Automating the Design of Visualizations

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Good Design Improves Usability

- Visualizations are common
  - Newspapers, textbooks, training manuals, scientific papers, …
- Creating effective designs is time-consuming

Challenge

- Best visualizations are designed by humans
- Computing becoming ubiquitous
  - Data collection / dissemination getting faster
  - Most displays computer generated
- Therefore: Visualizations are regressing

- Can we build automated systems capable of designing effective visualizations?

Automation Allows Customization

- **Purpose:** Present data relevant to specific goals
- **Device:** Adapt to capabilities of display
- **Situation:** Update as data / goals change
- **Person:** Adapt to knowledge of user
- Customization increases effectiveness

Emulating Artistic Rendering Styles

- **Artistic rendering can improve perception**
- High-level design still specified manually
Automated Design as Optimization

- Page design
  - TeX [Knuth 81], GRIDS [Feiner 88], LayLab [Graf 92], [Westman & Wittenburg 94], [Sconing et al. 97, 00]
- 3D object visualization
  - APEX [Feiner 85], IBIS [Seligmann & Feiner 91], WIP [Rist et al. 94]
- Data graphics presentations
  - APT [Mackinlay 86], SAGE [Roth et al. 94, 96], SYSTAT [Wilkinson 99]
- UI layout, Label layout, VLSI design, Camera planning, 2D/3D packing, Graph drawing, …
- Need domain specific constraints

Outline

- Motivation
- Automated Route Map Design
  - Framework for Automated Design
  - Automated Assembly Instruction Design
- Future Directions

Contributions

- Analysis
  - Identify design principles
    - Route maps
    - Assembly instructions
- Synthesis
  - Automated design systems

Visualizing Routes

- Standard online route maps difficult to use

A Better Visualization

- Hand-drawn maps much easier to use

Communicative Intent of Route Maps

- Route is a sequence of turns [Tversky 92] [MacEachren 95]
  1. Start at 100 Serra
  2. Turn Right on University
  3. Turn Left on El Camino
  4. Turn Right on San Antonio
  …
- Verbal directions emphasize turns [Denis 97]
- Hand-drawn maps highlight turns [Tversky & Lee 99]
- Maps must communicate turning points
Depicting Turns

- Pair of roads (entering / exiting the turn)
- Turn direction (left / right)
- These graphic elements must be visible

Context can Facilitate Navigation

- Local context
  - Consistency checks
    - Cross-streets
    - Landmarks along route
    - Distance along each road
  - Overview context
    - Orient route to geography
    - Large area landmarks
    - Overall shape & heading
- Context is secondary to turning points

Geometric Properties Distorted

- Geometry not apprehended accurately [Tversky 81]
- Geometry not drawn accurately [Tversky & Lee 99]
- Topology is accurate

LineDrive: Route Map Design System

- Hand-drawn Route Map
- LineDrive Route Map

Automating Route Map Design

- Layout problem
  - Set of graphic elements
    - Roads
    - Labels
    - Cross-streets
  - Choose visual attributes
    - Position
    - Orientation
    - Size
  - Distortions increase choices
  - Large space of possible layouts

Layout as Search-Based Optimization

- Hard constraints
  - Required characteristics
- Soft constraints
  - Desired characteristics
- Challenge: Develop relevant constraints
- Simulated annealing
  - Perturb: Form a layout
  - Score: Evaluate quality
  - Minimize score
Cartographic Generalization
- Selection
- Simplification
- Exaggeration
- Regularization
- Displacement
- Aggregation

[Monmonier 96], [MacEachren 94], [DiBiase 91]

Three Generalizations for Route Maps
- Our observations from hand-drawn examples:
  - Exaggeration
    - Road length
  - Regularization
    - Turning angle
  - Simplification
    - Road shape
- Generalizations emphasize turning points!

