Automating the Design of Visualizations

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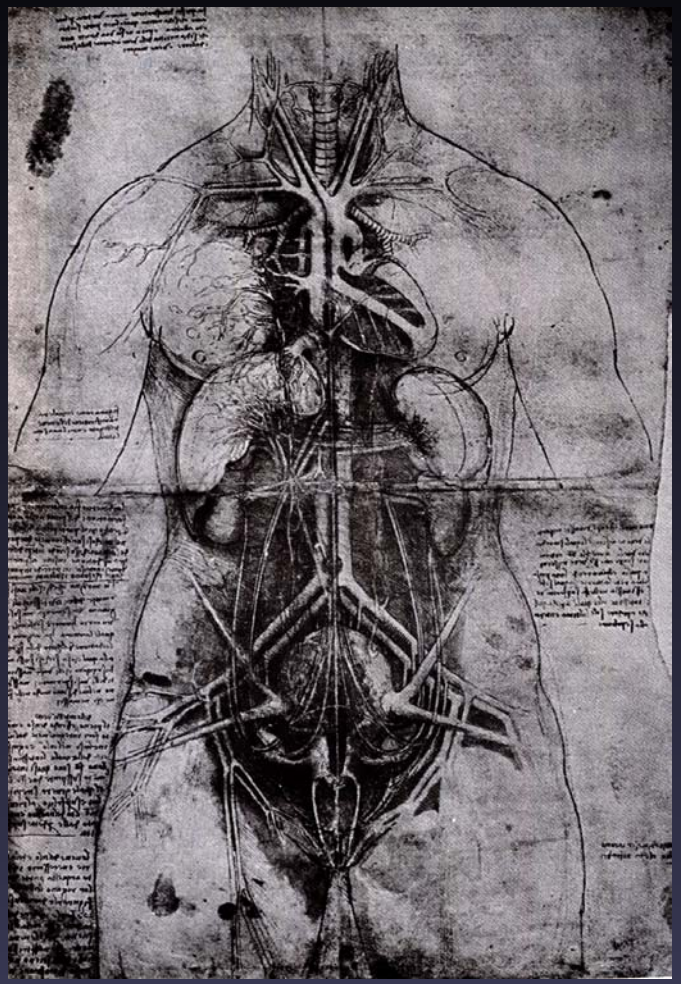
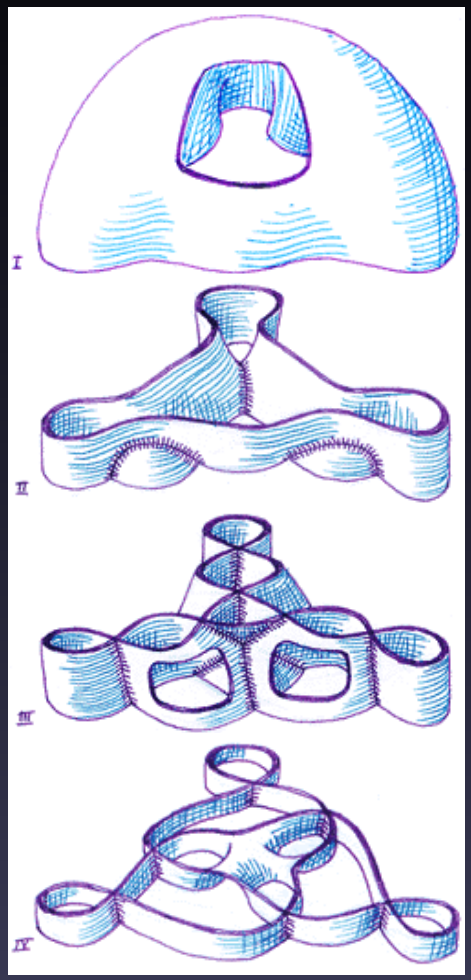
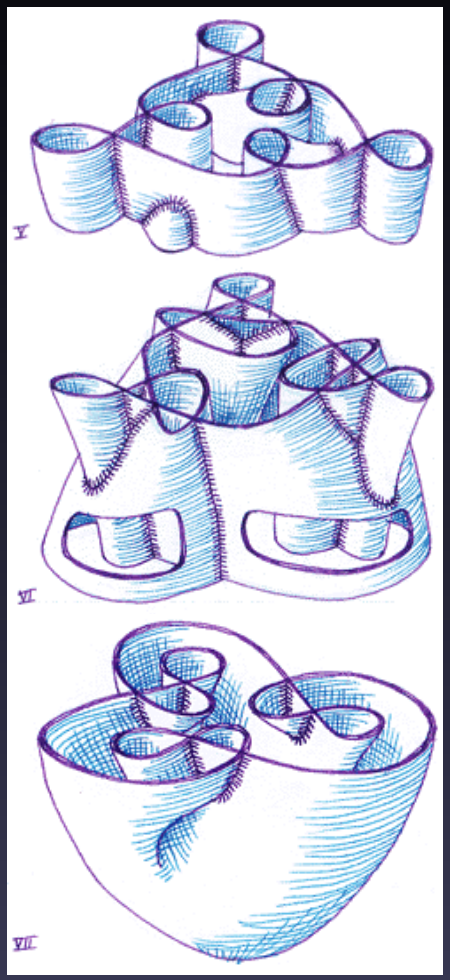
Visualization: Explore & Present Data



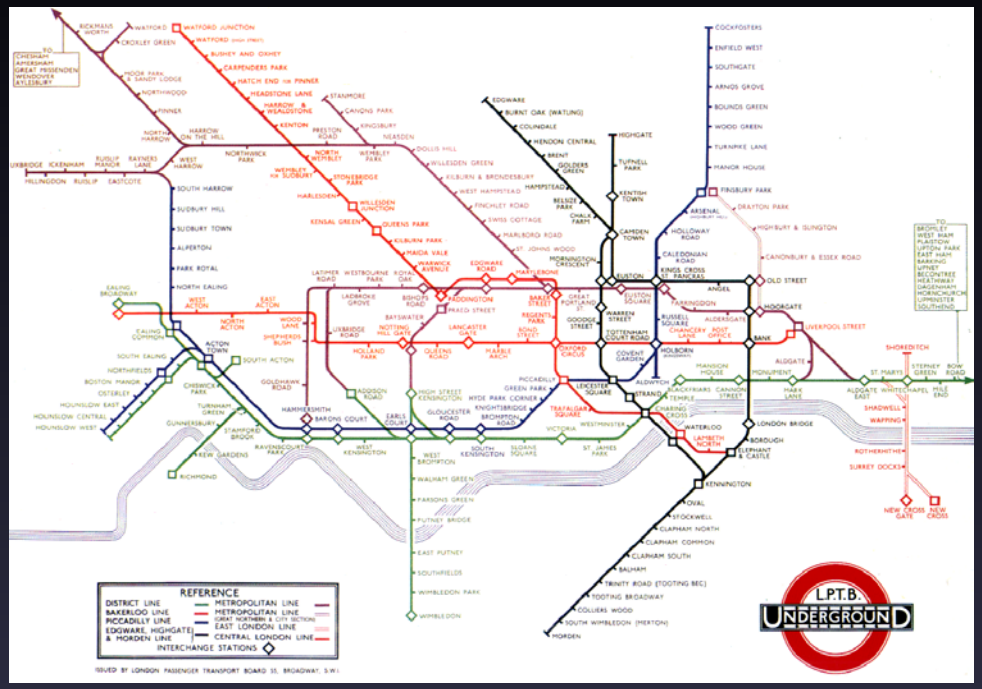
Principal Organs & Vascular System
[Leonardo da Vinci ca. 1490]



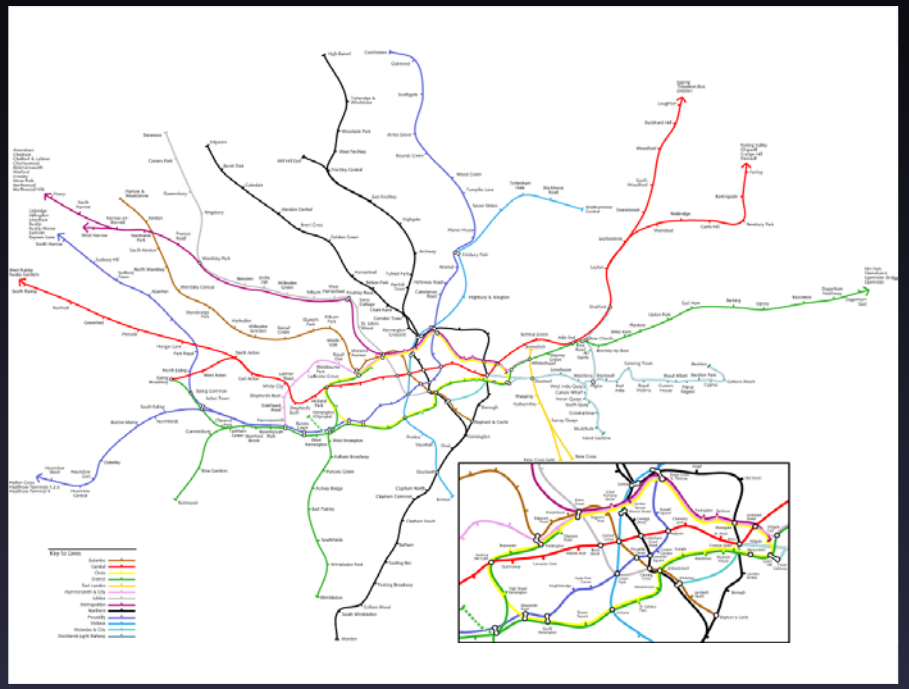


Strange Immersion of Torus in
3-Space [Curtis 92]

Good Design Improves Usability



London Underground [Beck 33]



Geographic Version of Map

- 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?**

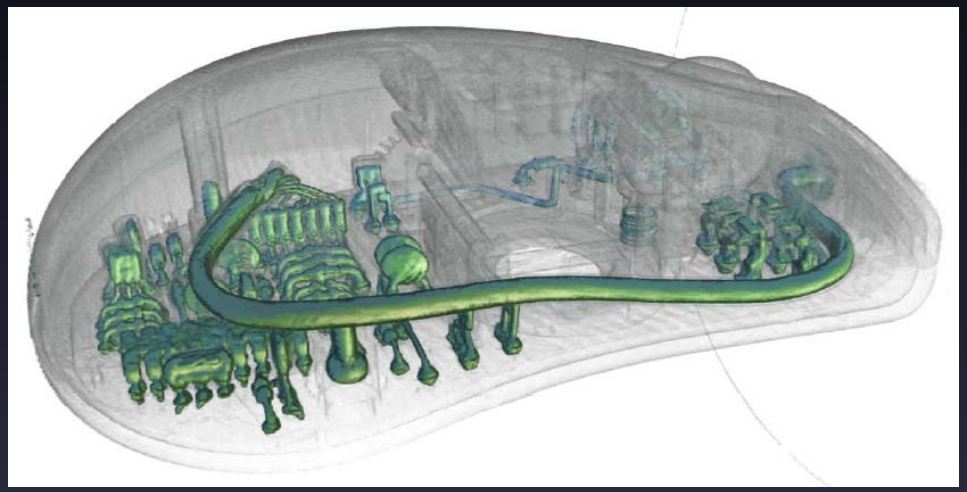
Automation Allows Customization

- **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

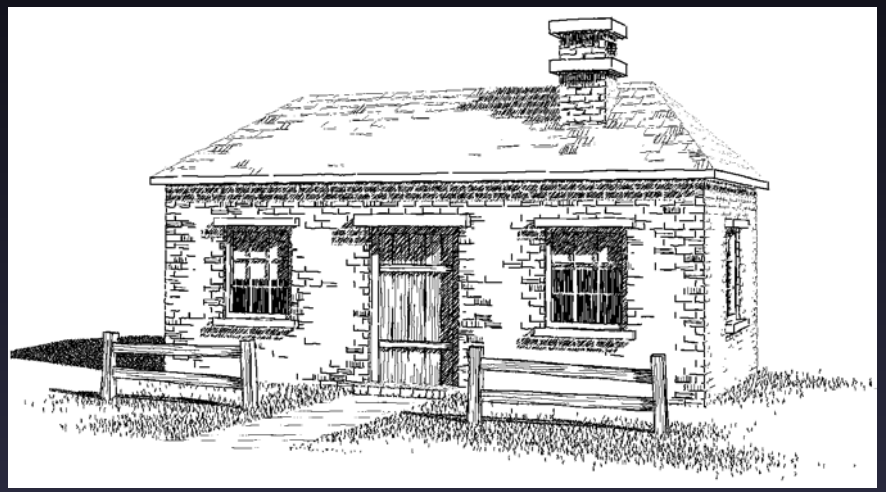
- Customization increases effectiveness

Emulating Artistic Rendering Styles

- Artistic rendering can improve perception



Mouse [Lum & Ma 02]



