Perception for Visualization

Nicholas F. Polys Ph.D.
VT Research Computing
theory = conceptual description of reality

experiment = test theory in physical world
model = formal representation of reality

simulation = behavior of model over time

Scientific method, 1950-present
model = formal representation of reality
simulation = behavior of model over time

Scientific method, 1950-present
Virtual environments can connect all models and simulations together

Scientific method, emerging 21st century
The Big Problem

Data Transfer

Data

Human

How?

Vision: Aural: Smell: Haptics Taste
Human Vision

- Highest bandwidth sense
- Fast, parallel
- Pattern recognition
- Pre-attentive
- Extends memory and cognitive capacity
  - (Multiplication test)
- People think visually
- Brain = 8 lbs, vision = 3 lbs

Impressive. Let's use it!
A definition

• Generally:
  – The use of computer-supported, interactive, visual representations of data to amplify cognition
    Card, McKinlay and Schneiderman
  – Scientific Visualization
  – Information Visualization
  – Virtual Environments
Visual Thinking

• Many of the great scientists were good at visual thinking:
  – Leonardo da Vinci
  – James Clerk Maxwell
  – Michael Faraday
  – Albert Einstein

• This was often at the expense of verbal skills

• Tom West: “In the Mind’s Eye”
  – See also http://www.krasnow.gmu.edu/twest/maxwell_visual.html

Maxwell’s clay model now in New Cavendish Laboratory, Cambridge
(picture by Tom West)
Goal

Data transfer

Data

Insight
(learning, knowledge extraction)
Method

Data transfer
Insight

Map: data → visual

Visualization

Visual transfer
(communication bandwidth)

~Map⁻¹: visual → data insight
Visual Mappings must be:

- **Computable** (math)
  \[ \text{visual} = f(\text{data}) \]

- **Comprehensible** (invertible)
  \[ \text{data} = f^{-1}(\text{visual}) \]

- *Creative!*
Visual Structure

- Spatial substrate
- Visual marks
- Visual properties
Visual Mapping: Step 1

1. Map: data items $\rightarrow$ visual marks

Visual marks:
- Points
- Lines
- Areas
- Volumes
- Glyphs
Of course, statistical graphics, just like statistical calculations, are only as good as what goes into them. An ill-specified or preposterous model or a puny data set cannot be rescued by a graphic (or by calculation), no matter how clever or fancy. A silly theory means a silly graphic:

**Solar Radiation and Stock Prices**

In this aggregation of individual deaths into six areas, the greatest number is concentrated at the Broad Street pump.

In this aggregation of the deaths, the two areas with the most deaths do not even include the infected pump!

Using different geographic subdivisions, the cholera numbers are nearly the same in four of the five areas.

Spatial Domain Reprise

What is the difference and when would you use one or the other?

- Finite Difference
- Finite Element
Visual Analysis Overview

Figure 2.1: Processing in a typical visualization pipeline (from Card et al, 1999)
Visualization Pipeline

1. Raw data (information)
2. Data tables
   - Data transformations
3. Visual structures
   - Visual mappings
4. Visualization (views)
   - View transformations
5. User interaction
# Data Table

**Attributes**  (aka: dimensions, variables, fields, columns, …)

**Values**
- Data Types:
  - Quantitative
  - Ordinal
  - Categorical
  - Nominal

**Items**  (aka: tuples, cases, records, data points, rows, …)

<table>
<thead>
<tr>
<th>Year</th>
<th>Length</th>
<th>Title</th>
<th>Subject</th>
<th>Actor</th>
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Attributes

- Dependent variables (measured)
- Independent variables (controlled)

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<th>Year</th>
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<td>...</td>
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Fundamental Data Types

- Spatial / perceptual data: 
  geometry, colors, textures, lighting
- Abstract data / world & object attributes:
  nominal, ordinal, quantitative
- Temporal data / behaviors:
  states, dynamics
Data Transformations

• **Data table operations:**
  - Selection
  - Projection
  - Aggregation
    - \( r = f(\text{rows}) \)
    - \( c = f(\text{cols}) \)
  - Join
  - Transpose
  - Sort
  - …
First Steps

