongly differ in their choice. As a consequence, it should be easy to generate such images and it should be easy to save parameters as individually preferred style which is reused for other images.

Line stylization may be used to control whether objects are conceived as FO or CO. One type of stylization is color which is widely used to emphasize objects. In addition, we will An interesting type of stylization refers to the visibility of lines. Hidden and visible lines may be depicted in a different manner to convey the spatial relationships (see Fig. 8). This is only feasible with the object-space approach to the visualization of lines.

Default values. Hybrid visualizations consisting of lines, surfaces and volume data provide excellent facilities for fine-tuning visualizations of medical volume data. However, the huge space of possible renderings is due to many parameters. To make hybrid visualizations feasible, it is essential

Figure 8: *Hidden feature lines are rendered as dashed lines. With this technique additional information concerning a tumor and the intrahepatic vasculature are included in a visualization. (Courtesy of Angela Brennecke, University of Magdeburg).*

to carefully select appropriate default values for the visualization of categories of anatomic and pathologic structures, such as organs, lesions or vascular structures. Users should be able to modify these values, but in general the interaction effort should be reduced.

4. Emphasis with Illustrative Rendering

With conventional local emphasis techniques, the CSO is emphasized with an appropriate color or with additional lines superimposed or by placing symbols which direct to the CSO. Local techniques might also be successful if parts of the CSO are hidden. If, however, larger portions or the CSO as a whole are hidden, local techniques are insufficient. In this section, we discuss cutaway and ghost views which ensure the visibility of the CSO.. We also discuss regional techniques to color selection; in particular, we consider contrasts between the CSO and adjoined objects.

4.1. Cutaway and Ghost Views

There are several possibilities how the visibility analysis might be employed. If the CSO is sufficiently visible a local technique should be used. If the CSO is heavily occluded, objects in front of the CSO might be rendered transparently or a combination of semitransparent rendering and silhouette rendering might be employed. As an alternative to the modification of objects, the modification of occluding regions is often appropriate. These regions are removed or at least shown strongly transparent. Such visualizations are called cutaway illustrations.

A slightly different illustration technique is referred to as *ghost view*. In these views, a region is shown semitransparently to reveal hidden structures. The generation of cutaway and ghost views is very similar since in both cases a cut region has to defined and considered. Compared to ghostviews cutaway views lead to a sharp contrast between foreground and background objects. Thus, ambiguities with respect to spatial ordering are avoided [DWE03]. Cutaway views have been introduced by [FS92] in computer-based illustration systems with applications in maintenance.

To indicate that an illustration technique is applied, the shape of the regions should differ strongly from the shape of anatomic or pathologic structures. While technical illustrators often create zig-zag-shaped cutaway views (these differ from shapes in technical domains), regular shapes such as prisms or cylinders are useful for medical visualization. Cutaway views may be generated in the context of volume rendering as well as in the context of surface rendering. Cutaways in volume rendering require to voxelize the clip geometry. Based on a voxel representation, volume rendering is modified such that voxels in the clip region are discarded.

Fig. 9 shows a ghostview based on a cylindrical cutaway in a volume visualization which emphasizes enlarged lymph nodes relevant for neck dissection planning. The circular cross-section is parallel to the view plane and located around the tumor. The cylinder height is chosen such that the lymph nodes become completely visible. Together, the circular clip region is scaled such that the tumor itself as well as a 5 mm margin in $x-$, $y-$, and $z-$direction is cut out. The borderline of the cut is depicted to be clearly recognizable.

Similar to other emphasis techniques, cutaway and ghost views have a limited applicability: Primarily small and compact objects may be emphasized with cutaway views. For objects with a branching structure and a large AABB this technique is less appropriate.

Cutaway views of small pathologic lesions may be combined with an interaction to systematically explore them. With a special key, for example the Tab-key, the user may step through emphasized visualizations of these objects. Additional information, such as size and volume, might be included for the currently selected object.

Realization of cut-away and ghost views. In the context of medical visualization (large models), an efficient approach is necessary to compute the cutaway region and to adapt it immediately to a changing viewing direction. A useful intermediate result is the convex hull of the object which should be displayed $ch(o)$. The convex hull of a 3D pointset P is the smallest convex polygon which contains all points of P. If the cut-region has a convex shape, for example a cylinder, the cut-region of the $ch(o)$ is the same as the cut-region of o itself. $ch(o$ has considerably less vertices than o and may be further geometrically simplified since the accuracy requirements are not distinctive.

The convex hull is projected into the viewing plane and the position and size of the cut shape in the viewing plane are determined in a second step. In case of cylindrical cut regions, an algorithm which determines minimally enclosing circles of a pointset is necessary. After a rotation, only the second step has to be carried out.

Convex hull determination is one of the most essential problems studied in computational geometry. For example [BKOS00] provide a chapter on convex hull algorithms. Minimally enclosing circle determination (or more general: minimally enclosing discs) are also discussed in computational geometry books [SE02, e.g.] and [BYB98]. The latter problem can be solved in $O(n)$ time which means that the computational effort only linearly increases with the number of points involved.

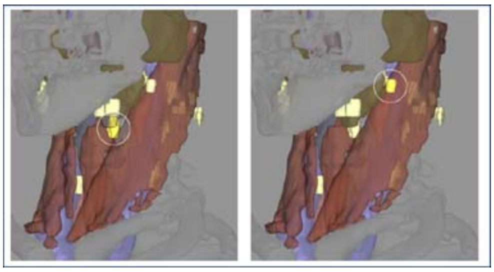


Figure 9: *Ghost view of enlarged lymph nodes for neck dissection planning. (From: [KTH*05]).*

Recently, cutaway views have been generalized to importance-driven volume rendering [VKG04]. Here, less important parts of the data are suppressed, for example by employing transparency. The general concept here is to transform *importance* to *visibility*. Importance-driven rendering is based on a visibility priority which is assigned to each object. It is thus more general, than an emphasis technique for the CSO only. Similar to cutaways, importance-driven rendering is most suitable to focus on smaller objects. If objects with high priorities occlude each other, the object with maximum priority is drawn (maximum importance projection). The straightforward application of this concept leads to a cylinder-shaped countersink for an important object. This variant suffers from similar problems as the maximum intensity projection where the depth relations are difficult to recognize. As a refined variant, a conical shape of the countersink.

5. Enhancing Slice-based Visualizations

In the following, we describe how slice-based visualizations can be enhanced to give an overview on anatomic structures. This description is motivated by the importance of slice-based views for surgery planning and based on [TMS*06].

5.1. Graphical Overview

For an overview of the segmented structures in a slice-based visualization, it is essential to present the relative position of structures in the current slice as well as their positions in

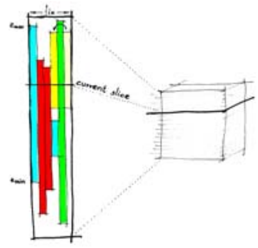


Figure 10: *Concept of the* LiftChart *widget. The colored bars represent z-dimensions of anatomical structures in a volume dataset (right portion). (From: [TMS*06]).*

the third dimension, i.e., within the whole set of slices. In the following, we refer to the in-plane coordinates as x, y and the slice number as the z-dimension.

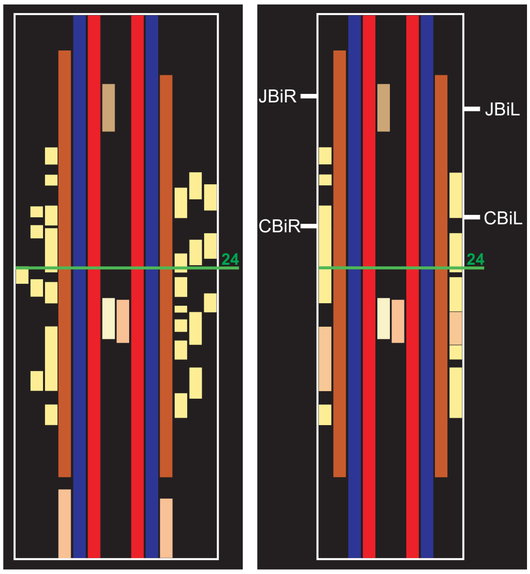
The visualization problem that occurs here is similar to time scheduling. In this area, different techniques have been developed to visualize data entries and their temporal relations. Graphical overviews should present appointments distinguishable from each other and the temporal relations between them (see for example, the LifeLines project [PMR*96]).

Translated to slice-based visualization, the interval of slices of the segmented structures corresponds to the lengths of appointments. We assume that each structure can be characterized by an interval of slices (z_{min}, z_{max}) to which it belongs. We do not consider disconnected structures occurring in several intervals. The current slice corresponds to the current time or date. Like appointments the intervals of slices to which anatomic structures belong may overlap each other.

Similar to temporal overviews in time scheduling, we attach a narrow frame next to the cross sectional image that represents the overall extent of slices in the volume data set. The top and bottom boundary of the frame correspond to the top and bottom slice of the dataset. Each segmented structure is displayed as a bar at the equivalent vertical position inside this frame. The vertical extent of the bar represents the interval (z_{min}, z_{max}) for each structure. Figure 10 presents a sketch of this concept. The overview is used to indicate in which slices certain structures occur. We refer to this combination of bars as LiftChart and regard it as a widget which provides interactive facilities to locate structures and slices.

The LiftChart enhances the recognition of relative positions of structures in the volume dataset by displaying their spatial relations. To simplify the correlation between the slice view and the LiftChart, the color and style of the bars should correspond with the color and style of the structures displayed in the slice view.

The currently displayed slice of the volume dataset is depicted by a horizontal line in the LiftChart widget. The



(a) (b)

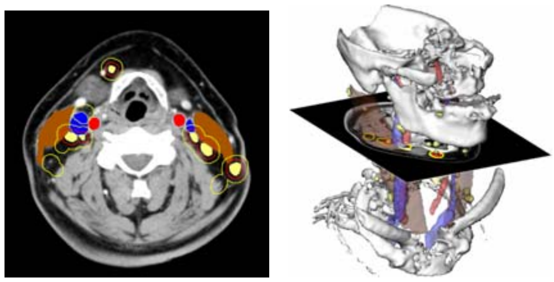
Figure 11: *Different possibilities of arranging structures in the* LIFTCHART. *Each anatomic structure is represented by one bar. In (a), the* LIFTCHART *is divided in three parts: one part for structures on the left and on the right side each and one part for structures in the middle. In (b), structures of one kind are aggregated in one column. Additional landmarks for orientation are displayed. (From: [TMS*06]).*

slice number is displayed next to this representation. To visualize not only the z-distribution of structures in the volume, but also information about their horizontal position, we developed several arrangements of the bars in the LIFTCHART (Figure 11).

5.2. Slice-based Visualization of Safety Margins

Safety margins are useful for preoperative planning and intraoperative navigation, but for different domains. During a tumor resection, the tissue around the tumor is also resected to be sure that all pathologic tissue is removed. During the intraoperative navigation, it is useful to give the surgeon a hint about structures at risk near the surgical tool.