House [Winkenbach & Salesin 94]

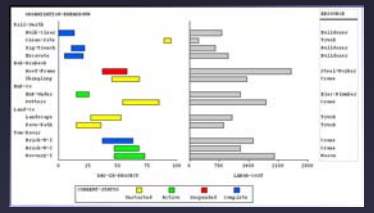
- **High-level design still specified manually**

Automated Design as Optimization

- Page design
  - TeX [Knuth 81], GRIDS [Feiner 88], LayLab [Graf 92], [Weitzman & Wittenburg 94], [Borning et al. 97, 00]

- 3D object visualization
  - APEX [Feiner 85], IBIS [Seligmann & Feiner 91], WIP [Rist et al. 94]

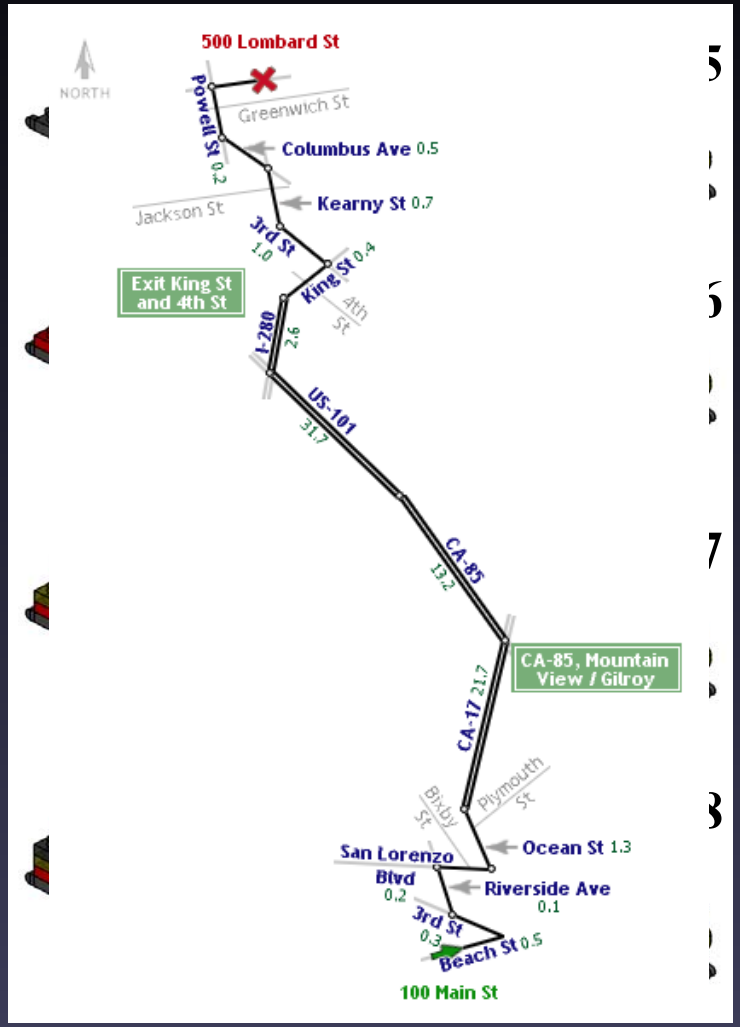
- Data graphics presentations
  - APT [Mackinlay 86], SAGE [Roth et al. 94, 96], SYSTAT [Wilkinson 99]



- UI layout, Label layout, VLSI design, Camera planning, 2D/3D packing, Graph drawing, …
- **Need domain specific constraints**

Contributions

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

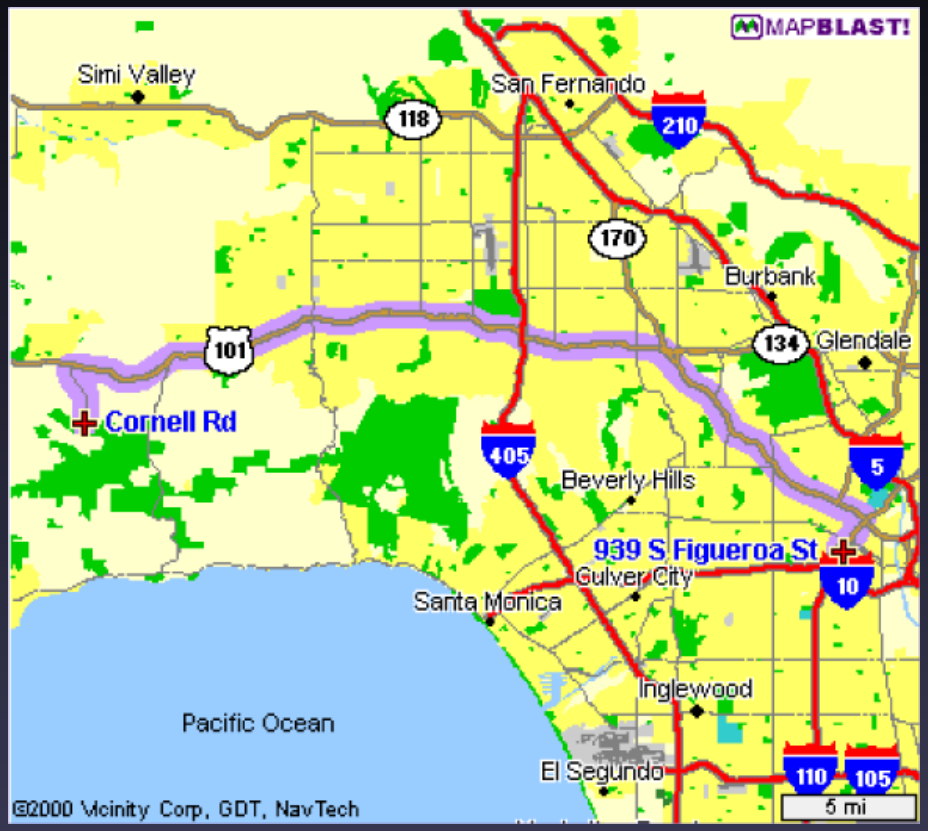


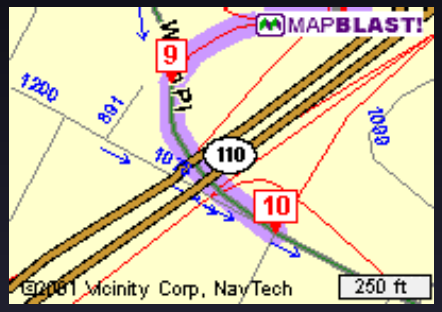
Outline

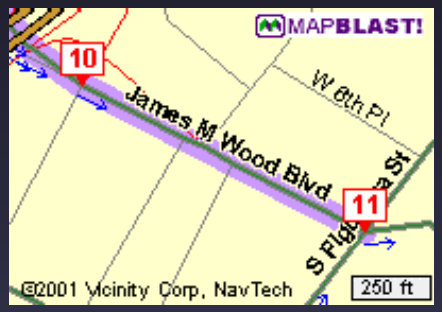
- Motivation
- Automated Route Map Design
- Framework for Automated Design
- Automated Assembly Instruction Design
- Future Directions

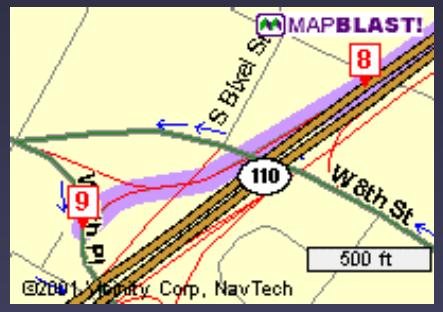
Visualizing Routes

- Standard online route maps difficult to use



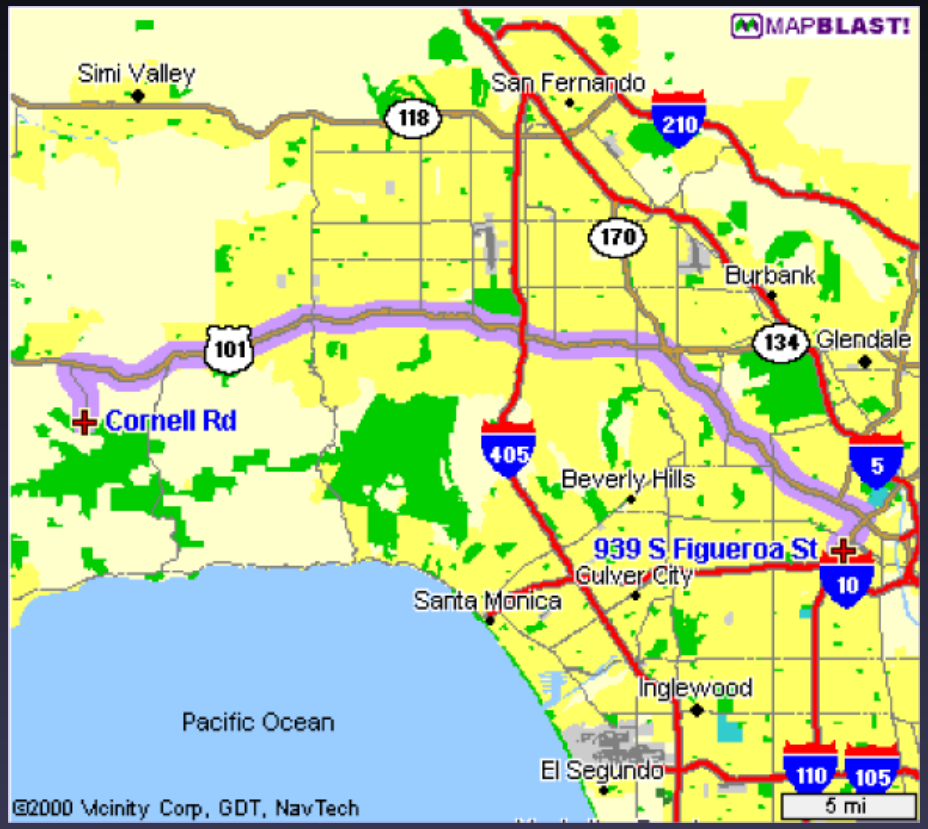


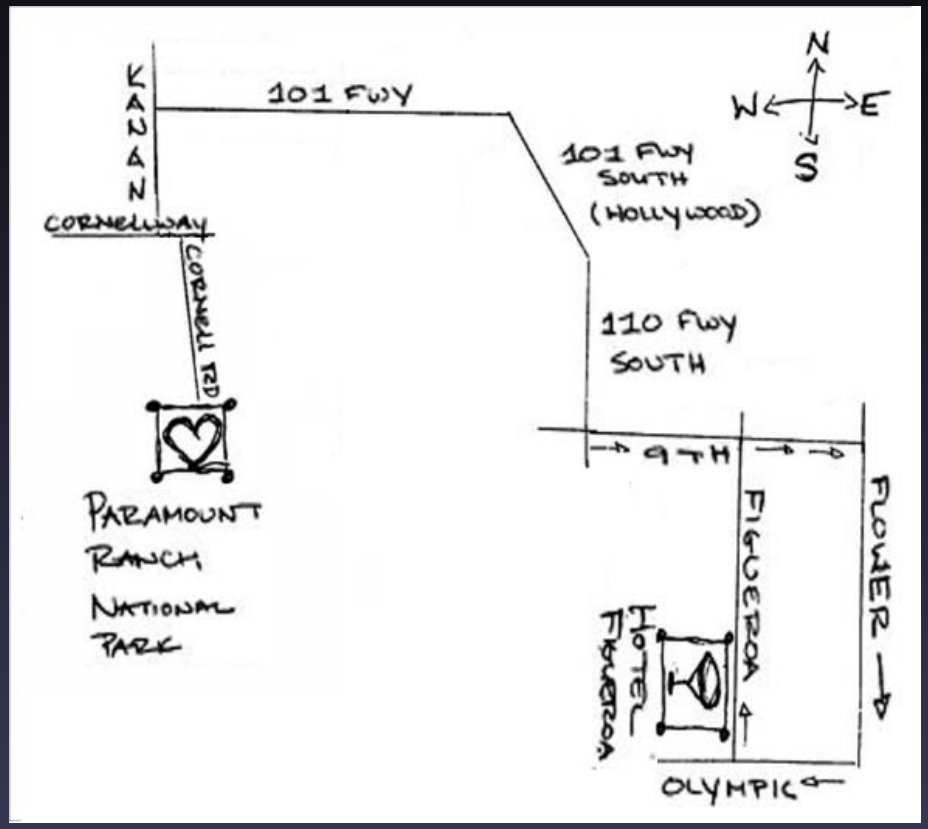




A Better Visualization

- Hand-drawn maps much easier to use





Communicative Intent of Route Maps

- Route is a sequence of turns [Tversky 92] [MacEachren 95]