Extract data and Map

• Data transformation
  – Raw data -> attributes of interest
  – File formats or scripts are usually employed

• Visual attributes
  – Assign attributes -> visual representation
  – Typically use some tool (e.g. Paraview, Excel, Gnuplot)
Second Steps

Publish and Deliver

• View transformation
  – ‘Camera’ location and properties

• Rendering assignment
  – Print vs. interactive
  – Resolution, size
  – Stereo, immersion
Visualization Pipeline

- Raw data (information)
- Data tables
- Visual structures
- Visualization (views)

Data transformations
Visual mappings
View transformations
User interaction

task
Visual Encoding Examples

Sci Vis

- Spatial substrate
- Visual ‘marks’
  - Visual properties
  - Time-varying
Visualization

• An instrument / tool to
  – look at your data and see things otherwise hidden…
  – Amplify Cognition

• 3 key stages:
  – Transforming data
  – Encoding data
  – Delivering / Rendering
Visual Analysis Overview

![Diagram of a visualization pipeline](image)

**Figure 2.1: Processing in a typical visualization pipeline (from Card et al, 1999)**
Information Visualization

Mantra

(Shneiderman)

- Overview first, zoom and filter, then details on demand
- Overview first, zoom and filter, then details on demand
- Overview first, zoom and filter, then details on demand
- Overview first, zoom and filter, then details on demand
- Overview first, zoom and filter, then details on demand
Rewind- to first principles

- The human mind is still the best analyst; how do we:
  - discover trends and relationships
  - communicate concept and results graphically
- How can perception inform design?
What is HCI?

- A multidisciplinary science of the interface: *psychology, design & media, human factors, sociology, computer science*

- Experimental methods to rationalize UI features, design, and software architecture
Norman’s Gulfs

Gulf of Evaluation
- Interpretation
  - Making sense
- Perception
  - Execution

Gulf of Execution
- Action Plan
  - Task / System Goal
- System Interface
  - User Mental Model

Virginia Tech
Communication
Across the Gulfs

User-centered design:

• **Evaluation** : Information Design
  – What do I see?
  – What does it mean?

• **Execution** : Interaction Design
  – What is my next goal?
  – How do I achieve it?
  – Make it happen!
HCI Design Process

- Iterative, progressively concrete
HCI UI Evaluation Metrics

- **User learnability:**
  - Learning time
  - Retention time

- **User performance:** ***
  - Performance time
  - Success rates
  - Error rates, recovery
  - Clicks, actions

- **User satisfaction:**
  - Surveys

Not “user friendly”
Visualization Design

• Analyze problem:
  • Data: schema, structures, scalability
  • Tasks/insights
  • Prioritize tasks and data attributes

• Design solutions:
  • Data transformations
  • Mappings: data→visual
  • Overview strategies
  • Navigation strategies
  • Interaction techniques
  • multiple views vs. integrated views

• Evaluate solutions:
  • Analytic: Claims analysis, tradeoffs
  • Empirical: Usability studies, controlled experiments
Information Design

Goal: identify methods for representing and arranging the objects and actions possible in a system in a way that facilitates perception and understanding.
Information Design

• Define and arrange the visual (and other modality) elements of a user interface
  – Screen layout, icon design, vocabulary selection
  – But also the “big picture” or overall info model
  – Models of perception, psychology guide this

• Engineering an information design
  – Make sure what people see (hear, etc.) makes sense, and helps them to pursue meaningful goals
  – Depends on what they are doing, hence the important role of user interaction scenarios
Good Graphics

- Precision
- Clarity
- Maximize Data-to-ink ratio
  - Data Ink Ratio = (data ink) / (total ink in the plot)
- Minimize Lie factor
  - Lie factor = (size of graphic) / (size of data)
Making Sense of an Information Display