To prevent damage to structures at risk, the distances of the surgical tool to such structures have to be carefully observed during the surgery and, therefore, to be displayed. Halos (in the original sense of the word) can convey this distance information. Therefore, for all structures at risk an Euclidean distance transform [Bor83, Loh98] is performed and the resulting distance information is overlaid on the slice image. We considered color-coding the distance information but rejected this idea, since presenting a color map of the distance transform would display too much information not



(a) Slice view. (b) 3D view for comparison

Figure 12: *Depicting safety margins around pathologic lymph nodes as special halos on the current slice. Left and right are swapped in the slice view, because the viewing direction is from bottom to top. (From: [TMS*06]).*

relevant for the surgical strategy. Depicting important distance thresholds as halos by drawing two isolines representing 2 and 5*mm* distances turned out to be more appropriate in discussions with clinical partners. Thus, the quantitative distance information is reduced to a few categories which is easier to interpret. Figure 12 gives an example of such a visualization. On the left hand side the safety margins of 2*mm* (red) and 5*mm* (yellow) are shown as the user would see them in the slice view. The right hand side illustrates the position of the slide with the displayed structures for comparison.

6. Case Study: Neck Dissection Planning

In this section, we discuss how conventional and illustrative rendering techniques might be employed to support a particular surgical intervention: neck dissection planning. Neck dissection planning poses challenging visualization problems due to the enormous density of crucial anatomic structures: Muscles, vascular structures, and nerves share the same small space.

This discussion is based on an ongoing research project and describes experiences gained in the first two years. In total, 30 CT and MRI datasets have been analyzed and visualized to support preoperative planning.

6.1. Medical Background

Neck dissections are carried out for patients with malignant tumors in the head and neck region. These surgical procedures are necessary because the majority of the patients develops lymph node metastases in the neck region.

The extent of the intervention depends on the occurrence and location of enlarged (and probably) malignant lymph nodes. In particular, the infiltration of a large muscle (*M. sternocleidomastoideus*), a nerve (*N. facialis*) or blood vessel determine the surgical strategy. If for example the *A.*

carotis interna is infiltrated, the patient is regarded as not resectable. The identification and the quantitative analysis of lymph nodes with respect to size and shape is crucial for the surgeon's decision. Visualization techniques should be developed such that they support decisions regarding the resectability and the surgical strategy for neck dissections.

6.2. Conventional Surgical Planning

Surgical planning in general as well as neck dissection planning as a special problem are carried out by means of 2D slices. Surgeons prefer CT data compared to MRI since these are easier to interpret for them. Computer support allows to browse quickly through the slices, to change brightness and contrast and to perform measurements such as distances between selected points. 3D renderings are rarely used and many surgeons are not convinced of the additional value of 3D renderings at all. This attitude is not only due to their habits but has some serious arguments: in 2D slices each and every voxel is visible—it can be selected and its intensity value can be inquired. Instead, 3D visualizations provide an overview which is often too coarse for an in-depth planning of surgical strategies.

Since conventional surgical planning relies on 2D slices it is a good strategy to include 2D slices and the related manipulation techniques in advanced surgical planning systems. With this strategy, surgeons can plan their interventions as they did it before and can use the advanced techniques additionally. The most benefit can be achieved if 2D and 3D visualizations are not only available but carefully synchronized. A simple yet very efficient synchronization relates to the selection of an object. Whenever an object is selected in one view it is also selected and emphasized in the other view (Fig. 13). This coordination allows surgeons to recognize which structures of the original volume data correspond to a 3D surface.

6.3. Advanced Surgical Planning

Advanced surgical planning requires reliable segmentation results. Segmentation of the relevant structures is a challenging task and computer support for minimally-interactive solutions is an area of ongoing research. We omit this important problem here and assume that segmentation of all relevant structures are available. For most anatomic structures the segmentation result comprises a connected set of voxels. For some structures, such as nerves, only selected voxels can be identified in a few slices. Nevertheless, it is desirable for surgical planning to see the rough course of the nerves. A special rendering technique is required for such incomplete structures.

Illustrative Rendering. Silhouette rendering is employed for two purposes. The obvious use is to indicate the context objects, such as bones (Fig. 14). In addition, silhouettes may be used to discriminate two classes of objects; those

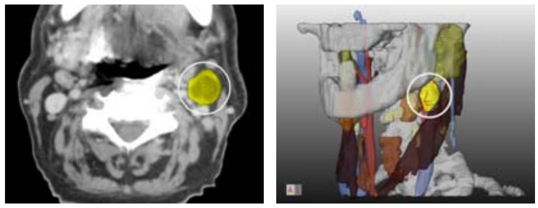


Figure 13: *The lymph node emphasized in the 3D visualization is simultaneously emphasized in the original slices.*

which exhibit a certain feature are rendered with silhouettes enabled whereas the remaining objects are drawn without silhouettes. A reasonable use of this strategy is to enable silhouettes for these objects which are more "interesting" since silhouettes direct the user's attention.

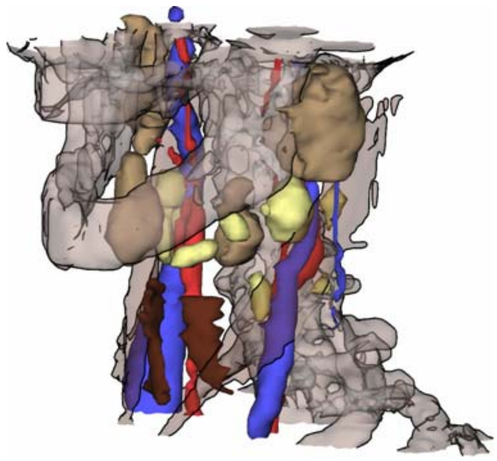


Figure 14: *Illustrative rendering for neck dissection planning. Silhouettes are generated for the bones which serve as anatomic context.*

Visualizing Distances to Risk-Structures. In neck surgery planning, many lymph nodes have to be shown and explored by the user. In particular, lymph nodes which are enlarged and touch a critical structure are essential. We employ a distance-dependent coloring of the neck vessels and muscles, which conveys the distance to the lymph nodes. With a discrete color scale (gradation: 2 and 5*mm*) the resectability of this target may be evaluated (Figure 15).

In 2D, the safety margins are shown for all enlarged lymph nodes. Since the distances are computed in 3D, margins for lymph nodes outside the current slice are also visible (Figure 16).

Enhanced overview using the LIFTCHART. Due to the (potentially) large amount of lymph nodes, all lymph nodes of one side may be combined in one bar indicating in which slices lymph nodes may occur. The separation in lymph

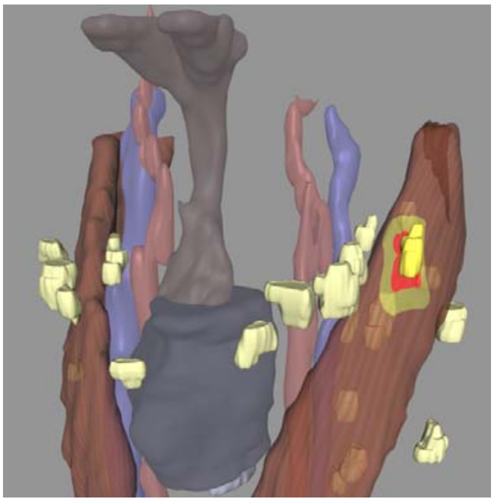


Figure 15: *Color coded distance of a lymph node to the M. sternocleidomastoideus. The 2mm distance is coded in red, 5mm in yellow. (From: [KTH*05]).*

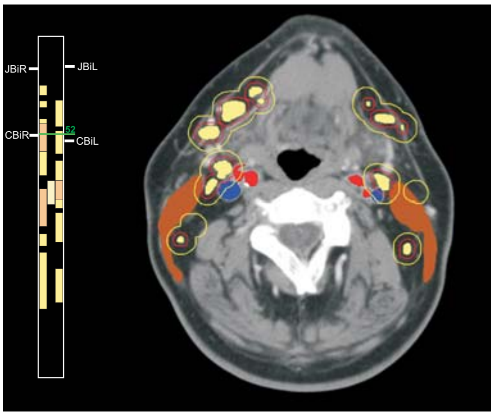


Figure 16: *The probably pathologic structures (tumor and lymph nodes) are shown in the* LIFTCHART. *The lymph nodes of one side are combined into one column. Enlarged lymph nodes are colored red. For the lymph nodes safety margins of 2mm (red) and 5mm (yellow) are shown. (From: [TMS*06]).*

nodes located at the left and right side is motivated by the surgical strategies (left and/or right-sided surgery). The identification of pathological lymph nodes is important, thus, all noticeable nodes are emphasized. Some elongated structures like muscles and vessels occur in all slices, and are therefore not displayed (Figure 16). Other structures like the larynx are displayed, because they represent important landmarks for the orientation in the dataset. Furthermore, landmarks for orientation in the dataset are displayed at the frame of the LIFTCHART. In Figure 11(b), the bifurcations of the *Vena Jugularis* (JBiL/JBiR) and *Arteria Carotis* (CBiL/CBiR) are indicated.

Approximative Rendering of Nervs. Nerves are very small structures compared to the spatial resolution of the data. Therefore, a single voxel contains nerve tissue and other adjacent tissue resulting in an intensity value which is very hard to distinguish from its surrounding. As a consequence, only in some slices a nerve could be identified at all. Anatomic experience shows that nerves proceed almost linearly and do not deviate strongly from the straight connection between positions found in some slices. Since it is an important goal to prevent the injury of nerves we decided with the surgical partners that approximate visualizations should be generated where the segmented portions are emphasized and the part in between is reconstructed as linear connection. The emphasis of the segmented portions is accomplished by means of small cylindrical disks (see Fig. 17).

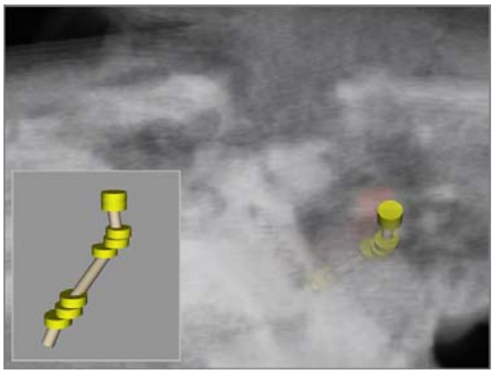


Figure 17: *Approximate visualization of N. facialis for neck dissection planning.*

6.4. Discussion

From an applications point of view, illustrative renderings target only a portion of the overall problem. Whether or not all relevant lymph nodes are detected and correctly delineated is probably more important than the details of their visualization. Valuable computer support for surgical planning requires high-quality and dedicated image acquisition, reliable and fast image analysis techniques *and* comprehensible visualizations. With respect to the visualization, conventional as well as more recent rendering techniques have their merits if appropriately combined. The combination of 2D and 3D renderings is an essential aspect for the acceptance and use of computer-supported surgical planning systems.

7. Concluding Remarks

We presented a variety of illustration techniques applicable and viable to medical visualization and surgical planning in particular. The case study on neck dissection planning is based on a close collaboration with clinicians. The ideas how to use illustrative techniques were developed in discussions with them and the informal feedback is positive and encouraging.

Illustrative techniques are not wide-spread in surgical planning. Our research results indicate however, that illustrative techniques have a potential to improve surgical planning. The need for illustrative techniques will likely increase since more and more information is available preoperatively. The development of illustrative techniques should be directed to support the integrated and comprehensible visualization of these different sources of information.