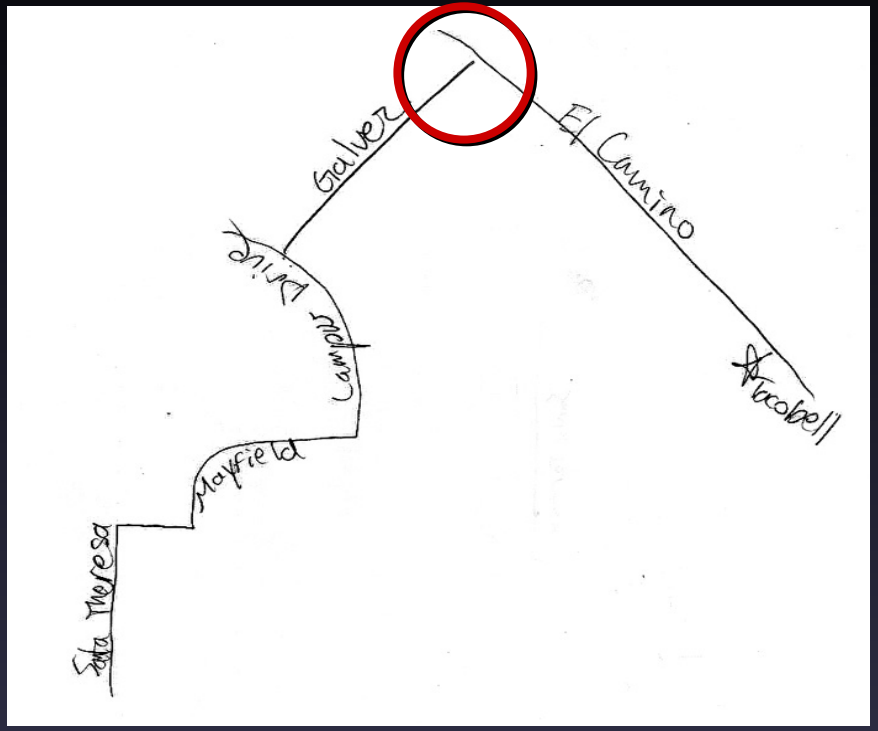
  1. Start at 100 Serra
  2. Turn Right on University
  3. Turn Left on El Camino
  4. Turn Right on San Antonio

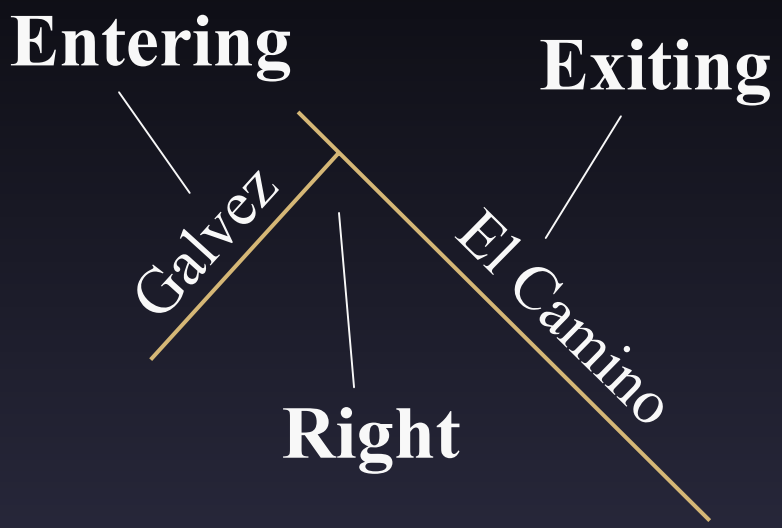
  …

  - Verbal directions emphasize turns [Denis 97]
  - Hand-drawn maps highlight turns [Tversky & Lee 99]

- **Maps must communicate turning points**

Depicting Turns

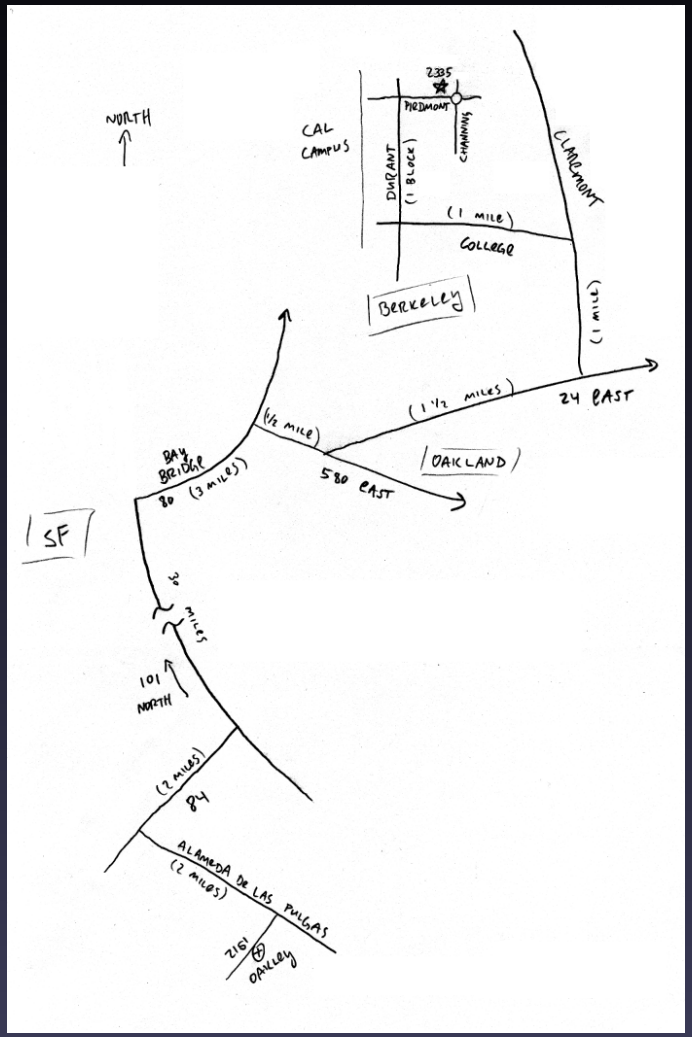




- Pair of roads (entering / exiting the turn)
- Turn direction (left / right)
- **These graphic elements must be visible**

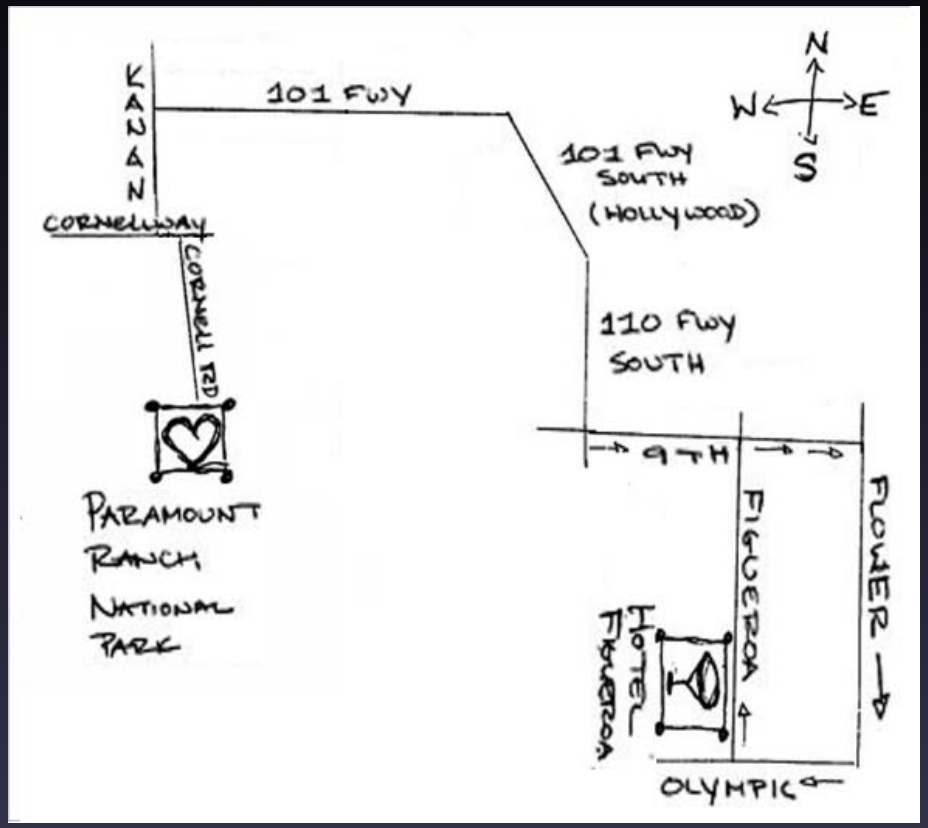
Context can Facilitate Navigation

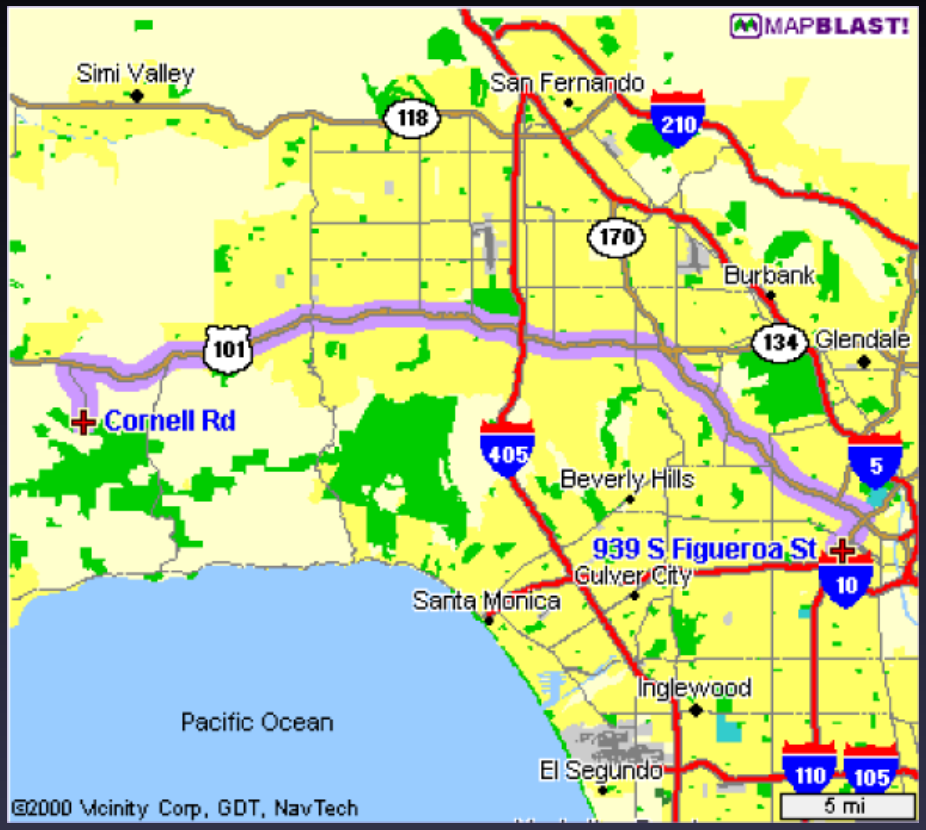
- Local context
  - Consistency checks
    - Cross-streets
    - Landmarks along route
    - Distance along each road
- Overview context
  - Orient route to geography
    - Large area landmarks
    - Overall shape & heading