**Perception**
color, shading, lines
characters, squares, spatial organization

**Interpretation**
Excel worksheet, a cell is selected, formula is displayed at top

**Making Sense**
Income worksheet, Total tax income is being calculated, the wrong multiplier is being used

Last month’s budget...?
Perception for Design

• Using our understanding of the human perceptual systems to guide design
  – Visual system
  – Auditory system
  – Vestibular system
• Leverage pre-attentive facilities
• Reduce cognitive overhead
Perception

• Organize and encode sensory data in the mind
  – Lines, shapes, colors are “extracted”
  – Very fast, generally with no conscious thought
  – May be influenced by expectations, “top-down”

• Low-level units then grouped and organized
  – Perceived as rows, columns, grids, figures
  – Seeing the relationships among different elements

• Design goal: make this perceptual process rapid and accurate
Background: Information Psychophysics

- Donald Norman, *Cognitive Engineering* (1986)
Pre-attentive Processing

• Involuntary, do not require conscious attention
• Parallel
• Efficient
• Resistant to instruction
Attention

- Pop out effects ‘stand out’ in some simple dimension (conjunctions don’t):
  - Rapid visual search
  - Form, color, simple motion/blinkng, spatial stereo depth, shading, position

12987621909023748
59432908706548394
05602485954372890
09890509874632234
Frame Rate

• Threshold for perceiving continuity:
  – flicker < 50 Hz
  – > 24 fps looks smooth & plenty interactive

• Flicker & Attention can lead to change blindness (Simmons, 2000)

• Browser.getCurrentFrameRate()
• Implementing X3DPerFrameObserverScript
  - public void prepareEvents (){}
Attention and blindness

- [http://viscog.beckman.uiuc.edu/djs_lab/demos.html](http://viscog.beckman.uiuc.edu/djs_lab/demos.html)
Animation Guidelines

- The higher the frame-rate the better
- Beware data assumptions: *Interpolation versus Sequencing*
- Provide user control over time? (e.g. DVDT imeController)
Representing multiple properties

- Flow of air around a car
  - Vectors and particle paths illustrate flow
  - Coloured slice indicates pressure
Features: Color

- Luminance channel (3x spatial accuracy)
- Red / Green channel
- Yellow / Blue channel

The spectrum is not a perceptually linear sequence (not pre-attentive)!
(Keller 1993; Ware, 2000)
Color (again)

- **IBM Research and color maps:**

- **Human factors in visualization research**
  Tory, M.; Moller, T.;
  Visualization and Computer Graphics, IEEE Transactions on
  Volume 10, Issue 1, Jan-Feb 2004 Page(s):72 - 84
  http://doi.ieeecomputersociety.org/10.1109/TVCG.2004.1260759

- **Color Spectra and Scales**
  http://geography.uoregon.edu/datagraphics/EOS/Light&Bartlein_EOS2004.pdf

- **Some guidelines for Sci Vis:**
  http://www-ugrad.cs.colorado.edu/~csci4576/SciVis/SciVisColor.html#ColorGuidelines

- **More detail about CG color models**
  http://www.ncsu.edu/scivis/lessons/colormodels/color_models2.html
Making Sense of an Information Display

**Perception**
color, shading, lines
characters, squares,
spatial organization

**Interpretation**
Excel worksheet, a cell
is selected, formula is
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**Making Sense**
Income worksheet,
Total tax income is being
calculated, the wrong
multiplier is being used

Last month’s budget...?
Interpretation

• Perceiving enables interpretation
  – Perceptual processing identifies major display structures (rectangles, text strings, etc)
  – Users must interpret what these display structures mean in the system
• Designers must anticipate and support user reactions to interface elements
  – Choosing familiar images, symbols, words
  – Refining elements through abstraction
  – Promoting affordances that users can recognize
Depth Cues

Structure the world- locating objects and relationships in space

• Stereoscopy
• Motion parallax
• Relative size / scale
• Fog / atmosphere…
Patterns & Grouping

- Gestalt principles
- Also: continuation, closure, common fate
- Guiding Law of Pragnanz (simplest, most stable configuration)
Gestalt principles

- Palmer & Rock, 1990—review & update principles; grouping based on perceived proximity in 3D space (not 2D proximity on retina)
- Quinlan & Wilton, 1998—study involving Gestalt conflict; proposed resolution mechanisms
Objects