The great advantage of using illustrative techniques is the additional freedom to fine-tune visualizations with respect to task-specific needs. The major drawback is that additional effort is required to process segmentation results and to select appropriate techniques and parameters. In clinical settings, these steps need to be strongly supported and automized if possible since the time for surgical planning remains severely restricted.

Future work. Illustrative rendering of medical volume data is one of the most active research areas in medical visualization. We discussed emphasis and illustration in static volume data. We briefly described the idea by [VKG04] to adjust visualization parameters to the importance of objects. This idea can be extended in many ways; in particular, the importance may be different for different parts of objects (the shape of a long muscle near a tumor is highly important whereas other areas are less important). More insight is necessary to automatically choose and combine illustrative techniques.

The most important work to be done concerns an evaluation of illustrative techniques by means of controlled user studies (see [KHI*03] for a discussion of issues in the preparation, execution, and analysis of user studies of visualization techniques). Such studies should investigate which visualization techniques provide additional insight into the patient's anatomy and should explore whether these insights influence the surgical strategy.

Further reading. For an overview on NPR, two dedicated books can be recommended: [SS02] and [GG01]. Since 2000, the conference Non-Photorealistic Rendering and Animation (NPAR) has been established as biannual conference (see the conference website http://www.npar.org). Concerning hatching, [PHWF01], [ZISS04] and [JEGPO02] are recommended; concerning silhouettes and feature lines we refer to [RC99] and [IHS02]. [IHS02] give an overview discussing requirements and appropriate silhouette detection methods. [XNYC04] describe high quality silhouette rendering based on point-based models. Some papers are dedicated to fast object-space detection of silhouettes. Hierarchical data structures [SGG*00], precomputed information [BS00, GSG*99] or probabilistic methods [MKT*97] are employed to accelerate the computation.

[NSW02] describe interactive volume illustration where expressive hatchings are generated based on the estimated curvature, transparency and lightings. The placement of hatchings is guided by seed points specified by the user which are used as starting points for tracking lines with high curvature. [KWTM03] designed curvature-based transfer functions which make it possible to emphasize regions with large values for the major curvature κ_1 and κ_2. With this approach,ridges and valleys can be emphasized effectively, and silhouettes with a constant strengths can be computed. In [RKS00b,RKS00a], the approximation of curvature information in polygonal meshes is used to guide the extraction of feature lines. The use of line-based illustrations for displaying several isosurfaces and the value of line-based illustration for emphasis is discussed in [TC00]. We omitted a discussion of stippling techniques although these techniques are relevant for emphasis. Stippling is based on points or small filled circles as rendering primitives. Meanwhile,complex objects can be stippled sufficiently fast and they can be easily parameterized. Stippling techniques are described for example in [DHvOS00], [Sec02] and [PS02]. [LME*02] and [LME*03] also considered stippling techniques for the visualization of medical volume data. Gradient direction and gradient magnitude are estimated to adjust the local resolution of points so that silhouettes and local features are highlighted.For medical visualization, the combination of stippling with other rendering techniques is needed (see Fig. 18). An integrated approach to stippling and silhouette generation and stippling is described in [YNZC05]. Silhouette rendering and stippling is also combined by [SBS05]. Expressive visualizations arise in particular if shading effects are integrated for controlling the density of points. [LSM02] presents a novel visualization technique—kinetic visualization—that uses particle systems to add motion cues which can aid in the perception of shape and spatial relationships of static objects. It is recommended to look at applications of illustrative renderings in other application areas, such as illustration of terrain data [WV03] and illustration in technical areas [GSG*99]. Shape perception by means of computerized line drawings has been investigated—among others—by [Koe84, KvDCL96].

Visibility analysis is important for the selection of emphasis techniques. For conventional computer graphics, this topic is also essential to accelerate the rendering of very large scenes with a small portion of visible polygons. A tutorial on the ACM SIGGRAPH conference gives an overview [COCSD00]. A more recent survey can be found in [COS03]. Also in this survey, the majority of the algorithms estimates visibility by using hierarchies of bounding volumes. In contrast to the visibility analysis discussed here,individual polygons are considered in computer graphics instead of(high-level) objects such as anatomic struc-

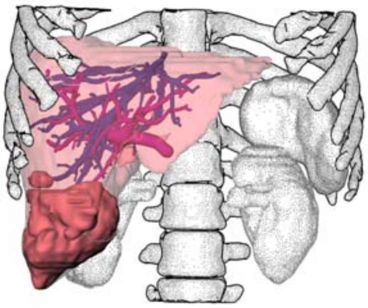


Figure 18: *Stippling, silhouette and surface rendering combined. Stippling is applied to context objects only, whereas focus objects are rendered as surfaces. (Courtesy of Alexandra Baer, University of Magdeburg).*

tures. Despite this difference, fast computer graphics algorithms can be modified tobe useful for emphasis techniques. Many of the emphasis techniques discussed here have been used for an educational system based on the metaphor of a 3D jigsaw puzzle [RPDS00]. The generation of cutaway illustrations is discussed in [DWE03].

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EUROGRAPHICS - IEEE VGTC Symposium on Visualization (2005)
K. W. Brodlie, D. J. Duke, K. I. Joy (Editors)

Interactive Visualization for Neck-Dissection Planning

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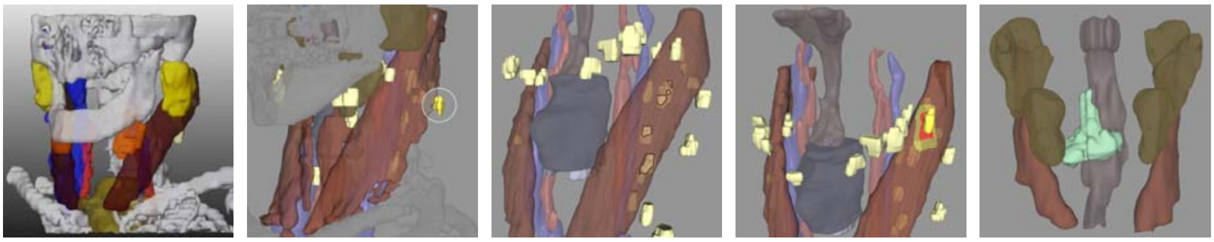


Abstract

In this paper, we present visualization techniques for neck dissection planning. These interventions are carried out to remove lymph node metastasis in the neck region. 3d visualization is intended to explore and to quantify anatomic and pathologic structures and thus support decisions concerning the surgical strategy. For this purpose we developed and combined visualization and interaction techniques such as cutaway views, silhouettes and color-coded distances. In addition, a standardized procedure for processing and visualization of the patient data is presented.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computing Methodologies]: Computer GraphicsMethodology and Techniques; I.4.m [Computing Methodologies]: Image Processing and Computer VisionMiscellaneous; J.3 [Computer Applications]: Live and Medical SciencesHealth;

Keywords: Medical visualization, neck dissection, operation planning, lymph node exploration

1. Introduction

Neck dissections are carried out for patients with malignant tumors in the head and neck region. These surgical procedures are necessary because the majority of the patients develops lymph node metastases in the neck region.

The extent of the intervention depends on the occurrence and location of enlarged (and probably) malignant lymph nodes. In particular, the infiltration of a large muscle (*M. sternocleidomastoideus*), a nerve (*N. facialis*) or blood vessel determine the surgical strategy. If for example the *A. carotis interna* is infiltrated, the patient is regarded as not resectable. The identification and the quantitative analysis of lymph nodes with respect to size and shape is crucial for the surgeon's decision. The image analysis and visualization techniques described in this paper support decisions regarding the resectability and the surgical strategy for neck dissections.

Visualization techniques aim at comprehensible renderings of the relevant information. This includes the visualization of the target structures and some context information necessary to illustrate the spatial relations. By means of our visualizations, we convey information concerning shape and size of lymph nodes, as well as critical distances or even infiltrations of lymph nodes into important structures. In addition to carefully parameterizing surface rendering, we explore silhouette rendering and cutaway views for parts of an object's surface. Although these visualizations are targeted at neck dissection planning they are applicable to other applications such as the evaluation of lung nodules. We also discuss interaction facilities to explore the data. In particular, we discuss the selection of lymph nodes based on their properties. Our case study report is based on 18 clinical CT-datasets which have been acquired and processed for the planning of neck dissections.

2. Image Analysis

In order to support neck dissection planning, it is crucial to segment the relevant anatomic and pathologic structures. The segmentation is a prerequisite for the selective visualization and the quantitative analysis of the patient data. For surgical planning, the extent of pathologic structures, distances to important anatomic structures and the potential infiltration are of special interest.

2.1. CT Data

We employed 18 CT-datasets which have been acquired for neck dissection planning. Eleven of these datasets contained a tumor in the head and neck region and were suspected of containing lymph node metastases as well. The quality of the datasets was diverse with respect to the signal-to-noise ratio, motion artifacts as well as the slice distance (0.7 to 3 mm), resulting from different CT scanning devices and acquisition parameter.

The data were exchanged based on a WWW upload including information concerning the diagnosis of the patient and specific requirements for computer-supported planning.We choose not to employ MRI data, although they are wide-spread for diagnosis in the neck region due to their inherent inhomogeneity and low resolution.

2.2. Requirements

In collaboration with our clinical partners, the target structures of the segmentation were identified as being most relevant for preoperative planning:

- Vascular structures (*V. jugularis, A. carotis*)
- Muscles (*M. sternocleidomastoideus*)
- Skeletal structures (*Mandible* and *Clavicle*)
- Salivary glands (*Gl. submandibularis, Gl. parotidea*)
- *Pharynx*
- *N. accessorius* (where visible),
- Primary tumor,
- Lymph nodes, with emphasis on enlarged and potentially malignant nodes.

In selected cases, the segmentation of additional structures is desirable, e.g. additional muscles or nerves.

2.3. Segmentation

Segmentation was carried out by means of the software platform MeVisLab (MeVis, Bremen, http://www.mevislab.de), a library which provides a variety of image preprocessing and segmentation methods. A live wire approach was employed for the segmentation of muscles (*M. sternocleidomastoideus, M. omohyoideus*) and the salivary glands. With this semi-automatic approach, the user selects seedpoints and the system calculates a path of minimal cost in between. This procedure is carried out in selected slices; the intermediate contours are interpolated [SPP00]. The interactive watershed transform [HP03] proved to be suitable to identify and delineate the *V. jugularis* and *A. carotis*. Intensity-based region growing was used for bone and *Pharynx* segmentation.

While the muscles and the glands could be identified in the majority of the datasets, most of the desired nerves could not be identified due to their size in relation to the image resolution. Among the vascular structures, only the *A. carotis* and *V. jugularis* could be segmented in most of the data.

Nerves are very difficult to detect in CT-images because they are very small. In datasets with a large slice distance (>3 mm), they could not be detected at all. In CT-data with low slice distance, the *N. accessorius* and *N. vagus* could be identified manually in a few slices. Due to the low slice distance the partial volume effect (averaging of signal intensities in a volume element) is less disturbing. As the approximate course of these nerves is essential for surgeons, we chose to segment the nerves partially and to employ this information for an approximate visualization (see Section 6).