- **Context is secondary to turning points**

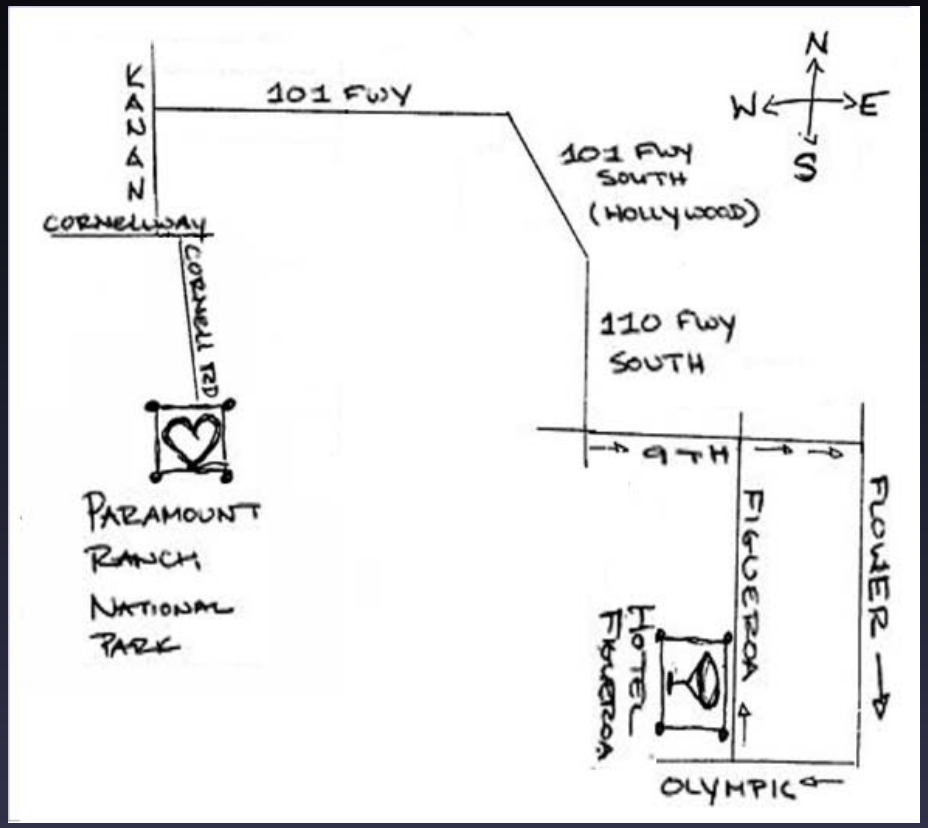
Geometric Properties Distorted



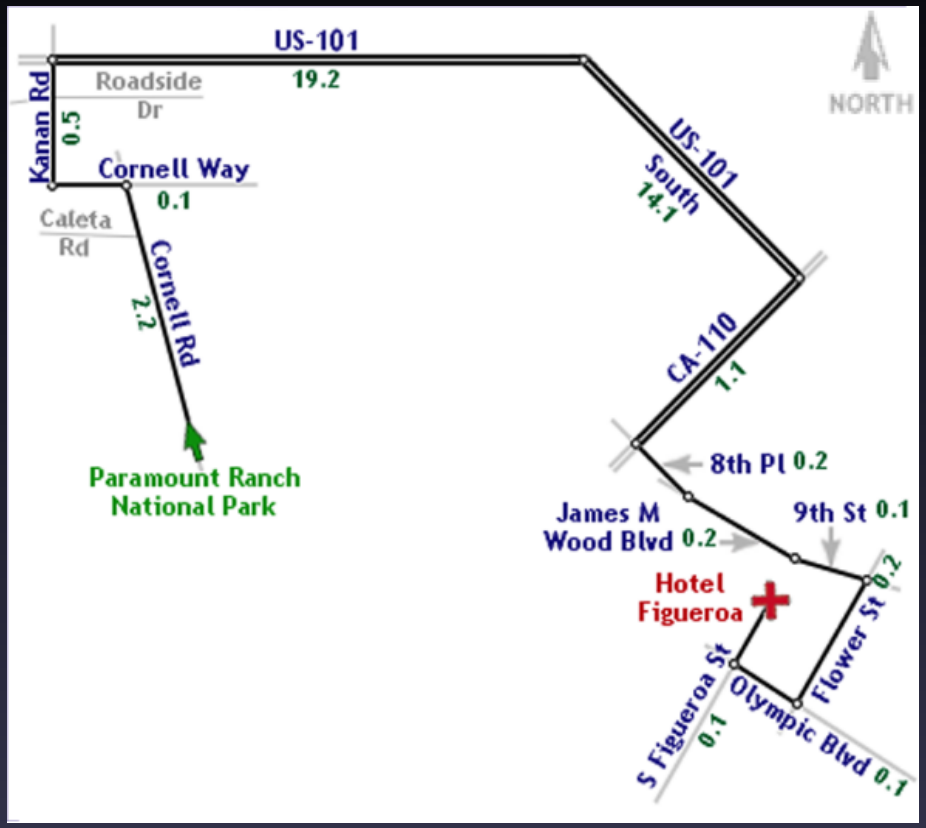


- Geometry *not* apprehended accurately [Tversky 81]
- Geometry *not* drawn accurately [Tversky & Lee 99]
  - Topology is accurate

LineDrive: Route Map Design System



Hand-drawn Route Map



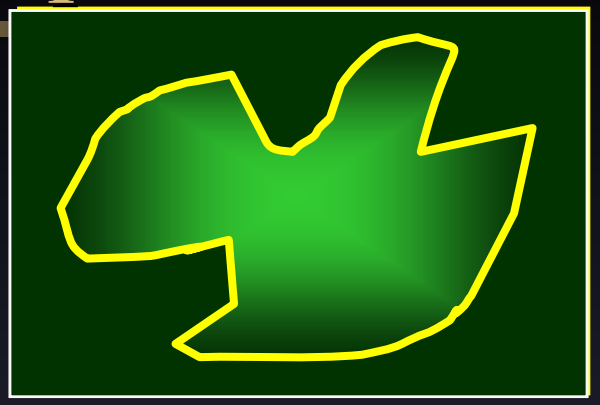
LineDrive Route Map

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

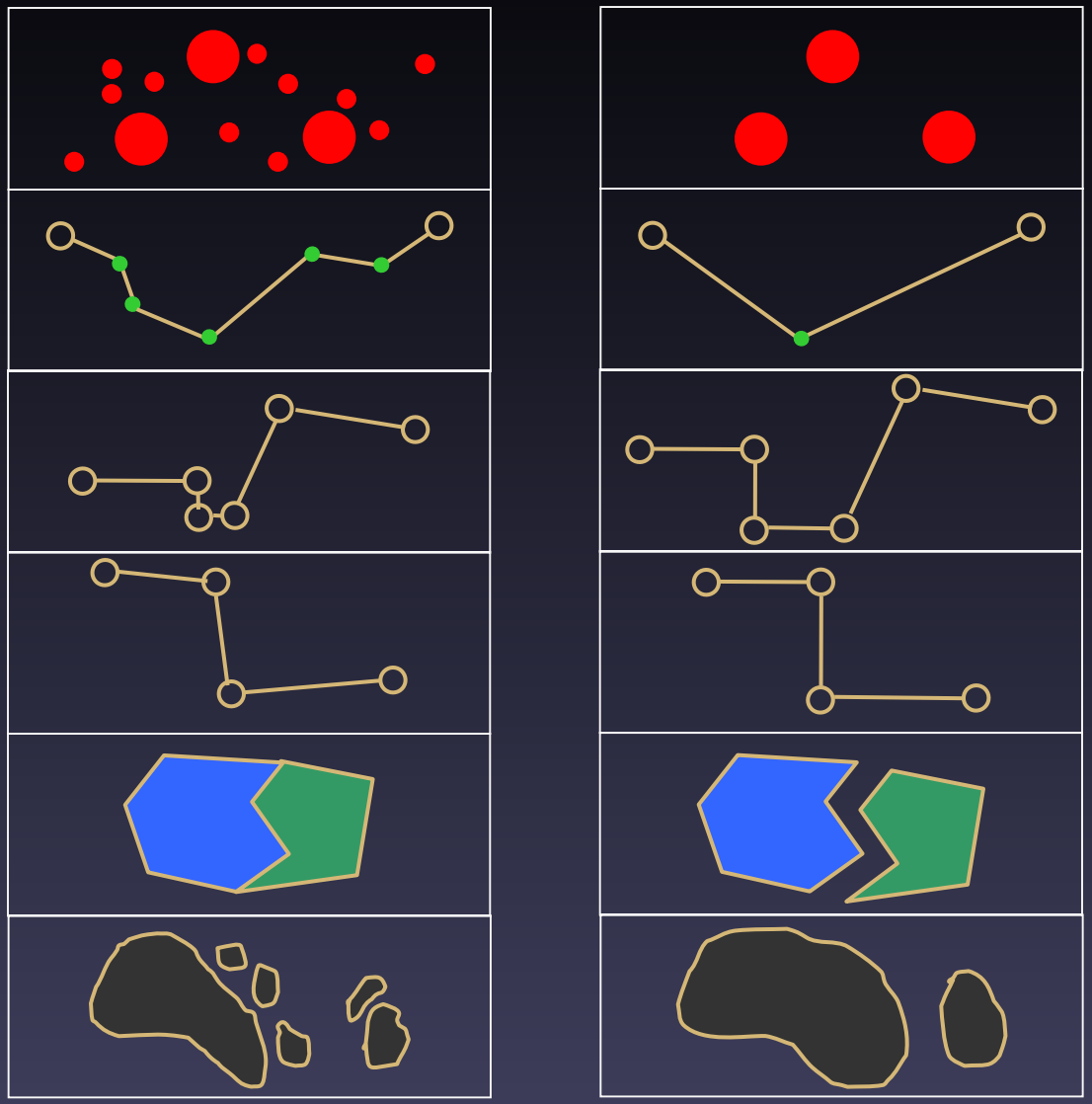


- **Challenge: Develop relevant constraints**

- Simulated annealing
  - *Perturb:* Form a layout
  - *Score:* Evaluate quality
  - Minimize score

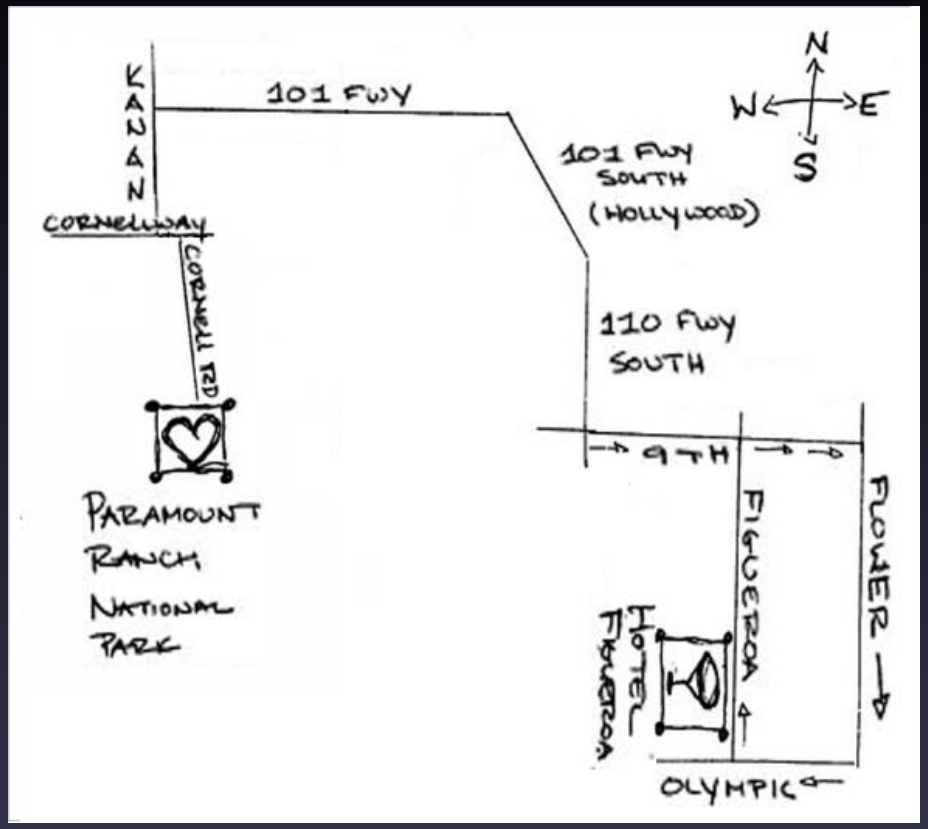
Cartographic Generalization

- Selection
- Simplification
- Exaggeration
- Regularization
- Displacement
- Aggregation