• Feature Binding – putting the streams together for internal representation
  – color, form, motion
  – Just in time?
• 2.5 D sketch (Marr, 1982)
• Geons (Biederman, 1993)
Fundamental Data Types

- Spatial / perceptual data: 
  *geometry, colors, textures, lighting*

- Abstract data / world & object attributes: 
  *nominal, ordinal, quantitative*

- Temporal data / behaviors: 
  *states, dynamics*
## InfoVis: Visual Markers

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<td>position density color texture connection containment length angle slope area volume (Mackinlay, 1986)</td>
<td>position color texture connection containment density shape length angle slope area volume (Mackinlay, 1986)</td>
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PathSim example
- Which state has highest income?
- Relationship between income and education?
- Outliers?

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<tr>
<td>Louisiana</td>
<td>19.4%</td>
<td>10635</td>
</tr>
<tr>
<td>Maine</td>
<td>25.7%</td>
<td>12957</td>
</tr>
<tr>
<td>Maryland</td>
<td>31.7%</td>
<td>17730</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>34.5%</td>
<td>17224</td>
</tr>
<tr>
<td>Michigan</td>
<td>24.1%</td>
<td>14154</td>
</tr>
<tr>
<td>Minnesota</td>
<td>30.4%</td>
<td>14389</td>
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Evolución of Salaries

$ vs. Year

- Group A
- Group B


Salaries in dollars over time.
Lying

From Tufte
1983

THE SHRINKING FAMILY DOCTOR
In California

Percentage of Doctors Devoted Solely to Family Practice

<table>
<thead>
<tr>
<th>Year</th>
<th>1964</th>
<th>1975</th>
<th>1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>27%</td>
<td>16.0%</td>
<td>12.0%</td>
<td></td>
</tr>
</tbody>
</table>

T: 3,167
I: 4,232
5,212

T: 2,247
I: 8,823

OPEC Oil Prices: After 18
Months of Stability, Prices Are
Due to Rise Again

Dollars per barrel

Yearly

Quarterly


Los Angeles Times, August 5, 1979, p. 3.
Human Limitations for Short-Term Memory

- **Miller’s 7 +/- 2 magic number**
  - People can recognize 7 +/- 2 chunks of information at a time and hold these chunks in memory for 15-30 seconds

- **Chunking**
  - Ability to cluster information together
  - Size of chunk depends on knowledge, experience, and familiarity
Chunking Example 1

HEC ATR ANU PTH ETR EET
Chunking Example 2

THE CAT RAN UP THE TREE
Other Chunking Examples

- Image sequences
- Facial recognition
- Word/letter familiarity
- Hierarchies of information
- Others?
Making Sense of an Information Display

**Perception**
color, shading, lines
characters, squares, spatial organization

**Interpretation**
Excel worksheet, a cell is selected, formula is displayed at top

**Making Sense**
Income worksheet, Total tax income is being calculated, the wrong multiplier is being used

Last month’s budget...?
Making Sense

• Last step in crossing the Gulf of Evaluation
  – Information has been perceived and interpreted
  – Users must “make sense” of information by relating it to their tasks, goals, and interests
• Designers must support people’s abilities to detect patterns and relationships
  – Consistent use of shape, size, color, position
  – Information models (e.g., hierarchies) organize data
  – Dynamic displays cue users to structure
Important Considerations

• Understanding the domain
• Understanding the Research Question
• Understanding the purpose of the Vis – User and reader tasks
Which network is easier to understand?

See Graph Vis!
Graph Layout is still hard

- Prefuse.org – GraphML
- GraphVis – dot format
- Network Workbench - nwb
http://nwb.cns.iu.edu/
Context Required
Immersive Virtual Environments

• Leveraging Spatial perception and knowledge
• Embodied interaction
• Examples
• More at last class!
Stereo Walls

Torg (active)  Andrews (passive)

3-4 additional in labs around campus
ParaView

• Use your knowledge to present the important aspects of the simulation data as:
  • An image
  • A movie