Primary tumors were segmented manually as well. They exhibited low contrasts and could only be distinguished by exploiting considerable anatomic knowledge, in particular symmetry considerations. At present, also the lymph nodes are identified manually. Our ongoing research aims at an automatic detection of lymph nodes, using assumptions regarding their grey values, size and shape. The segmentation is described in more detail in [HCP*05].

3. Visualization of the Segmented Target Structures

We discarded volume rendering because it does not provide essential information for our purposes. By relying on surface visualizations, we provide all necessary information within rather small surface models which can be easily transmitted over the internet and explored using wide-spread software. In addition we use functionalities from modern graphics hardware (GPU) which is optimized for surface rendering.

3.1. Color Selection

Our color selection was guided by observations from textbooks [Net02] and later refined in discussions with the clinical partners. Transparency was primarily used to expose important structures, such as lymph nodes. This type of visualization is shown in Figure 1.

After processing three CT-datasets, we evaluated all visualization parameters. In several in-depth discussions, we modified colors and transparencies for all structures to enhance contrasts and recognizability of object borders. As a result, a final color table was developed which represents our standardization (see Table 1). Finally, all datasets have been adapted to these values.

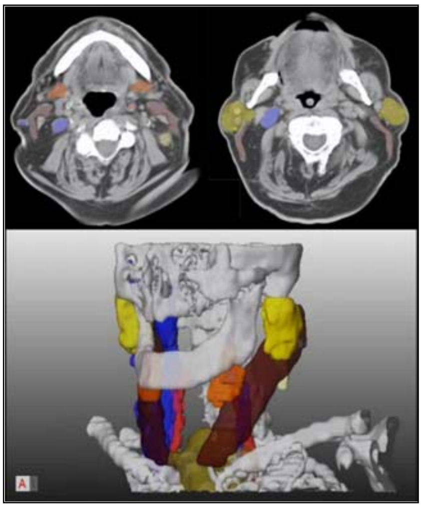


Figure 1: *2d and 3d visualizations are combined for neck dissection planning. The colors used in the 3d visualization are also used to superimpose segmentation results in 2d slice data.*

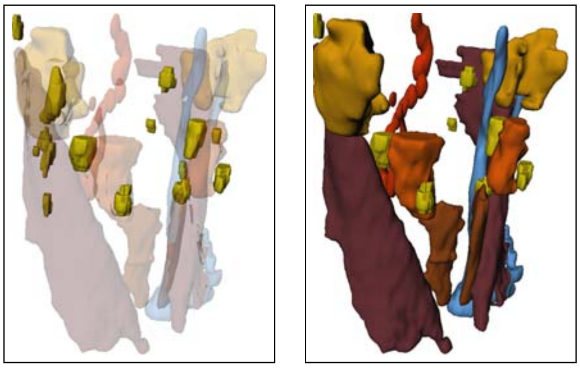
3.2. Material Effects for the Visualization

It turned out that object-based transparency specification does not allow a comprehensible visualization of complex structures. With multiple highly transparent objects, the specific location of a target object is barely visible with a high opacity on the other hand the spatial relations between emphasized objects are difficult to recognize (see Fig. 2).

The key for the solution is employing object-based opacity maps with alternating opaque and semi-transparent stripes. They are mapped to the neck muscles in roughly the same direction as real fibers. For this purpose we use the calculated envelope of each muscle and compute its bounding cylinder. By using the normals of the muscle we transfer the texture coordinates from the cylinder to each vertex of the muscle. With this technique the real texturing of neck muscles is slightly indicated in the visualization. In [DCLK03] the identification of muscle fibres for hatching is presented. This technique was found to be too complex for our purposes, since neck muscles are regarded as context information only.

Structure	Red	Green	Blue
A. carotis	240	50	50
V. jugularis	80	80	250
Muscles	100	40	20
Skeletal structures	255	255	255
Salivary glands	180	150	110
Pharynx	255	190	150
Nerves	240	185	80
Primary tumor	255	255	200
Lymph nodes	255	255	150

Table 1: *Color table for the standardized visualization of neck structures*



(a) Neck structures drawn too transparent.

(b) Neck structures opaque.

Figure 2: *With object-based transparency assignment, the location of lymph nodes cannot be depicted effectively.*

To improve the visibility of lymph nodes and tumors, all colors from other objects are reduced in saturation and lightness. Especially skeletal structures are invisible during surgery and provide only spatial orientation, e.g. *Mandible* and *Clavicle* serve as landmarks. In Figure 3, the improved color selection for lymph node emphasis is shown.

Inspired by illustrations from textbooks [Net02], we use a material with shiny impression for vascular structures. This technique enhances the recognizability of vascular structures (cf. Fig. 3 or 6).

Segmented objects from clinical datasets mostly exhibit unnatural artifacts. Therefore we smoothed all objects visually (not geometrically), by assigning a slight self-illumination (emissive color in an SoMaterial node of OpenInventor) to these objects. This effected a visual flatness of the surface because the shading does not render hard contrasts (see the bones in Fig. 3 and 5).

Further visualization techniques were investigated. The use of silhouettes for highly transparent objects considerably increases the recognizability. As a result, silhouettes are used e.g. to enhance strongly transparent objects (see Fig. 3). We do not consider hatching as a promising technique for surgery planning. It seems to be challenging to reliably derive appropriate hatching parameters from the complex geometries of segmented objects. The improved spatial understanding is probably not significant to justify additional interaction effort.

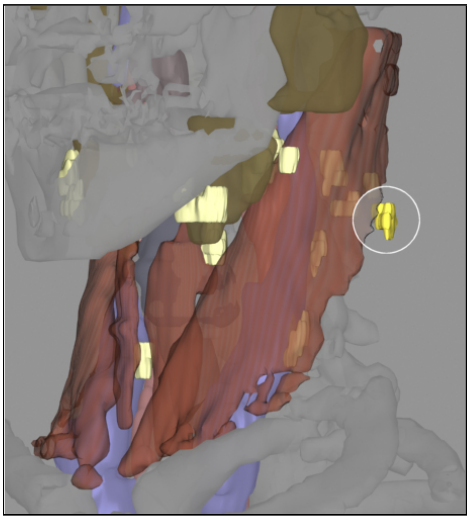


Figure 3: *Emphasized lymph node partially behind the M. sternocleidomastoideus. Note the use of a cutaway view as well as the thin silhouette line to enhance depth perception.*

In contrast, the use of cutaway views is promising. As an example, a muscle which is covering a tumor should be rendered only transparent in regions, where the tumor is behind. In Section 4.2 the use of cutaway views is presented.

3.3. Integrating Measurement in Neck Dissection Planning

Measurement tools to compute the extent of anatomic structures and the distance between structures are also provided [PTSP02]. With these tools (see Fig. 4), the extent of enlarged lymph nodes can be determined precisely. The measurements are directly included in the 3d visualization.

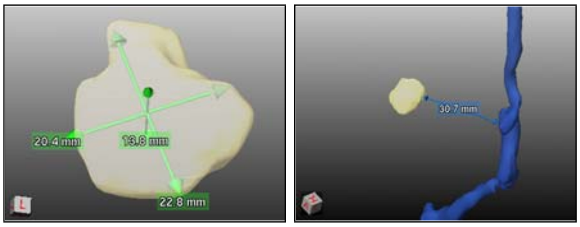
4. Interaction Techniques for Exploring Lymph Nodes

The exploration of a complex set of enlarged and therefore surgically relevant lymph nodes requires appropriate interaction techniques. The usual selection of objects via their name is not feasible. The selection of entire lymph node groups or via measurement results is more appropriate. Extent or minimal distances to risk structures are possible criteria. Two problems related to lymph nodes are essential for surgery planning: the exploration of enlarged lymph nodes (partly over 20) and the evaluation of infiltration or resectability of lymph nodes.

4.1. Sequential Visualization of Lymph Nodes

The basic interaction for the exploration of lymph nodes is the selection. We suggest a facility to step through all lymph nodes with a simple interaction. We found that the most interesting information are the quantity of enlarged lymph nodes and their potential malignity. Therefore, a simple list, ordered by the lymph node number, is not appropriate for exploration. In our planning tool we provide three different selection criteria - extent, volume or malignity from TNM-classification, discussed in Section 4.5.

As a feedback after selection, lymph nodes should become visible. It is not appropriate to render a large object, such as the *M. sternocleidomastoideus*, highly transparent, to expose a small lymph node. A better alternative is to render only a small part of the muscle transparent which can be achieved by cutaway views (see [VKG04]).



(a) Extension measurement of a tumor, automatically computed via principal axis transformation.

(b) Minimal distance between an enlarged lymph node and the *V. jugularis*.

Figure 4: *Measurement tools for automated computing the extent of structures and minimal distances.*

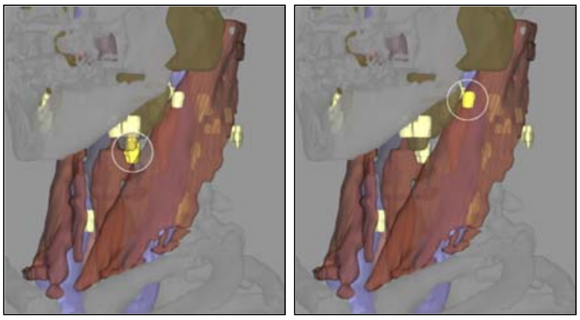
4.2. Emphasis with Cutaway Views

For the exploration of lymph nodes, we generate a cutaway view with a cylindrical cutting volumen. We calculate the convex hull from the lymph node in 3d and project it via OpenGL to the screen. From the result wie calculate the convex hull in 2d and finally the minimal enclosing circle plus a fixed margin around a lymph node. So with each step we reduce the involved points to enhance the speed. The resulting volume is cutting all structures in front of the lymph node. The cylinder is aligned orthogonal to the viewing plane and is terminated at the lymph node. OpenInventor, OpenGL 2.0 and the fragment shader functionality from modern GPUs is used to realize the cutting of the structures in realtime.

The intersecting parts of foreground objects within the bounding volume are displayed strongly transparent. However, the depth perception is limited in this region. Therefore a thin silhouette (see [IFH*03]) of the muscle is included brightly, calculated simply from the scalar product between viewing vector and the surface normals.

With these visualization parameters, foreground and background objects are correctly perceived. The emphasized area is additionally marked with a bright circle. The radius of this area is the same as the radius of the cutting cylinder. In technical illustrations in contrast, organic shapes or zigzag should be used to compute cutaway views (see [DWE03]). The lymph node is also visually enhanced by raising the saturation of color (see Figure 3 for the interactive visualization result).

As shown in Figure 5, this combination of visualization techniques is applicable also for multiple occlusions 5(a) or full visibility 5(b). Hence, the surgeon may interactively step through all lymph nodes, e.g. by pressing the tab key. The currently selected object (CSO) will always be clearly emphasized. We chose not to rotate the camera automatically to emphasize the CSO because of distracting effects.



(a) Lymph node behind the *M. sternocleidomastoideus* and the *Gl. submandibularis.*

(b) Lymph node in front of all other structures.