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

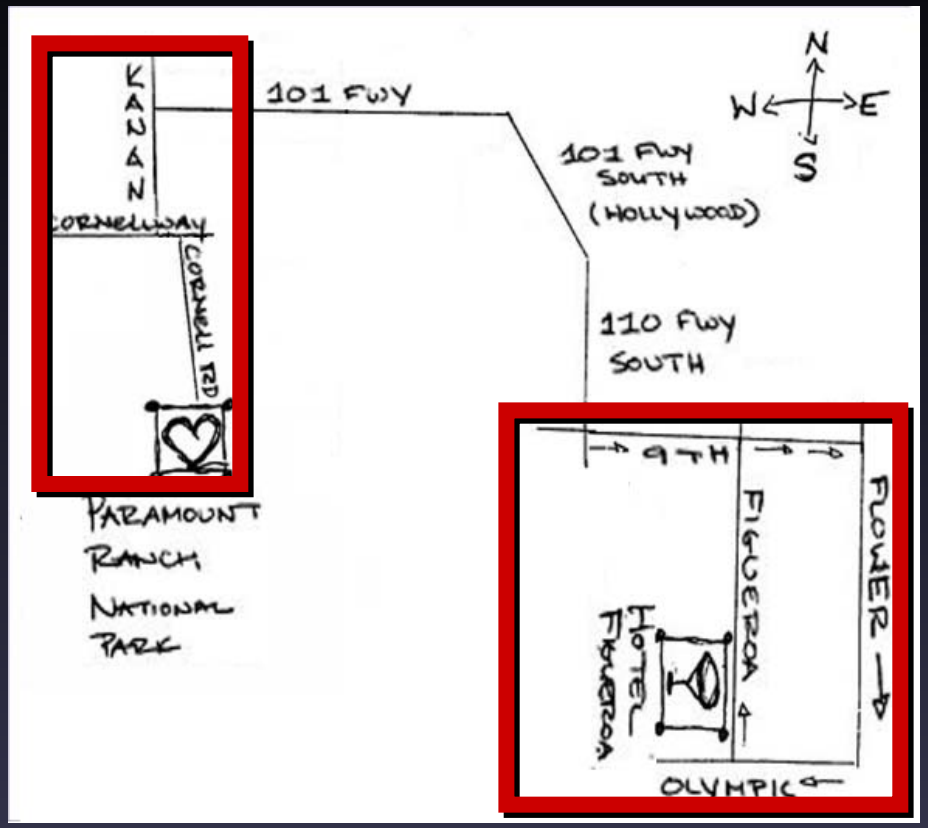
Three Generalizations for Route Maps

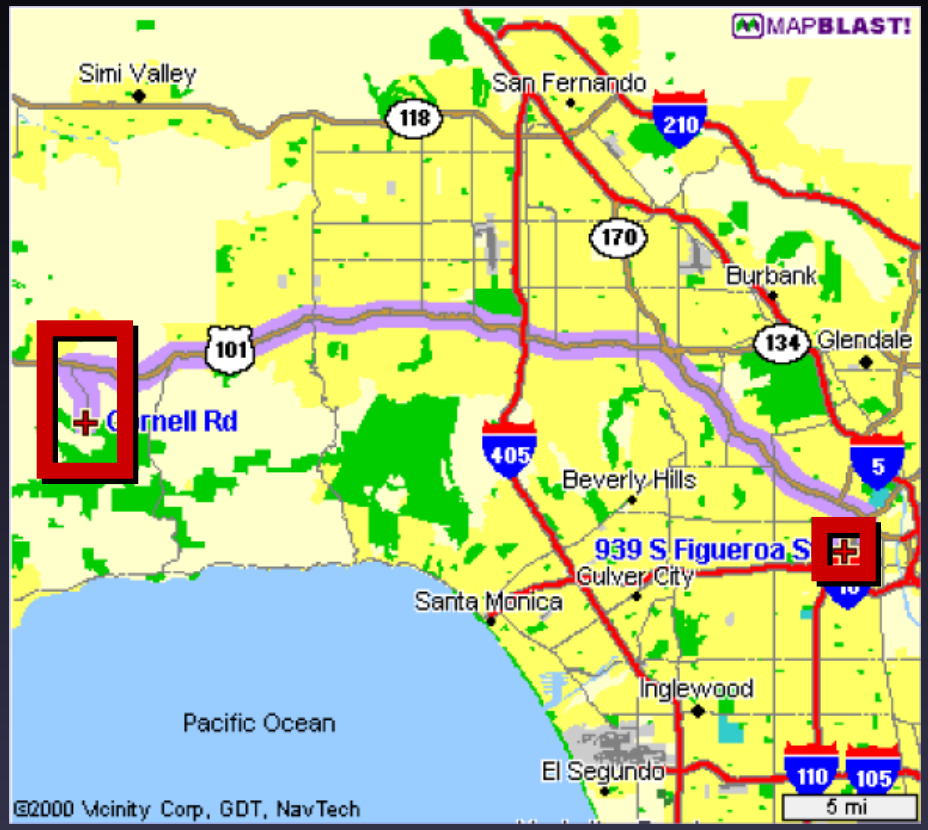


- Our observations from hand-drawn examples:
  - Exaggeration
    - Road length
  - Regularization
    - Turning angle
  - Simplification
    - Road shape

- **Generalizations emphasize turning points!**

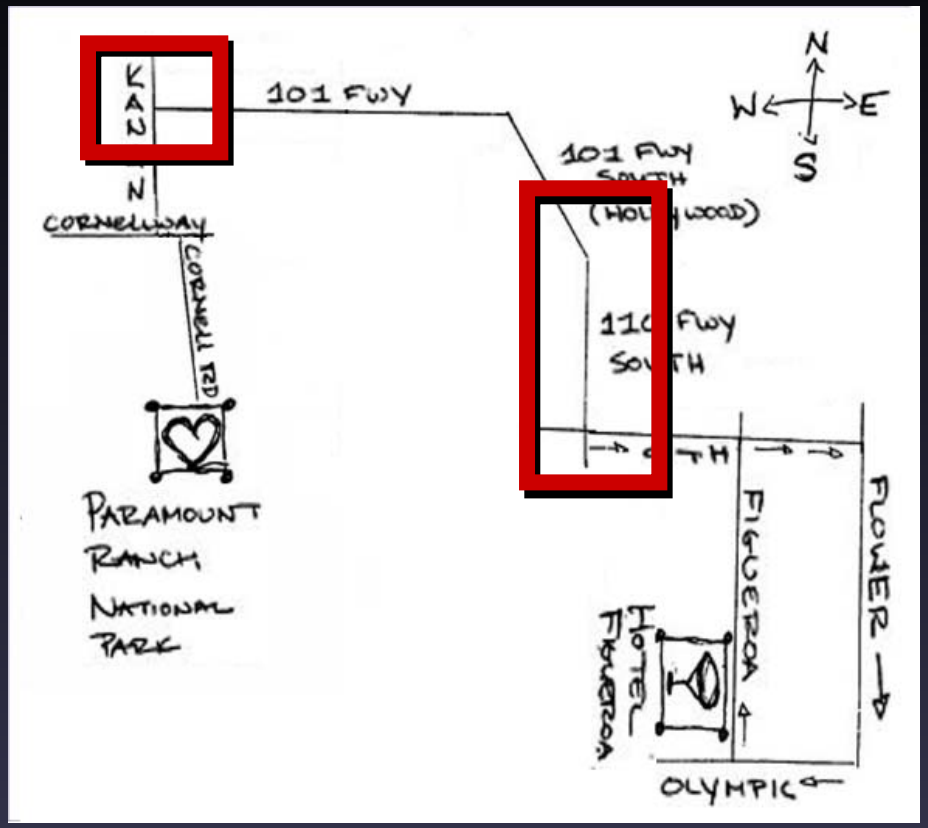
Exaggeration: Length Generalization

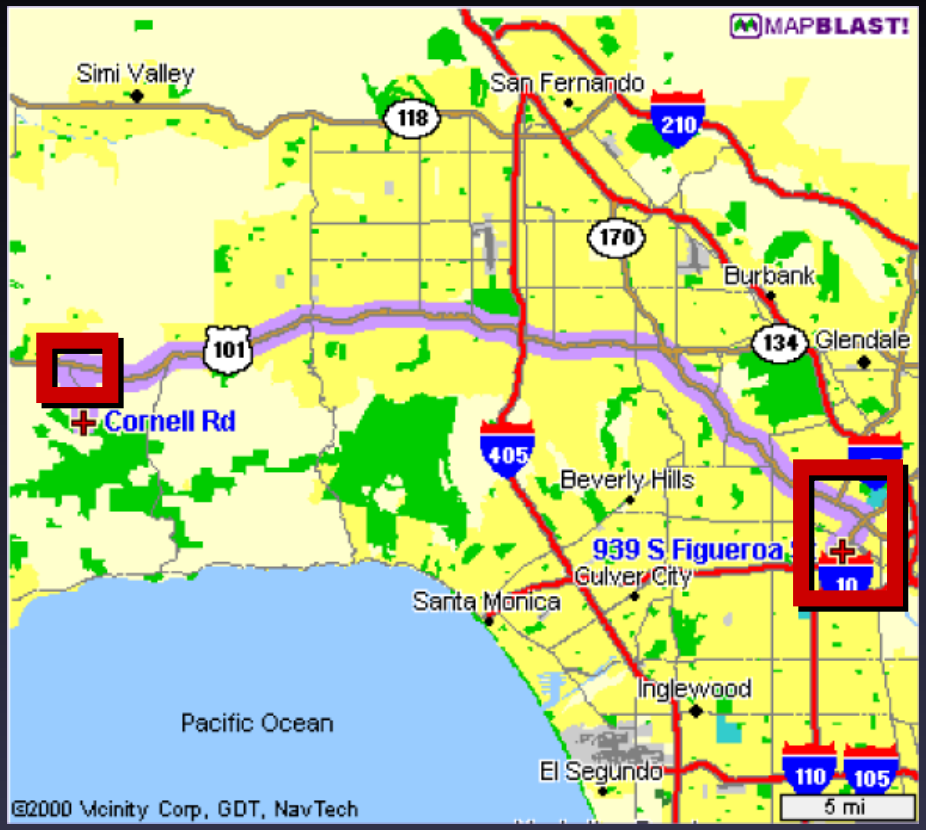




- Grow short roads, shrink long roads
  - Ensures all roads visible
  - Maintain relative ordering by length