Exaggeration: Length Generalization
- Grow short roads, shrink long roads
  - Ensures all roads visible
  - Maintain relative ordering by length

Regularization: Angle Generalization
- Regularize turning angles
  - Reduces visual complexity
  - Maintain consistent turn direction

Simplification: Shape Generalization
- Simplify roads to straight lines
  - Differentiates roads and turning points
  - Maintain overall shape of route

Request for Directions
Route Finding Service
Route Data
- LineDrive
- Shape Simplification
- Road Layout
- Label Layout
- Context Layout
- Decoration
- Route Map
Stage 2: Road Layout

- Goal: Choose road lengths & orientations

Road Layout Search

- Initialize
  - Uniformly scale route to fit given viewport

- Perturb
  - Pick random road
  - Either
    - Rescale by random factor
    - Reorient by random angle
  - Rescale entire route to fit viewport

- Hard Constraints
  - Must fit in viewport
  - Must maintain consistent turn direction

Designing Soft Constraints

- Challenges
  - Choose desirable characteristics
  - Express as numerical score function
  - Balance constraints, deal with conflicts

- Desired characteristics for road layout
  - All roads visible
  - Prevent excessive distortion

Constraints

- Length
  - Ensure all roads visible: \((L_{\text{min}} \cdot l(r_j)/L_{\text{max}})^2 \cdot W_{\text{small}}\)
  - Maintain ordering by length: \(W_{\text{shuffle}}\)

- Orientation
  - Maintain original orientation: \(|\alpha_{\text{curr}}(r_j) - \alpha_{\text{orig}}(r_j)| \cdot W_{\text{orient}}\)

- Topological errors
  - Prevent false: \(\min(d_{\text{orig}}, d_{\text{dest}}) \cdot W_{\text{false}}\)
  - Prevent missing: \(d \cdot W_{\text{missing}}\)
  - Ensure separation: \(\min(d_{\text{dest}}, E) \cdot W_{\text{ext}}\)

- Overall route shape
  - Maintain endpoint direction: \(|\alpha_{\text{curr}}(v) - \alpha_{\text{orig}}(v)| \cdot W_{\text{enddir}}\)
  - Maintain endpoint distance: \(|d_{\text{orig}}(v) - d_{\text{dest}}(v)| \cdot W_{\text{enddist}}\)

Balancing Soft Constraints

- Prioritize scores by importance
  1. Prevent topological errors
  2. Ensure all roads visible
  3. Maintain original orientation
  4. Maintain ordering by length
  5. Maintain overall route shape

- Informal usability engineering
  - Consider maps containing errors
  - Rate which errors most confusing

Bellevue to Seattle
User Response

- Beta publicly accessible Oct 00 – Mar 01
- 150,000 maps served
- 2242 voluntary responses
  - Should replace standard maps 55.6%
  - Use along with standard maps 43.5%
  - Standard maps preferable 0.9%
- Most common suggestion
  - Choose better routes (not a LineDrive issue)
  - More context in unfamiliar areas

Current Status

- Default rendering style www.mapblast.com
- 250,000 maps/day

Next Steps

- Map enhancements
  - Cross-street after turning point
  - Large area landmarks
- In-depth user study
  - Watch users following LineDrive maps

Future: Point Location Maps

Hand-designed Wedding Map [www.WeddingMaps.CC 01]
Two-Step Approach

1. Analyze cognitive science research and examples of most effective hand-designed visualizations
2. Encode principles as constraints and algorithmically find design satisfying constraints

Step 1: Identify visualization design principles

Step 2: Build Automated Algorithm

Step 1: Identify Design Principles

- Cognitive science
  - How people conceive information
  - How people apprehend visual representations
- Conception
  - Routes conceived as sequence of turns
- Apprehension
  - Route geometry not apprehended accurately
- High-level cognitive model

Step 2: Build Automated Algorithm

- Space of possible visualization designs
  - Graphic elements
  - Visual attributes
- Design principles → Constraints
  - Generative rules: How to vary visual attributes
  - Evaluation criteria: Measure effectiveness
  - Main algorithmic challenge
- Find most effective visualization design
  - Search-based optimization
  - Balance constraints
  - Efficiency

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Goal: Create step-by-step instructions from 3D model

Geometrically Valid Sequences

Robotics / Mechanical Engineering
[DeFazio & Whitney 87] [Wolter 89] [Wilson 95] [Romney et al. 95]

Many Geometrically Valid Sequences

How do we choose most effective sequence?