Figure 5: *Combining color, transparency mapping and a cutaway view to emphasize a single lymph node. In the interactive tool the stepping through all lymph nodes is facilitated.*

4.3. Visualizing Distances to Risk-Structures

For the evaluation of the resectability, distances to risk structures are crucial. We employ a distance-dependent coloring of the neck vessels and muscles which conveys the distance to the lymph nodes. With a discrete color scale (gradation: 2 and 5 mm) the resectability of this target may be evaluated.

The emphasized lymph node in Figure 6 is located in front of the *M. sternocleidomastoideus*, where the distance information is displayed. Two depending levels are encoded for the distance. For a well-defined separation of the structures in the 3d scene, the used colors were evaluated by the clinical partners and regarded as appropriate. This kind of accentuation leads to a more simple application for several objects, so the visual focus is located at the CSO. Distance information relating to multiple objects would more likely confuse the viewer.

A color-coding of the distances does not indicate an infiltration of a muscle or a vessel. We employ a line character accentuation (see [TIP05]) of the cut line which is marked above the illustration. In Figure 7, the potential infiltration of the *M. sternocleidomastoideus* is shown. According to the segmentation results, these lymph nodes reach into the muscle. In reality it is possible, that the muscle tissue is displaced, but not infiltrated. A displacement occurs considerably more often. Distance-related visualizations may be generated for each anatomic structure. Other relevant examples are the *A. carotis* and the *V. jugularis*.

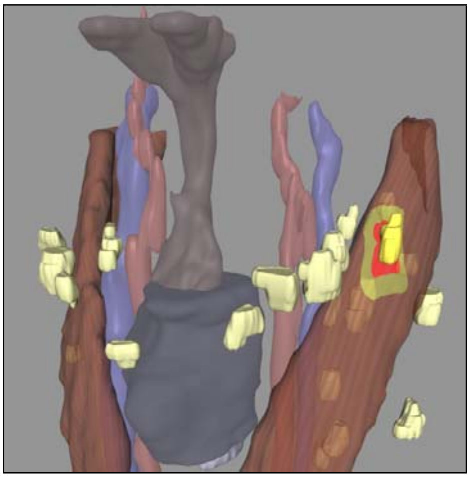


Figure 6: *Color-coded distance of a lymph node to the M. sternocleidomastoideus. The 2 mm distance is coded in red, 5 mm in yellow.*

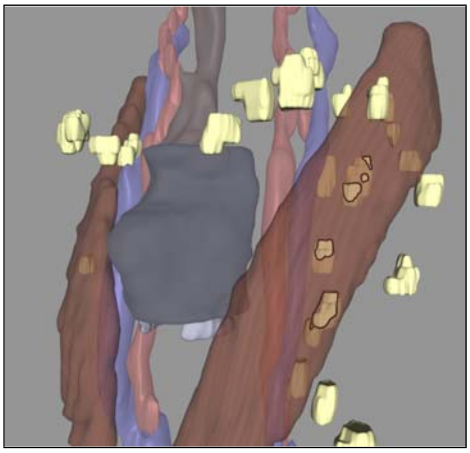


Figure 7: *Possible infiltration of the M. sternocleidomastoideus. Silhouette lines form an intersection line between muscle and lymph nodes.*

A drawback of this visualization technique is, that lymph nodes which are in front and potentially infiltrate the muscle, will not be accentuated in the current viewing position. Therefore the user should rotate the 3d scene. A color-coded view for potentially infiltrating lymph nodes is also provided for a fast overview.

4.4. Visualization of Lymph Node Size

Primarily, the size of lymph nodes is important. Medical doctors consider lymph nodes with an extent of more than 1 cm as critical (potentially malignant) and would resect them. Therefore, we generate an initial visualization which conveys the size of lymph nodes. In Figure 8, this is realized by a front view and color-coded lymph nodes. The color graduation appears via two discrete values: yellow for lymph nodes smaller than 1 cm and turquoise for extents beyond. Here, we emphasize lymph nodes larger than 1 cm minus the slice thickness, to account for possible inaccuracies from image acquisition and segmentation. The maximum extent is used to realize the color-coding. If this value exceeds the calculated threshold, the lymph node will be classified as bigger than 1 cm and is coded as enlarged. A discrete color-coding with more than two grades turns out to be inappropriate, because the surgical decision is of binary nature, too. In the real surgical procedure, all lymph nodes will be removed, that are palpably enlarged.

This visualization is based on data known from the segmentation process. All lymph nodes and tumors are measured automatically by a principal component analysis from which the extent is derived [PTSP02]. We do not calculate the volumes of lymph nodes since high measurement inaccuracies due to very small volumes are to be expected (volumetry is uncertain when a large portion of border voxels occurs).

By a mouse-over interaction, tooltips, respectively text boxes, fade in with the precise measurement values of extent and minimal distances to risk structures (see Fig. 8). For primary tumors the same interaction is provided.

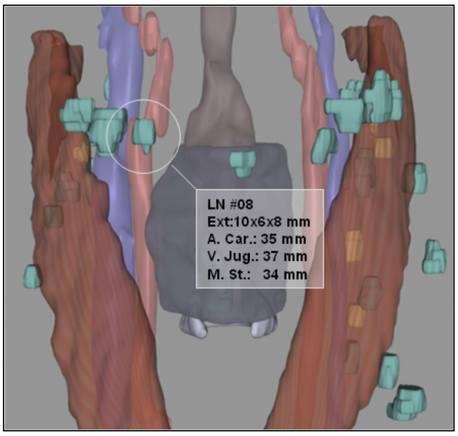


Figure 8: *Color-coded lymph node size. Two levels are used: yellow below 1cm and turquoise above. The exact values are readable via tooltip.*

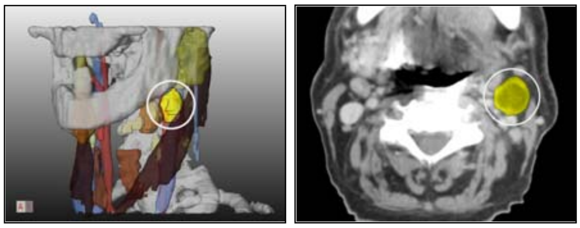
4.5. Malignity and TNM Classification

Surgeons grade the level of a tumor disease according to a fixed scheme, the TNM classification. It is constructed based on three numerical values, with possible levels for each. T stands for the tumor grade (five levels), N for the lymph node state (N0 or N1) and M for the level of distant metastases (M0 or M1). About the last one we cannot state anything with computer assistance, but the T and N values can be determined algorithmically.

The lower levels of the T-classification (1, 2 and 3) characterize mostly the size of pathological structures. Level 4 and 5 are assigned with respect to the infiltration of critical structures, such as vasculature. An adhesion with a neck arteria tends to a level 5 classification, because such cases are not resectable.

For tumor classification, the computer cannot perform an automatic estimation. The shapes vary strongly and the spatial relationships are too complex. A computer assistance for the surgeon is reasonable: According to the measurement results, the extent can be employed for a suggestion of the T-level is presented. By observing the 3d-visualization and the overlayed segmentation in the CT-slices (see Fig. 1), the surgeon can correct the initial level.

The N part of the classification can be automated. This is reasonable, because of the large number of lymph nodes in most cases. The extent of a lymph node is considered in determining conclusion about malignancy. Spherical structures are more likely malignant than longish ones and their roundness can be calculated by comparing the 3 principal directions.



(a) 3d-visualization. (b) Axial CT-slice.

Figure 9: *Representation of a lymph node with a central necrosis marked in 3d and in a 2d view.*

Another clue concerning malignancy is the inner gray value characteristic. A central necrosis has much darker values in the center than on the border. In Figure 9, such a case is shown. Detectable characteristics in gray values can be used for an automated N classification. If required, the suggested TNM is displayed on the screen border in our operation planning tool, like other patient data.

5. The Segmentation and Visualization Process

It was a major goal to produce comparable visualizations for different patient data. Besides the visualization, a procedure for the treatment of datasets is to be defined. This includes the type and resolution of the datasets, the application of segmentation methods, the type of visualization and the presentation of the results. We consider the following aspects of standardization:

- type and resolution of the processed datasets (CT, < 3 mm slice distance)
- standardized "order sheet" with specifications regarding structures, that should be segmented besides the standard in this case
- technique of segmentation for the different structures
- naming of the structures
- colors, views and types of visualization
- measurement of segmented lymph nodes, tumors and the distances to risk structures
- data exchange and result presentation on the project's web page

The segmentation and visualization is carried out as a service for the surgical partner in the framework of a research project. Patient datasets are always submitted with an "order sheet". By this, the diagnosis is stated and target structures and measurements besides the standard are listed (see Section 2).

The segmentation process is also standardized (sequence of segmentation tasks). However, parameters have to be adapted to each dataset. The result is presented as images and small animation sequences. 2d-slice views with the segmentation results (which are radiologically evaluated) transparently overlaid to the original data were created to support the verification of segmentation results and the mental integration of 3d visualizations with the underlying slice data. Selective clipping of bony structures was used to enhance the interpretation of the spatial relations. The clips, images and interactive 3d-data are available for the project partner via a secured web page.

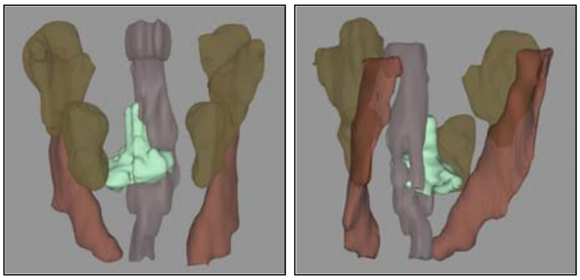
The average time for image analysis and creation of the visualizations was approximately 90 minutes. Most of the time was spent on the segmentation of lymph nodes.

6. Influence on Surgical Strategies

The visualization results were compared with the experiences of real surgical interventions. The surgeons attested a high degree of correspondence to intraoperative views. In some cases, the results of computer assisted planning were essential for the surgical decision.

For the surgeon it is necessary to evaluate distances to risk structures (see Section 4.4). The number of lymph nodes is employed to develop an understanding of the expected difficulty of the resection. These nodes are not visible in the neck area, but hidden in e.g. fatty tissue.

The above-mentioned information improves neck dissections with respect to speed and safety. In contrast, other information a priori can lead to choose another surgical strategy. If it turns out, that possibly important structures are infiltrated, the involved areas are not resectable, without previous radiation therapy. Therefore, it is important to estimate the resectability as reliably as possible and to choose the right surgical strategy preoperatively. In neck dissections, there are the following strategies: left or right sided and with different kinds of radicality e.g. with resection of muscles.



(a) Front view. (b) Back view.

Figure 10: *A large tumor (green) is infiltrating the Pharynx. The upper tail also infiltrates the cranial base.*

Figure 10 presents a case, where the tumor had a long tail, that was not noticeable on CT-slices. Due to the infiltration of the cranial base, the intervention had to be terminated unsuccessfully. The surgeon stated, that having seen the segmentation results in advance might have led to another surgical strategy. Currently, CT-data is acquired close before surgery. There is almost no time for preparing the operation planning.