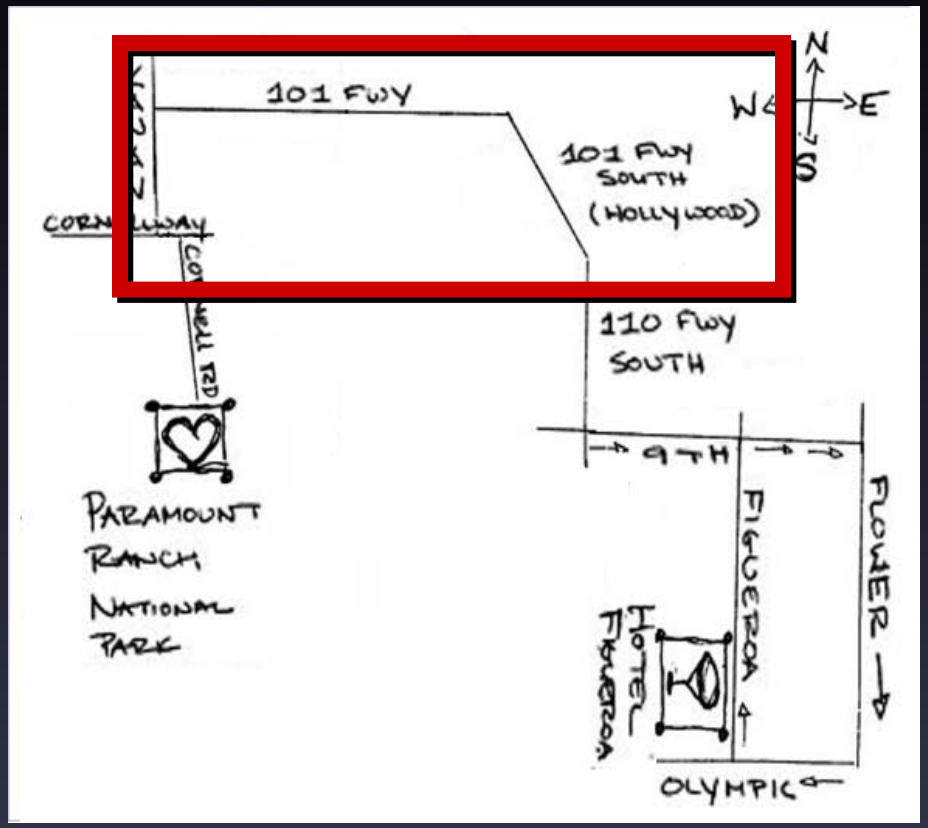
Regularization: Angle Generalization

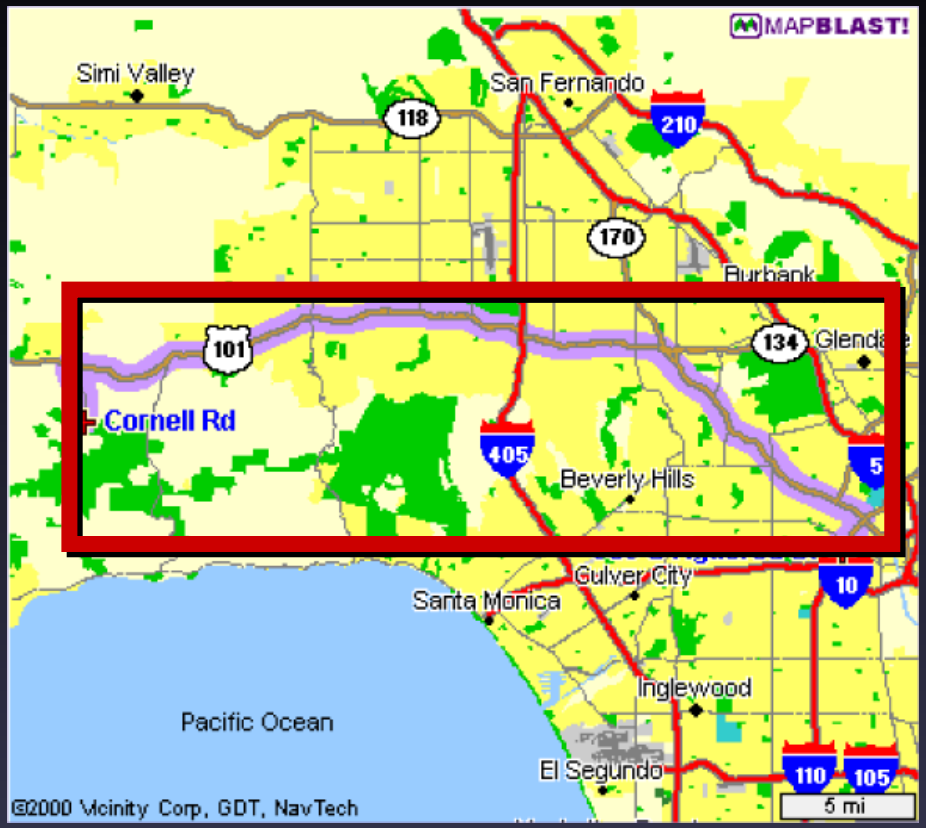




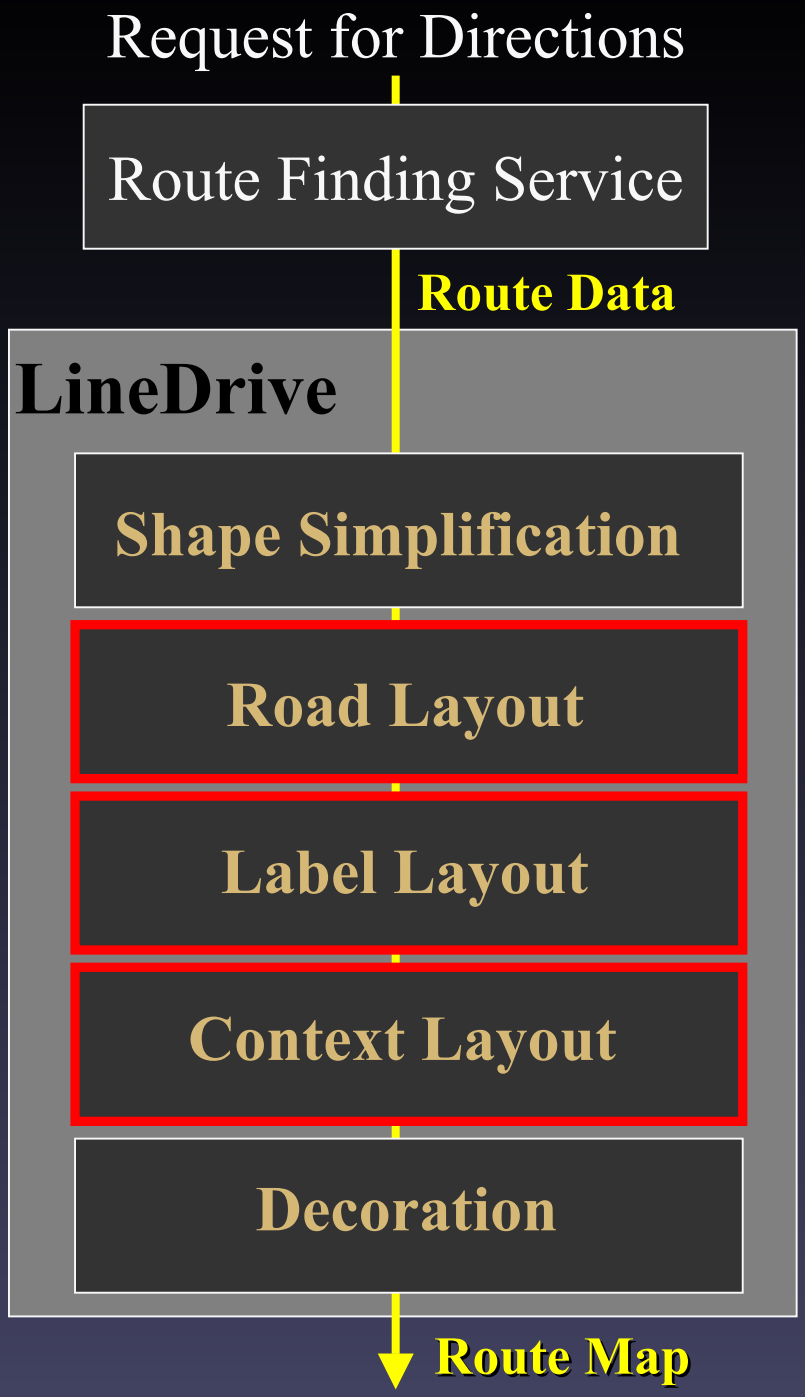
- Regularize turning angles
  - Reduces visual complexity
  - Maintain consistent turn direction

Simplification: Shape Generalization



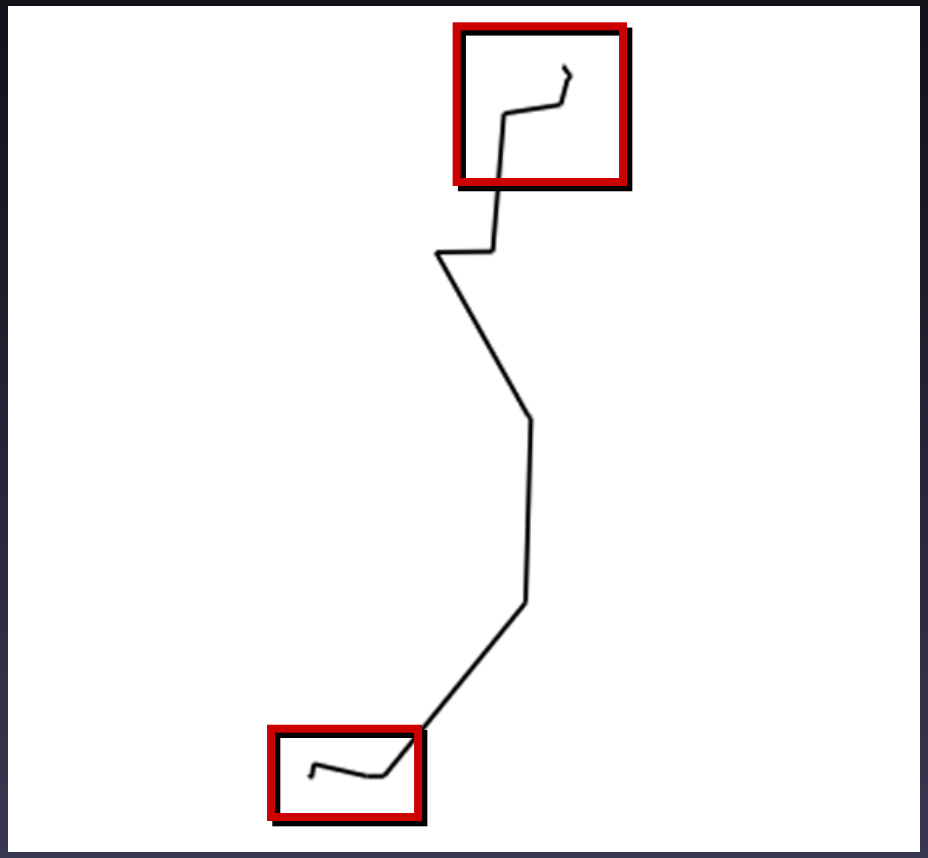


- Simplify roads to straight lines
  - Differentiates roads and turning points
  - Maintain overall shape of route

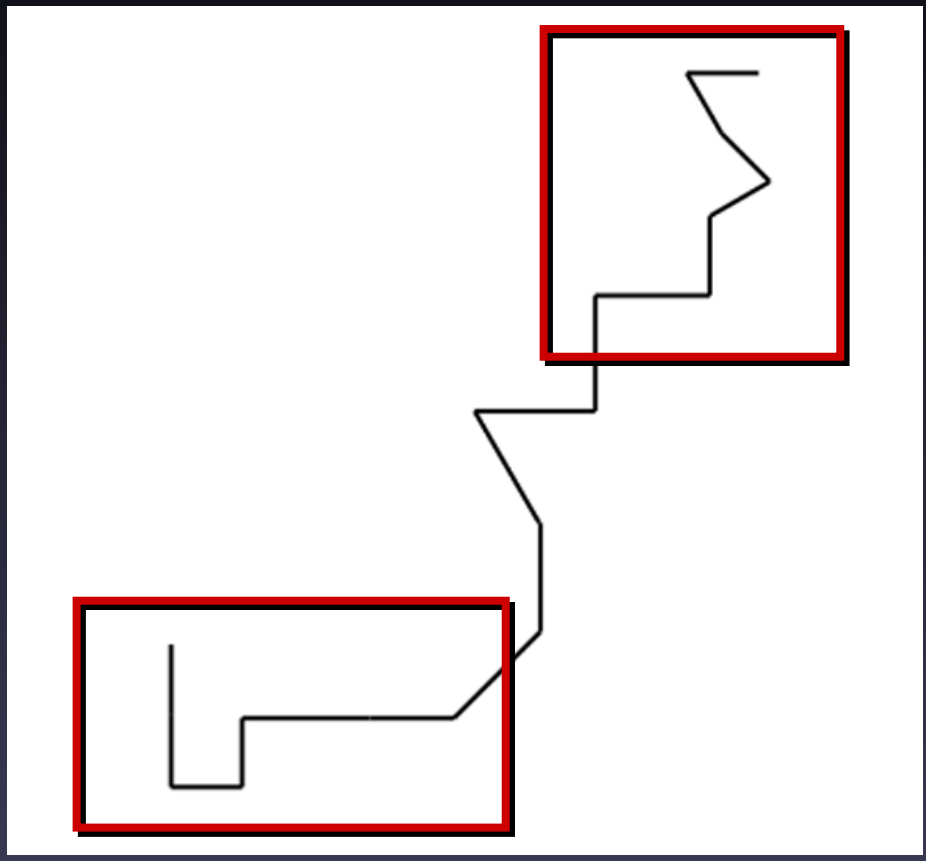

Request for Directions
Route Finding Service
Route Data
LineDrive
Shape Simplification
Road Layout
Label Layout
Context Layout
Decoration
Route Map

Stage 2: Road Layout

- Goal: Choose road lengths & orientations



without road layout



with road layout

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 $((L_{min} - l(r_i)) / L_{min})^2 * W_{small}$
  - Maintain ordering by length $W_{shuffle}$
- **Orientation**
  - Maintain original orientation $| \alpha_{curr}(r_i) - \alpha_{orig}(r_i) | * W_{orient}$
- **Topological errors**
  - Prevent false $\min(d_{origin}, d_{dest}) * W_{false}$
  - Prevent missing $d * W_{missing}$
  - Ensure separation $\min(d_{ext}, E) * W_{ext}$
- **Overall route shape**
  - Maintain endpoint direction $| \alpha_{curr}(v) - \alpha_{orig}(v) | * W_{enddir}$
  - Maintain endpoint distance $| d_{curr}(v) - d_{orig}(v) | * W_{enddist}$