Cognitive Science

• Experiments to learn how people understand assembly instructions
  [Heiser in progress]

• Assemblies conceived as groupings of parts
  • Coarse level - functional units
  • Finer levels - symmetry, similarity, proximity

• People prefer certain assembly sequences
  • Add all supporting parts then supported parts
  • Add all internal parts then external parts
  • Add grouped parts in same step, or in sequence
  • Add new parts onto existing parts

Analysis of Hand-Designed Examples

• Essential graphic elements
  • Parts added in step (visibility)
  • Previous parts (context)

• Graphic design techniques
  • Small multiples
  • Technical illustration style
  • Insets improve part visibility
  • Arrows show attachments
**Constraints**

- **Support**: All supporting parts added before supported
- **Adjacency**: All parts in step touch previous parts
- **Symmetry**: All symmetric parts added in same step
- **Linearity**: New parts added onto existing parts

- **Visibility**: If part $A$ occludes $B$
  
  \[ \text{Penalty} = \text{Occlusion}(A, B) \times W_{\text{visibility}} \]

- **Context**: If $< 25\%$ of step $N-1$ parts visible
  
  \[ \text{Penalty} = \text{Occlusion}(\text{Step } N, \text{Step } N-1) \times W_{\text{context}} \]

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**Lego Car**

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**Landspeeder**

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**Mechanical Assembly**

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**Assembling TV Stand**

- Subjects assemble TV stand without instructions
- Then asked to produce clear set of assembly instructions

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**Analysis of Hand-Drawn Diagrams**

- **Static**: Show object after each assembly step
- **Action**: Show operations required in each step
  - Emphasize new parts
  - Show motion of parts
  - Show alignment of parts
  - Show how fasteners attach parts
Computer-Generated Instructions

Current Agenda
- Identify more design principles
- Incorporate other graphic design techniques
  - Insets
  - Scale exaggeration
  - Cutaways
  - Sections
  - Text labels
- User studies

Future: Exploded Views

Train [from Mijksenaar 99]  Camping Stove [from Mijksenaar 99]

Future: 3D Environments

MoMA Design Entry [Tschumi 99]  IBM Building Plan [from Holmes 93]

Summary
- General two-step approach
  - Step 1: Identify cognitive design principles
  - Step 2: Encode principles as constraints and find most effective visualization
- Automated design systems
  - Route maps
  - Assembly instructions
- Benefits
  - Novices can leverage skills of experts
  - Deal with data overload
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Many Other Domains To Consider

- Medical illustration: Complex biological organisms
- Scientific diagrams: Depict scientific concept
- Graphs and charts: Scatter plots, bar charts, etc.
- Architectural plans: Room and furniture layout
- Proof visualization: Depict complex logical statements

Interaction and Animation

- Interaction
  - Hide clutter, let user request details
  - Direct, intuitive, navigation controls
- Animation
  - Should add information [Hegarty 00] [Morrison 01]

Long-Term Challenge

- Current focus on how
  - Simulate realistic lighting, shading
  - Emulate artistic media (paint, pen & ink, …)
  - Display data using std. metaphors (bar graph, binary tree, …)
  - …
- Need principles guiding where, what, why
  - Where to place lights to communicate a mood?
  - What information does an artistic rendering style convey?
  - Why is a particular metaphor effective?
  - …
- Must understand and appreciate what makes an effective visualization

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