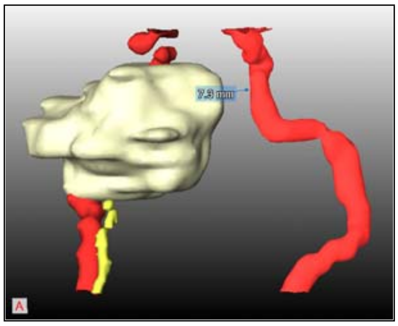


Figure 11: *N. hypoglossus (yellow) and A. jugularis (red). Notice the slice artifacts in the course of the nerve near the tumor (dark yellow).*

Information about the nerves are valuable, because they are often injured and patients carry away heavy intricacies for lifetime. Slice distance concerned in the project is 2-3 mm in average. A higher resolution is required to segment big facial nerves. Even then, only a partial segmentation is feasible, because their size and contrast is too small. This is the case even at the high resolution of the Visible Human dataset. Similar to [HPP*00], we model the course between selected points of the nerve. Instead of visually appealing B-Splines, we use simple lines with an appropriate thickness. Figure 11 shows such a segmentation result from a 1 mm slice distance data set. The visualization of the approximate course of the nerve was regarded as useful.

7. Conclusion & Future Work

We presented image analysis and visualization techniques for planning neck dissections. The focus of our work is the visualization of enlarged lymph nodes and the surrounding structures. The image analysis which requires considerable experience, is carried out as a service in the framework of a research project. As a result, surgeons are provided with standardized static visualizations and with standardized animation sequences, primarily rotations of different subsets of the relevant target structures. To explore the data themselves, they are provided with an interactive system with surface rendering and measurement facilities.

We attempted a standardized report consisting of images from standardized viewing directions. The correlation between 3d visualizations and the original 2d slices of the radiological data is crucial to assess whether the 3d visualizations are reliable. Therefore segmentation results are indicated as semitransparent overlays to the original CT-data. The potential of 3d visualizations for surgery planning cannot be fully exploited by means of standardization. Each and every case exhibits some peculiarities which require interaction techniques to explore them. In particular, the occurrence, number and size of enlarged lymph nodes differ from patient to patient. Therefore, we developed an "order sheet".

Our work is directed at a progress in planning neck dissections; more reliable preoperative decisions and more safety during the intervention are the primary goals. Our strategies to adjust 3d visualizations, to explore spatial relations, is applicable to other areas of computer assisted surgery. The use of silhouettes as well as the use of cutaway views to expose hidden pathologic structures turned out to be useful for surgery planning. Cutaway views are also useful for the exploration of round lesions (lung nodule) or small liver metastases.

Future work includes an in-depth user study to characterize the impact of 3d visualization on the surgical strategy. In this study, we will compare surgery planning based on conventional information (axial slices of CT-data) with surgery planning based on the additional information which is available after image processing. A specialized further development of the interactive planning tool, the "InterventionPlanner ENT" (ear nose throat), currently will be finished.

Acknowledgments

This work was carried out in the framework of a project supported by the Deutsche Forschungsgemeinschaft (DFG) (Priority Programme 1124, PR 660/3-1). Special thanks go to Jeanette Cordes and Ragnar Bade for good ideas and substantial support on visualization issues. Dr. Uta Preim validated image analysis results as radiologist.

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Eurographics/ IEEE-VGTC Symposium on Visualization (2006)
Thomas Ertl, Ken Joy, and Beatriz Santos (Editors)

Enhancing Slice-based Visualizations of Medical Volume Data

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Abstract

Slice-based visualizations of CT and MRI data are frequently used for diagnosis, intervention planning and intraoperative navigation since they allow a precise analysis and localization. We present new techniques to enhance the visualization of cross sectional medical image data. Our work is focussed on intervention planning and intraoperative navigation. We address the following problems of slice-based visualization in these areas: the lack of a graphical overview on the positions of anatomic structures, the localization of a target structure and the display of safety zones around pathologic structures. To improve the overview, we introduce LIFTCHARTs*, attached as vertical bars to a slice-based visualization. For localizing target structures, we introduce halos. These techniques restrict the occlusion of the original data to a minimum and avoid any modification of the original data. To demonstrate the usability of these visualization techniques, we show two application scenarios in which the techniques come into operation.*

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Display algorithms; J.3 [Life And Medical Sciences]: Medical information systems

1. Introduction

For the diagnosis of severe diseases, intervention planning and intraoperative monitoring, magnetic resonance imaging (MRI) or computer tomography (CT) data are acquired, such as cross sectional image data. Those modalities produce a set of slice images, which can be employed for 3D visualizations as well as for 2D slice-based visualizations. 3D visualizations provide an overview of the spatial relations which is appreciated for the diagnosis of complex pathologies as well as for many planning tasks. Slice-based visualizations, on the other hand, support a detailed analysis of the data and still represent the dominant mode of viewing CT and MRI data. For intervention planning and diagnosis, slice-based visualizations are always taken into account. Also, in anatomy education, *cross sectional anatomy* is an important aspect and deserves special attention. The Voxel-Man and the 3D Slicer for example, provide cross sectional images integrated in 3D visualizations [HPP*01, GKG*99].

Although slice-based visualizations are of paramount importance, in the visualization community research is focused almost exclusively on 3D visualization aspects, such as efficient and high-quality volume rendering, support for transfer function specification as well as efficient isosurface rendering. In this paper, we focus on slice-based visualizations and describe how these can be enhanced using segmentation information resulting from preoperative planning. Conventional slice-based visualizations do not provide an overview of relevant structures. As an example, when viewing the current slice it is not clear whether pathologies are above or below the current section and how many slices are in between. We present techniques to display distances to structures at risk, such as major blood vessels, simplify the localization of a target structure and target location. Moreover, we introduce an overview to a slice-based viewer. The original data is not modified and the occlusion by additional information is minimized. We consider applications for intervention planning as well as intraoperative navigation, where the relevant structures are segmented preoperatively [KTH*05].

In medical textbooks illustrative slice-based visualizations are common (Figure 1). In clinical applications, however, the unaltered data have to be displayed. Instead, the data may be enriched with additional information.

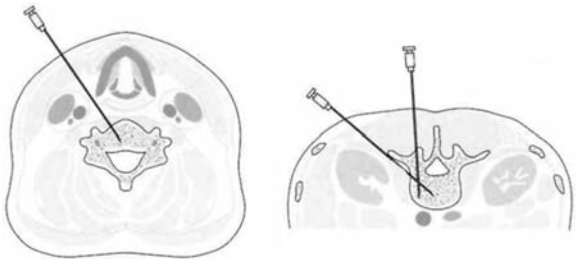


Figure 1: *Illustrative cross sectional images convey different strategies for the needle placement in the spine. From: [GP98]*

The remainder of this paper is organized as follows. Section 2 describes related work. Afterwards, we discuss the concept, driven by specific problems in computer-assisted surgery in Section 3. In Section 4, we describe the application of the visualization techniques to support two interventions from Ear-, Nose-, Throat surgery. Finally, in Section 5 we conclude the paper.

2. Related Work

[LE05] developed a 2D illustrative slice viewer to provide more information than the original data and visualize structures more effectively. To emulate example 2D illustrations, they composed a texture synthesis and color transfer method to generate illustrative 3D textures.

For preoperative liver surgery planning, [PBS*02] suggest the use of corresponding 2D and 3D viewers to exploit the advantages of both visualizations for interaction tasks, such as measurement and virtual resection. [LGF00] suggest the display of safety margins around liver tumors for risk analysis. [NWF*04] developed a virtual endoscopy system (STEPS), using 3D endoscopic techniques to aid in the navigation.

Research in intraoperative visualization focused on augmented reality solutions. [FNF*04] and [Sch03] track an intraoperative camera and project additional information derived from preoperative image analysis in the operating view. [MZK*05] investigate the usability of a *see through* screen, which enables the surgeon to look at the patient through a screen with the derived information. Birkfellner et al. propose the Varioscope, a light-weighted head-mounted operating microscope used as a head mounted display [BFH*00, BFH*02].

Commercial solutions, such as the VectorVision® family (BrainLab™) or NaviBase® (RoboDent™) employ three orthogonal slices and an optional view for a multi-planar reconstruction (MPR) or a 3D view. Additionally, target points are assigned by markers or crosshairs. These visualizations are not enhanced with any segmentation information derived preoperatively.

3. Concept

In this section, we introduce our concepts regarding three major problems of the exploration within slice-based visualization. In the following, we shall present conceptual solutions for those problems:

- *Graphical Overview:* On radiologic workstations, in general, only one slice is visible at a time. The display of more slices is feasible at the expense of image size and/or resolution. Even with several slices visible at a time, no overview is available.
- *Localization of Target Structures:* Especially for intraoperative navigation, the localization of target structures such as tumors is an urgent problem.
- *Safety Margins:* Malignant tumors have to be resected with a sufficient margin. Also, in intraoperative navigation it is important to maintain some distance from the structures at risk, such as nerves and blood vessels, to avoid damaging them.

Although our work is focused on medical visualization, we also consider other application areas to get ideas supporting an improved overview and localization of target structures.

3.1. Graphical Overview

For an overview of the segmented structures in a 2D visualization, it is essential to present the relative position of structures in the current slice as well as their positions in the third dimension, i. e. within the whole set of slices. For that purpose, we present a 2.5D approach to provide the essential information. In the following, we refer to the in-plane coordinates as x, y and the slice number as the z-dimension.

3.1.1. Graphical Overviews in Time Scheduling

The visualization problem that occurs here is similar to time scheduling. In this area, different techniques have been developed to visualize data entries and their temporal relations to each other. An appointment is characterized by an interval in time (t_{min}, t_{max}). Graphical overviews should present appointments distinguishable from each other and the temporal relations between appointments. Colored labels for different kinds of entries (e.g. private or business) and methods for handling chronological intersections allow a fast perception of the data. Examples for such techniques are found, for example, in Gantt charts or in the LifeLines project [PMR*96, PMS*98].

Translated to slice-based visualization, the interval of slices of the segmented structures corresponds to the lengths of appointments. We assume that each structure can be characterized by an interval of slices (z_{min}, z_{max}) to which it belongs. We do not consider disconnected structures occurring in several intervals. The current slice corresponds to the current time or date. Like appointments, the intervals of slices to which anatomic structures belong may overlap each other.

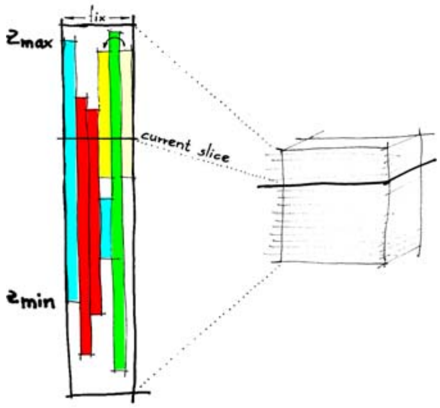
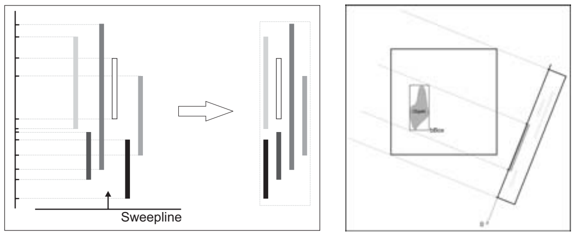


Figure 2: *Concept of the* LIFTCHART *widget. The colored bars represent z-dimensions of anatomical structures in a volume dataset (right portion).*



(a) Layout computation for the compact version

(b) Basic layout for MPRs

Figure 3: *Computation of the* LIFTCHART *layout. Left: the Sweepline moves from bottom to top and places the next available bar at the leftmost unused column. Right: the bounding box of the structure is used for computing the* LIFTCHART *from arbitrary directions.*

3.1.2. Graphical Overviews for Slice-based Visualizations

Similar to temporal overviews in time scheduling, we attach a narrow frame next to the cross sectional image that represents the overall extent of slices in the volume data set. The top and bottom boundary of the frame correspond to the top and bottom slice of the dataset. Each segmented structure is displayed as a bar at the equivalent vertical position inside this frame. The vertical extent of the bar represents the interval (z_{min}, z_{max}) for each structure. Upper bars correspond to higher structures in the body. Figure 2 presents a sketch of this concept. The overview is used to indicate in which slices certain structures occur. We refer to this combination of bars as LIFTCHART and regard it a widget which provides interactive facilities to locate structures and slices.