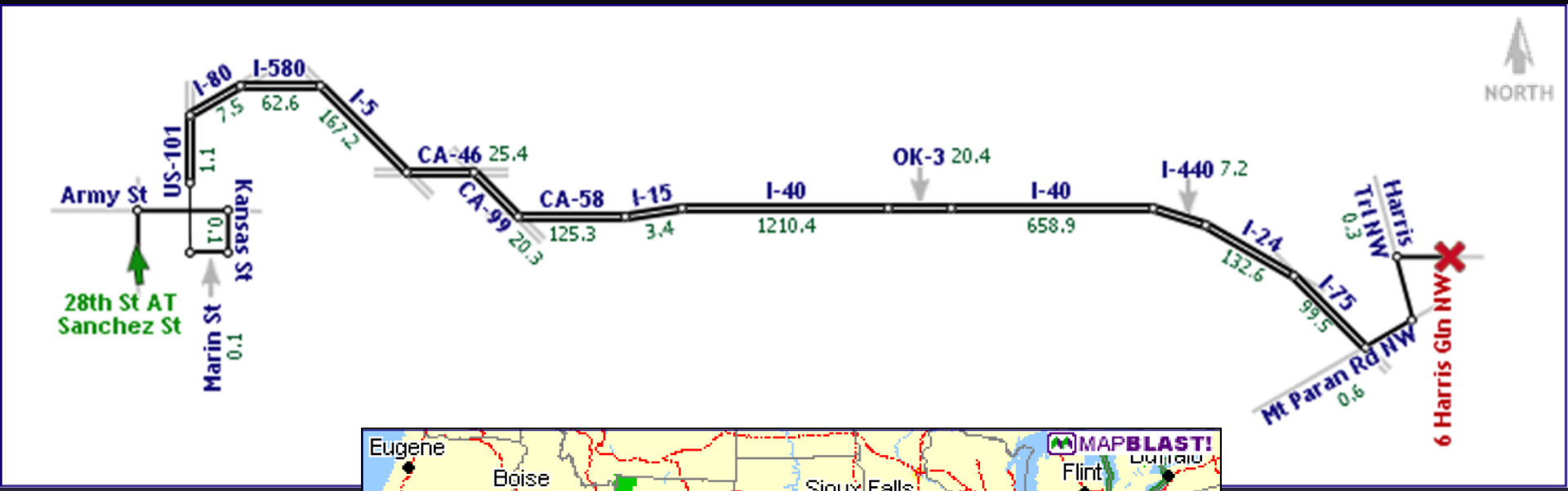
Balancing Soft Constraints

- 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

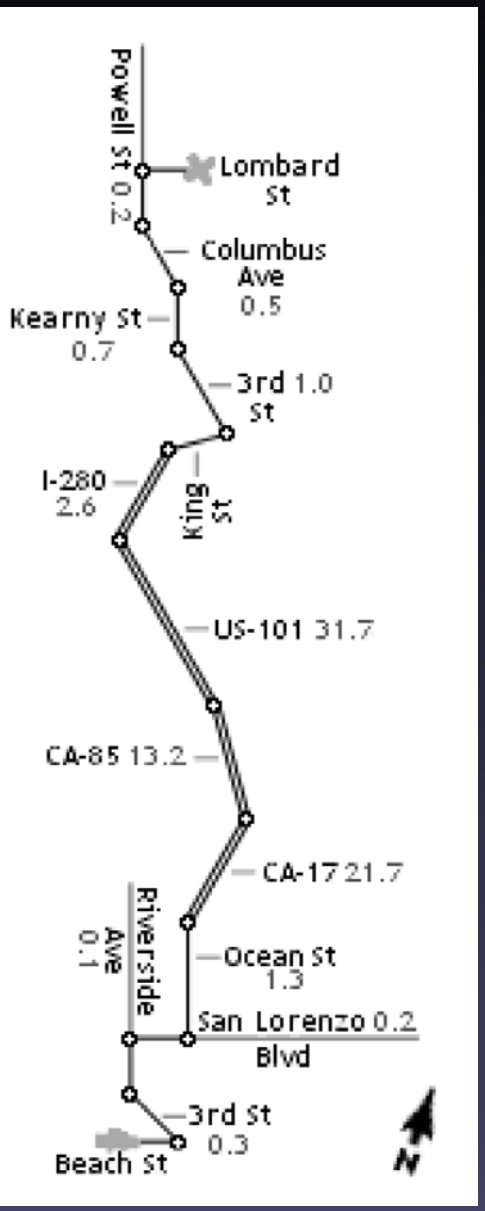
- Informal usability engineering
  - Consider maps containing errors
  - Rate which errors most confusing

Bellevue to Seattle

Cross-Country Route



Limited Resolution: Palm

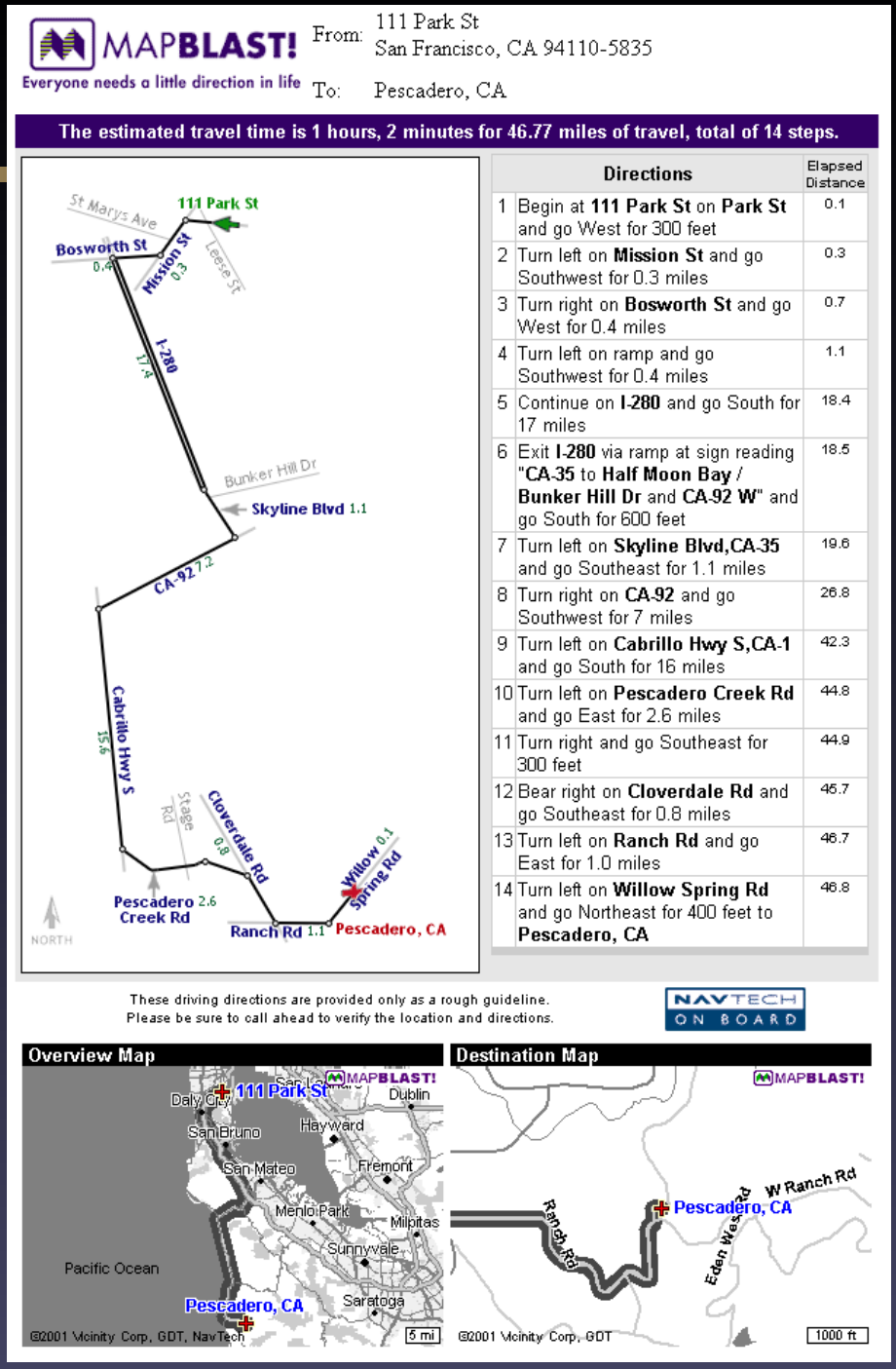


User Response

- 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

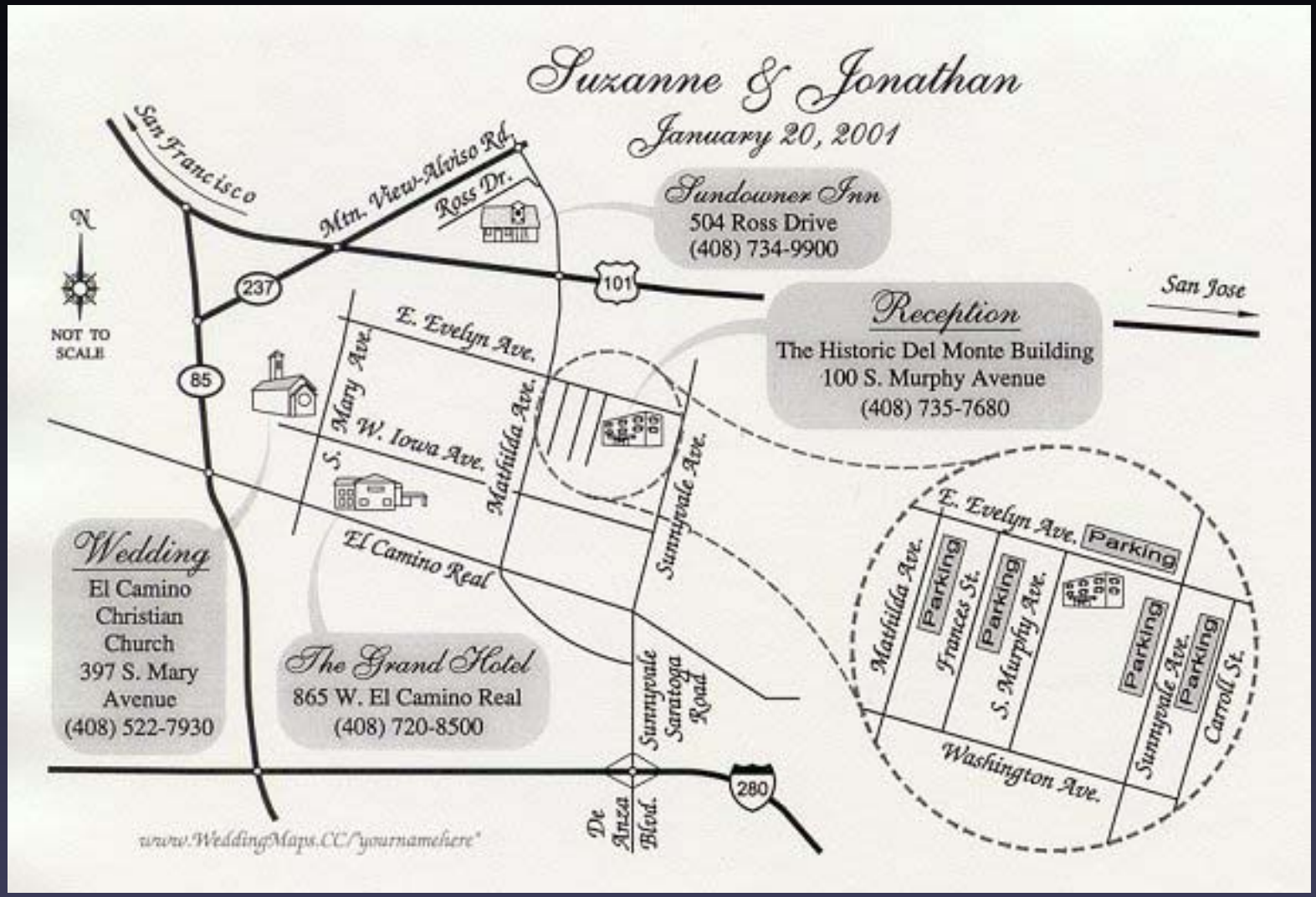
- Default rendering style
  www.mapblast.com
- 250,000 maps/day



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]