To achieve an optimal horizontal distribution of bars in the frame, they are ordered with a Sweepline algorithm [PS93]. The slices are processed from bottom to top and for each anatomic structure a bar is drawn in the leftmost available column. If a structure ends, the respective column is freed again and can hold the bar of a new structure starting farther above.

This visualization can be used not only in the standard cross sectional slices but also for MPRs, which cross the dataset in arbitrary direction. Here, the bounding boxes for each structure are projected onto a plane orthogonal to the MPR cutting plane which yields the appropriate extents of the structures (Figure 3(b)). The sorting algorithm remains the same.

The LIFTCHART enhances the recognition of relative positions of structures in the volume dataset by displaying their spatial relations. To simplify the correlation between the slice view and the LIFTCHART, the color and style (if different styles are used) of the bars should correspond with the color and style of the structures displayed in the slice view.

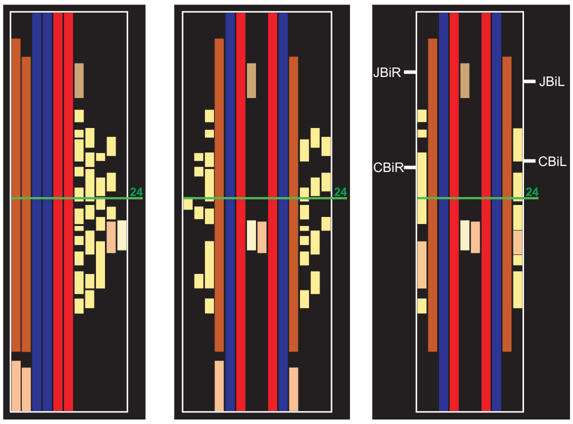
The currently displayed slice of the volume dataset is depicted by a horizontal line in the LIFTCHART widget. The slice number is displayed next to this representation. To visualize not only the z-distribution of structures in the volume, but also information about their horizontal position, we developed several arrangements of the bars in the LIFTCHART.

In Figure 4, some possibilities are displayed according to structures in the neck region. The LIFTCHARTs represent structures in the neck region. Muscles (brown), veins (blue), arteries (red) and the lung (skin-colored) are shown as context. The yellow bars represent lymph nodes, the tumor is represented as a beige bar. The green line denotes the current slice.

Figure 4(a) shows the most simple form including the optimization with the Sweepline algorithm. Each anatomic structure is represented by one bar. Note that due to the ordering, different categories of anatomic structures can be displayed in one column.

Separated LIFTCHART. Since some anatomic structures have a defined side, e. g. the left or right *Arteria Carotis Interna*, the LIFTCHART may be divided in three parts: one part for structures on the left and on the right side each and one part for structures in the middle (Figure 4(b)).

Aggregating Structures in the LIFTCHART. It is also possible to group bars which belong to the same class of anatomical structures to minimize the horizontal extent of the widget (Figure 4(c)). In contrast to Figure 4(a) and (b), the lymph nodes are aggregated into one column. The choice whether structures should overlap each other in the LIFTCHART or not depends on the clinical question. Pathologic lymph nodes are additionally emphasized by changing their color to a reddish tone. This is not possible in the other two versions of the LIFTCHART shown in Figure 4, because



(a) (b) (c)

Figure 4: *Different possibilities of arranging structures in the* LIFTCHART. *(a) shows the most simple form. Each anatomic structure is represented by one bar. In (b), the* LIFTCHART *is divided in three parts: one part for structures on the left and on the right side each and one part for structures in the middle. In (c), structures of one category are aggregated in one column. Additional landmarks for orientation are displayed.*

a different color denotes a different category of anatomic structures. Furthermore, landmarks for orientation in the dataset may be displayed at the frame of the LIFTCHART. As an example relevant for neck dissections, in Figure 4(c), the bifurcations of the *Vena Jugularis* (JBiL/JBiR) and *Arteria Carotis* (CBiL/CBiR) are indicated.

3.1.3. Interactive LIFTCHART

Besides visualizing intervals of slices, the LIFTCHART widget can be used for interaction and navigation. The horizontal slice indicator is operated like a normal scrollbar and moves through the slices. If the mouse is placed over a particular bar, specific information about the underlying anatomic structure is shown as a tool tip.

Directly selecting the LIFTCHART next to the bars moves the slice view to the slice number at the respective height. If a particular bar is selected, all slices containing the structure may be displayed by automatically cycling through the slices. In this way, a quick navigation between different structures on different slices is made possible.

3.2. Localization of Target Structures

For the localization of target structures, different techniques are known from other domains, like crosshairs or halos. Usually, crosshairs only show the exact location of one structure or position in a visualization. This position is indicated by the intersection point of two lines which form the crosshairs.

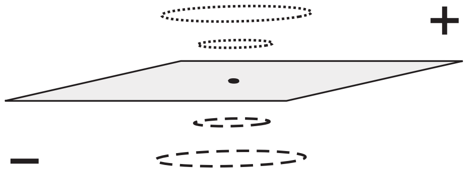


Figure 5: *The size of the halos depends on their distance from the target point (gray slice). The line style indicates if the current slice is above or below the target.*

For intraoperative navigation, one fixed structure (e.g. the tumor) needs to be focused while a second object (e.g. the surgical tip of tool) is tracked. Both positions need to be visualized.

3.2.1. Localization of Target Structures on Road Maps

Halos, as introduced by [BR03], are another technique to visualize distance and direction to a defined target. They are used for road maps on small displays to localize targets outside the visible screen area. These targets are marked by a circle with the respective distance as radius. The circles appear as circular arcs on the display since the center is outside the visible area.

3.2.2. Localization of Target Structures in Slice-based Visualizations

In contrast to road maps, in our scenario the target does not lay at the same level as the displayed section but either above or below. Therefore, the radius of the halo matches the difference in slices between the current section and the target point, whose *xy*-position specifies the center of the circle.

Given a target point in another than the current slice, a circle is drawn on the current slice with a radius equal to the distance between the current and the target slice. The line style of the circle indicates whether the position of the target is above or below the current slice (see Figure 5). If the current slice is moved towards the target, the radius of the circle decreases linearly with the target distance. To express the distance between the current slice and the target by the change of the radius, a non-linear decrease of the size might be preferable. This can be achieved by multiplying the computed halo radius with a function that increases the speed of decrease in radius the closer the target is. It is yet to be determined how much this modification affects the recognition of the distance between target and current slice. The linear form is preferable for viewing single slices since the size here is directly proportional to the distance. The non-linear form eases navigation since changes in size are larger the closer the target.

The already mentioned single crosshairs can be extended in such a way that the surgical tool (e. g. a drill) is tracked with the cross and the target region (tumor) is marked on

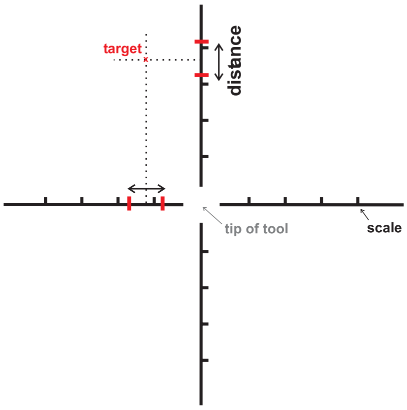


Figure 6: *The traditional crosshairs are enhanced to specify two points. The center is used to track a surgical tool, whereas the marks on the axes define a second target point.*

the lines that form the cross in different color or using tick marks. These markings for the target region can be varied according to the user's preferences – tick marks, colored regions, or a combination thereof. The center of these marks defines the *xy*-position of the target, whereas its distance to the current slice is depicted by the distance between the marks (Figure 6). The target direction can be color-coded or visualized by an arrow in the center of the crosshairs.

3.3. Slice-based Visualization of Safety Margins

Safety margins are useful for intervention planning and intraoperative navigation. During a tumor resection, the tissue around the tumor is also resected to be sure that all pathologic tissue is removed. During the intraoperative navigation, it is useful to give the surgeon a hint about structures at risk near the surgical tool.

To prevent structures at risk from damage, the distances of the surgical tool to such structures have to be carefully observed during the surgery and, therefore, to be displayed. Halos (in the original sense of the word) can convey this distance information. Therefore, for all structures at risk an Euclidean distance transform [Bor83, Loh98] is performed and the resulting distance information is overlaid on the slice image. We considered color-coding the distance information but rejected this idea, since presenting a color map would display too much information not relevant for the surgical strategy. Depicting important distance thresholds as halos by drawing two isolines representing defined distances turned out to be more appropriate in discussions with clinical partners. Thus, the quantitative distance information is reduced to a few categories which is easier to interpret. Note that these halos do not show distances to target structures as above but instead safety margins around structures.

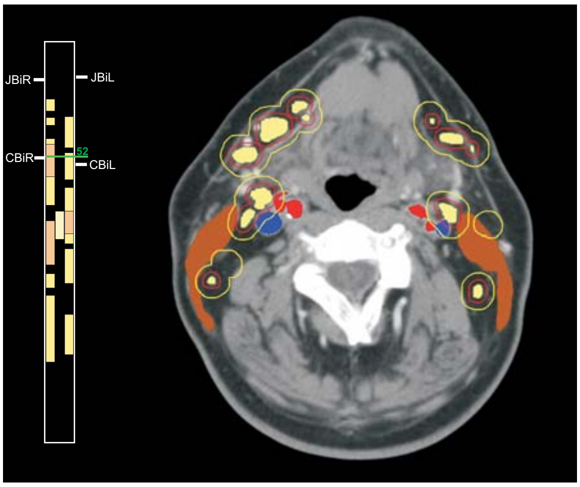


Figure 7: *The probably pathologic structures (tumor and lymph nodes) are shown in the* LiftChart. *The lymph nodes of one side are combined into one column. Enlarged lymph nodes are colored red. For the lymph nodes safety margins of* 2mm *(red) and* 5mm *(yellow) are shown.*

4. Application Scenarios

The enhanced slice-based visualizations are suitable for intervention planning and intraoperative navigation. To demonstrate the application of the techniques, we choose two different surgical interventions in the realm of Ear, Nose, Throat surgery (ENT) [KTH*05]. The segmentation of the relevant structures, which is a necessary prerequisite for the visualization, is accomplished with dedicated software assistants [APSH04, CDP*06]. Applications in other areas, like orthopedics, are also possible.

The first scenario relates to the planning of a neck dissection. Neck dissections cannot be carried out as minimally-invasive endoscopic interventions. Therefore, surgeons have direct visual access to the whole operative area and intraoperative navigation is less important. A graphical overview is essential since many anatomic structures are relevant, but the localization of a target structure is not necessary.

The second scenario relates to functional endoscopic sinus surgery (FESS) [Ken00]. For endoscopic interventions, intraoperative navigation is crucial because surgeons have no direct visual connection to the operative field.

4.1. Intervention Planning

Neck dissections are carried out for patients with malignant tumors in the head and neck region to remove lymph node metastases. The extent of the intervention depends on the occurrence and location of enlarged lymph nodes. If important structures are infiltrated, the involved areas are not resectable. Therefore, it is important to estimate the resectabil-

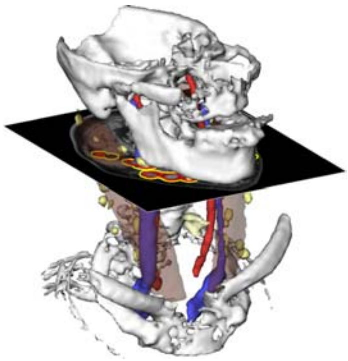


Figure 8: *Corresponding 3D visualization of Figure 7. Margins for lymph nodes outside the current slice are also visible.*

ity as reliably as possible. In neck dissections, there are the following strategies: left or right sided and with different kinds of radicality e.g. with resection of muscles.

A lot of structures have to be taken into account (e. g. muscles, vessels, nerves and up to 60 lymph nodes). In addition, critical distances or infiltrations of lymph nodes into important structures have to be identified. These two tasks can be supported using the LIFTCHART and the safety margin visualization.

Due to the (potentially) large amount of lymph nodes, all lymph nodes of one side may be combined in one bar indicating in which slices lymph nodes may occur. The separation in lymph nodes located at the left and right side is motivated by the surgical strategies (left and/or right-sided surgery). The identification of pathological lymph nodes is important, thus, all noticeable nodes are emphasized.

Some elongated structures like muscles and vessels occur in all slices, and are therefore not displayed (Figure 7). Other structures like the larynx are displayed, because they represent important landmarks for the orientation in the dataset. The safety margins are shown for all enlarged lymph nodes. Since the distances are computed in 3D, margins for lymph nodes outside the current slice are also visible (Figure 8).

While this application of the LIFTCHART is application-specific, similar considerations are applicable to other intervention tasks. Due to the symmetry of the human body, the separation of the LIFTCHART into a left and right portion is often useful.

4.2. Intraoperative Navigation

Endoscopic sinus surgery is an effective approach for removing lesions, including benign tumors, skull base defects with reduced trauma for the patient. Functional endoscopic sinus surgery is often supported by intraoperative navigation, especially in complex cases like relapse surgeries where important landmarks are missing. Computer-assisted navigation is regarded as a necessity when a tumor in a critical area should be removed [SKR*05]. As an example, navigation is used for the resection of tumors in the skull base in order to protect *Nervus Opticus* and *Arteria Carotis Interna*. The distance of a structure at risk to the surgical tool and the localization of the pathologic structure has to be supported visually.

In practice, the tip of a surgical tool, e. g. a drill or simply a pointer, is tracked and visualized on the screen of the navigation system. The screen shows in general three orthogonal slices or an MPR using crosshairs to denote the tip of the tool. The surgeon cannot see structures lying on a slice aside. We propose to integrate the visualization of safety margins and the halo technique in these visualizations.

In our scenario, we focus on a tumor near to the skull base. The surgeon has to navigate the surgical tools deep into the nasal cavity, passing a lot of bone lamella, so it is possible to get lost, even for a skillful surgeon. Near to the skull base the already mentioned *Arteria Carotis Interna* is located. Figure 9 demonstrates an orthographic view. The halo guides the surgeon to the tumor and the crosshairs track the tip of the tool. The different line styles of the halos indicate the required moving direction.

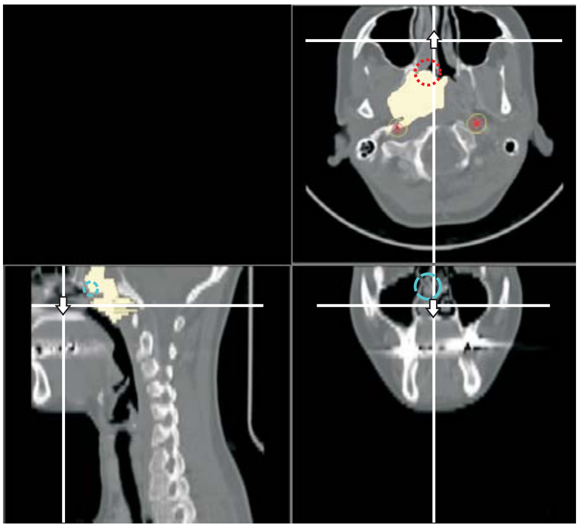
5. Conclusion & Future Work

We present new approaches for enhancing slice-based visualizations for surgical planning and intraoperative navigation. Our methods address the basic problems of slice-based visualization, namely the lack of an overview in cross-sectional images, the difficulty of localizing target structures, and the display of safety margins.

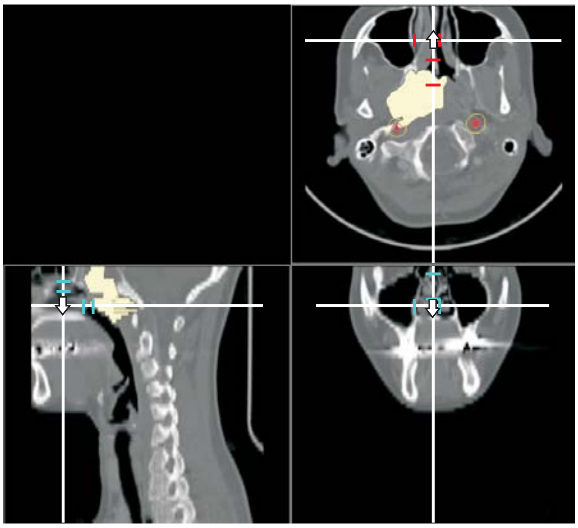
For the intraoperative visualization, we developed techniques supporting a target-driven navigation of surgical tools using the halo technique. Furthermore, we support intervention planning, because the occlusion problem is circumvented using the LIFTCHART. The division in columns representing the left and right sides directly supports the surgical strategy.

The enhancement of slice-based visualization using illustrative techniques has great potential. The work presented here is based on informal discussions between computer scientists and medical doctors specialized in ENT surgery. To enable a more goal-oriented development of the visualization techniques, a clinical evaluation of the visualization techniques is important.

The slice-based visualizations cannot substitute 3D visualizations. Especially in intervention planning, 3D visualizations convey the spatial relationships among structures. To achieve correspondence between slice-based and 3D visualizations, the rendering styles and coloration have to be consistent in the 2D and 3D visualization as well as in the LIFTCHART.



(a) The halo guides the surgeon to the target point. If the tool has to be moved upward, the lined red is shown. The stippled blue halo indicates a movement in the other direction.



(b) The crosshairs depict the current position of the surgical tool. The both marks on each hair indicate location and distance to the target.

Figure 9: *Intraoperative navigation in an orthogonal view. A surgical tool has to be moved to the tumor. The arteries may not be harmed. The crosshairs depict the current position of the surgical tool. The arrow in the center of the crosshairs is useful for navigation on narrow space. Not the xy-direction is indicated, but the direction in z-direction. The safety margin to the artery gives a hint whether the tool is navigated too close to it.*

We are considering several extensions of the LIFTCHART widget. For example, the distance to structures at risk could be color-coded into one bar. Other illustrative rendering styles, like stippling, hatching or silhouettes are also suitable to discriminate structures in the LIFTCHART. Furthermore, the cross sectional images themselves may be enhanced with illustrative rendering techniques primarily for educational purposes.

Acknowledgments

This work was carried out in the framework of a project supported by the Deutsche Forschungsgemeinschaft (DFG) (Priority Programme 1124, PR 660/3-1). Special thanks go to Jana Dornheim and Jeanette Cordes for segmentation and Oliver Burgert (ICCAS) for his helpful suggestions.

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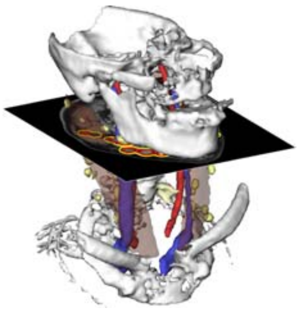

Figure 8: *Corresponding 3D visualization of Figure 7.*

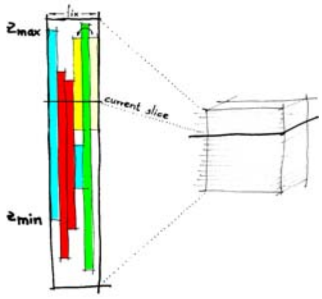

Figure 2: *Concept of the* LIFTCHART *widget.*

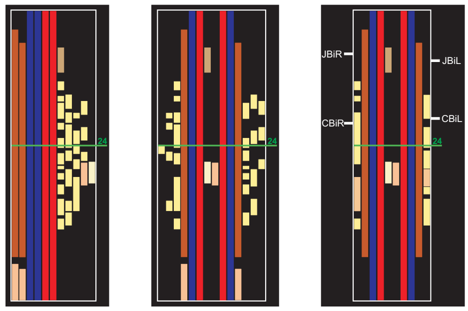

Figure 4: *Possibilities of arranging the* LIFTCHART.

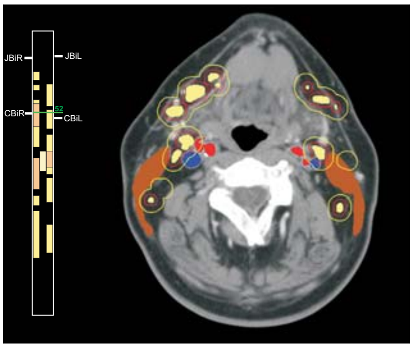

Figure 7: LIFTCHART *and safety margins.*

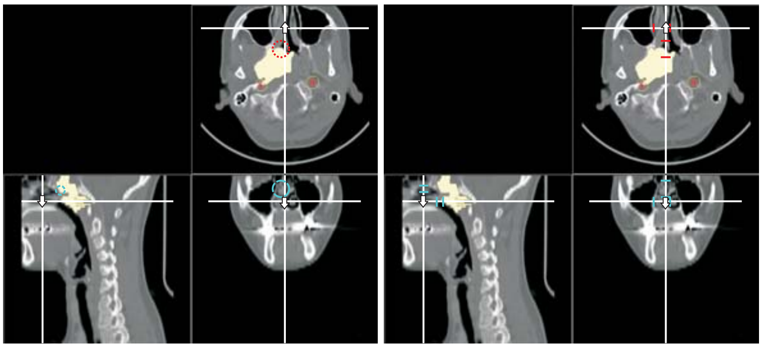

Figure 9: *Intraoperative navigation in an orthogonal view.*