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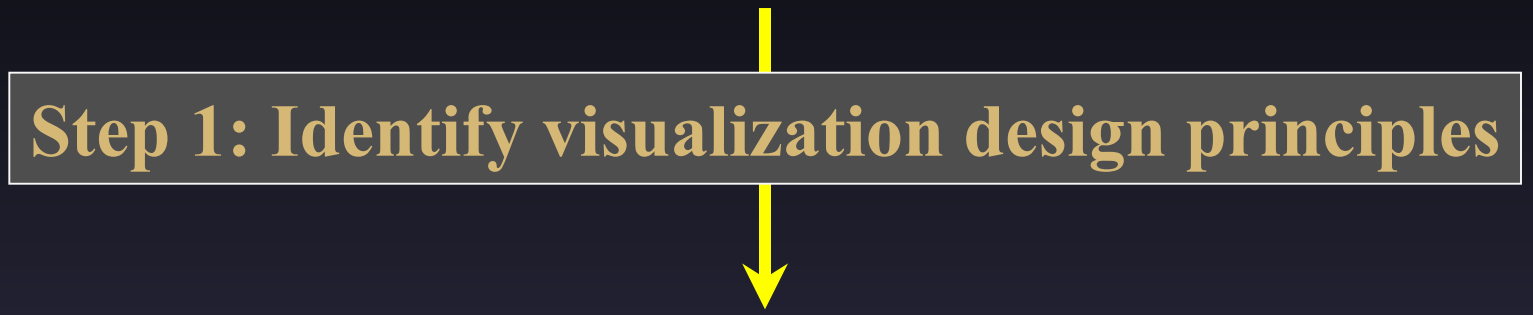
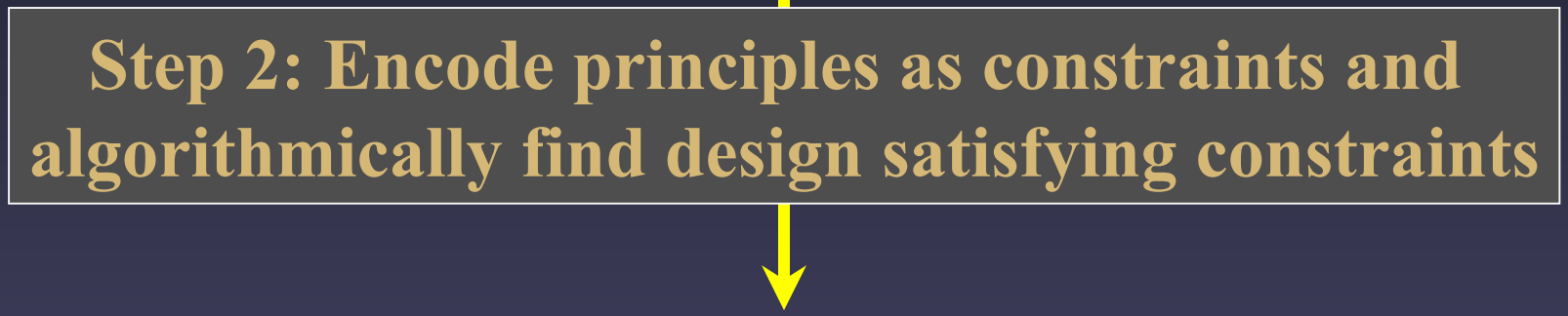
Two-Step Approach

Analyze cognitive science research and examples of most effective hand-designed visualizations



Low-level visualization design principles



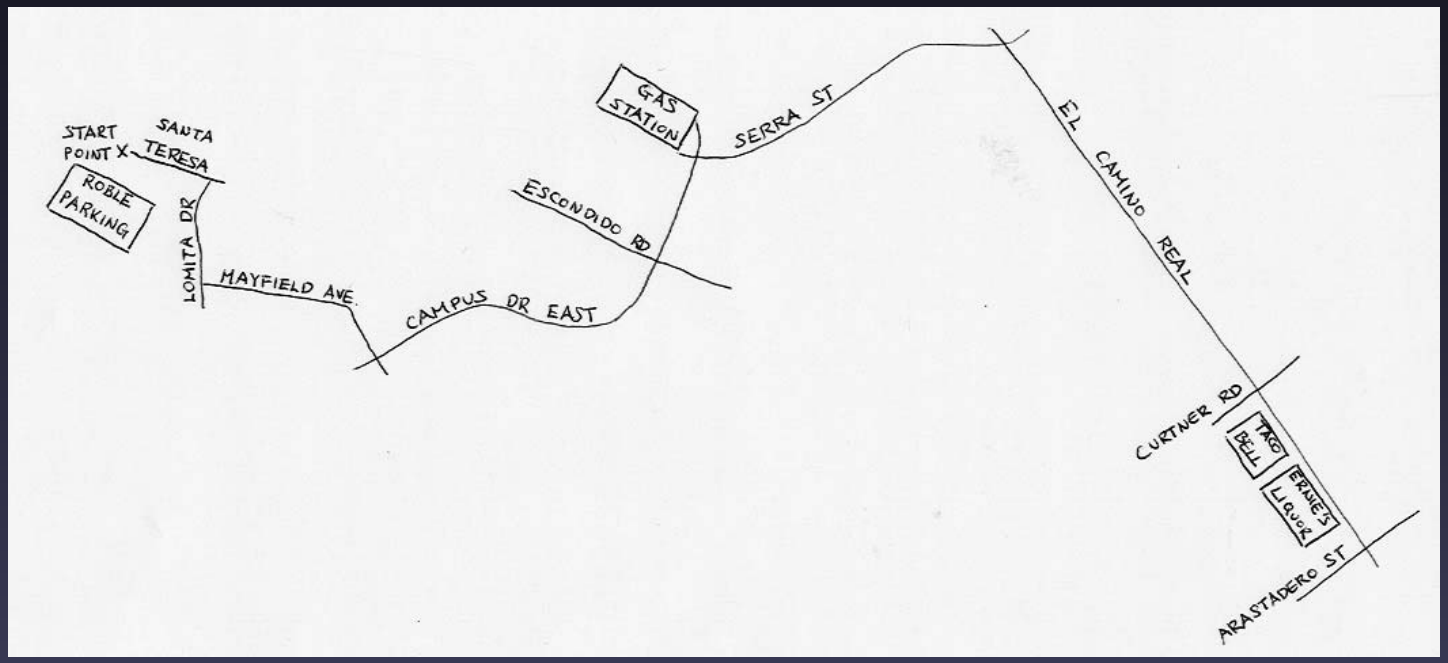
Automated design system

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 1: Identify Design Principles

- Analyze hand-designed visualizations
  - Identify essential graphic elements
  - Identify distortion techniques



- **Low-level visualization design principles**

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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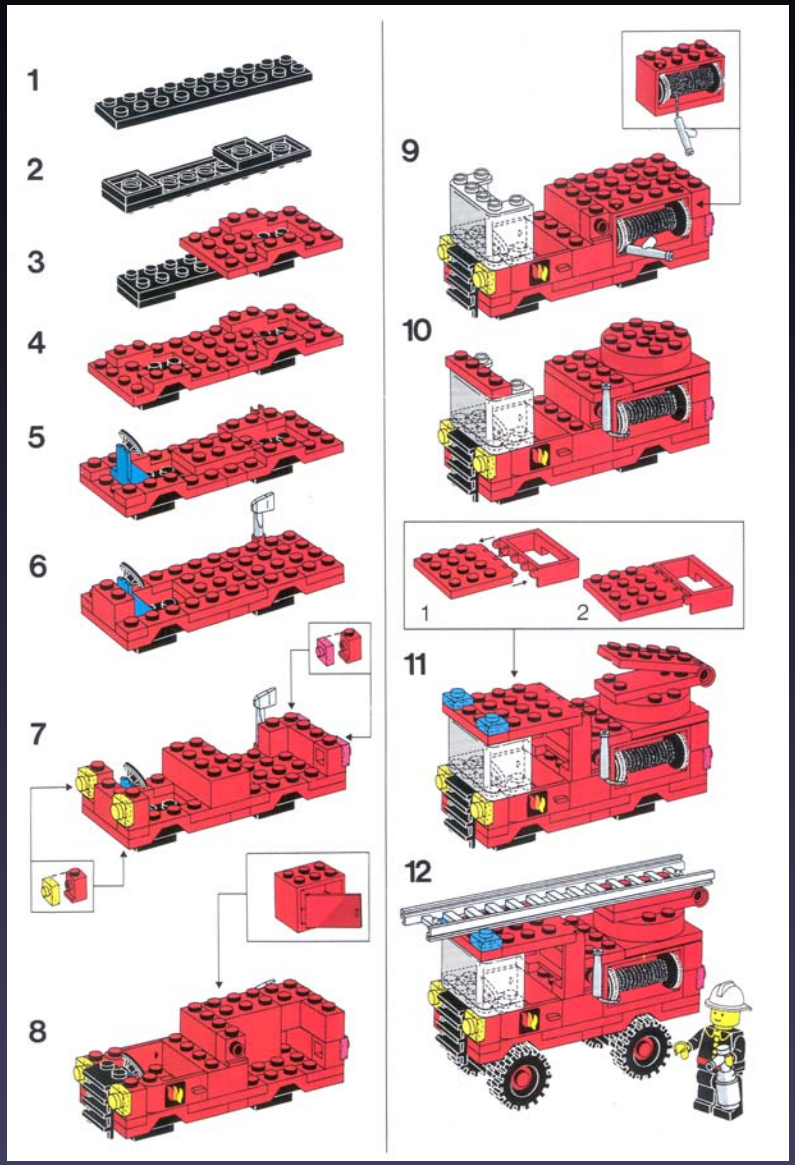
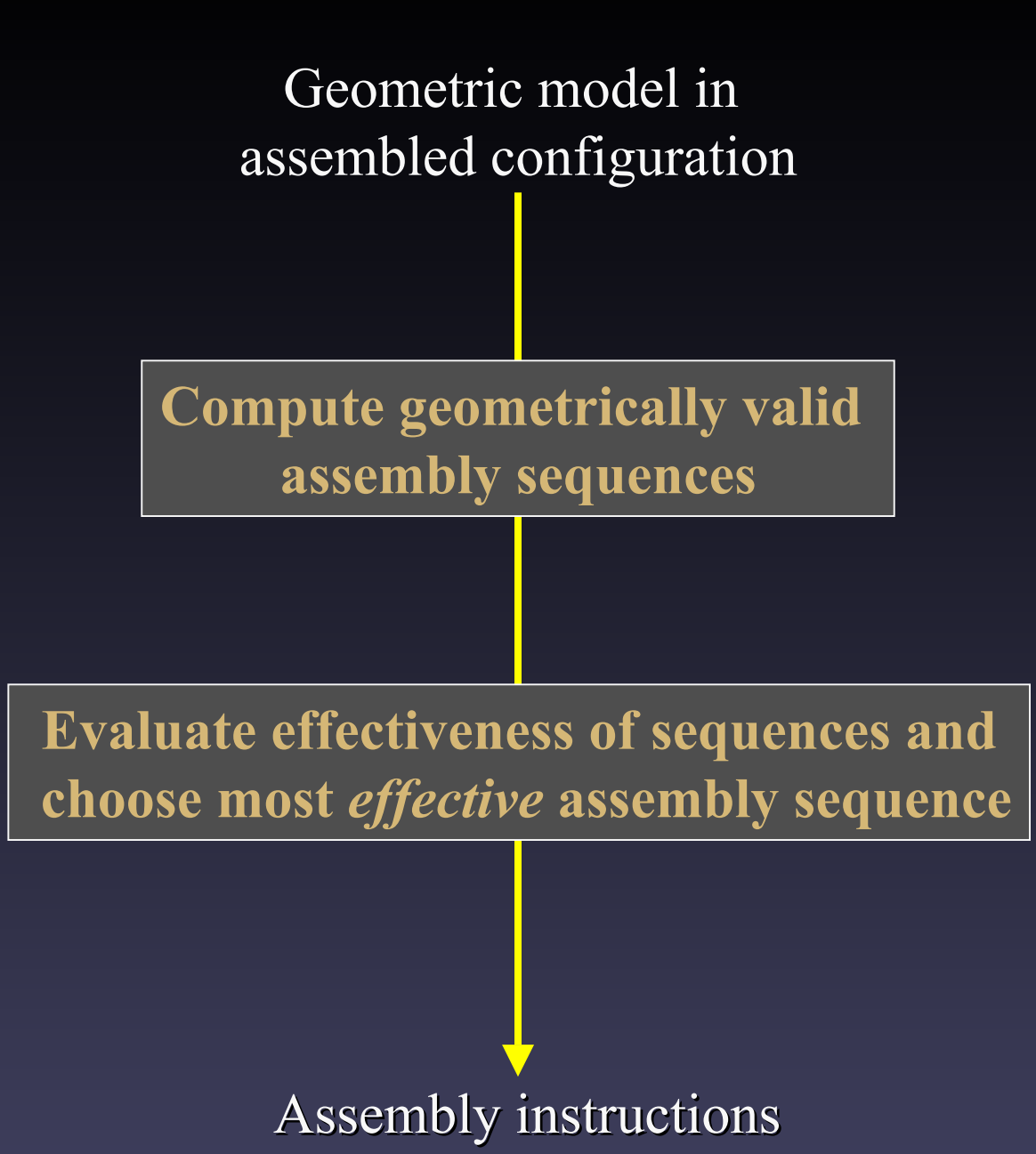
Assembly Instructions

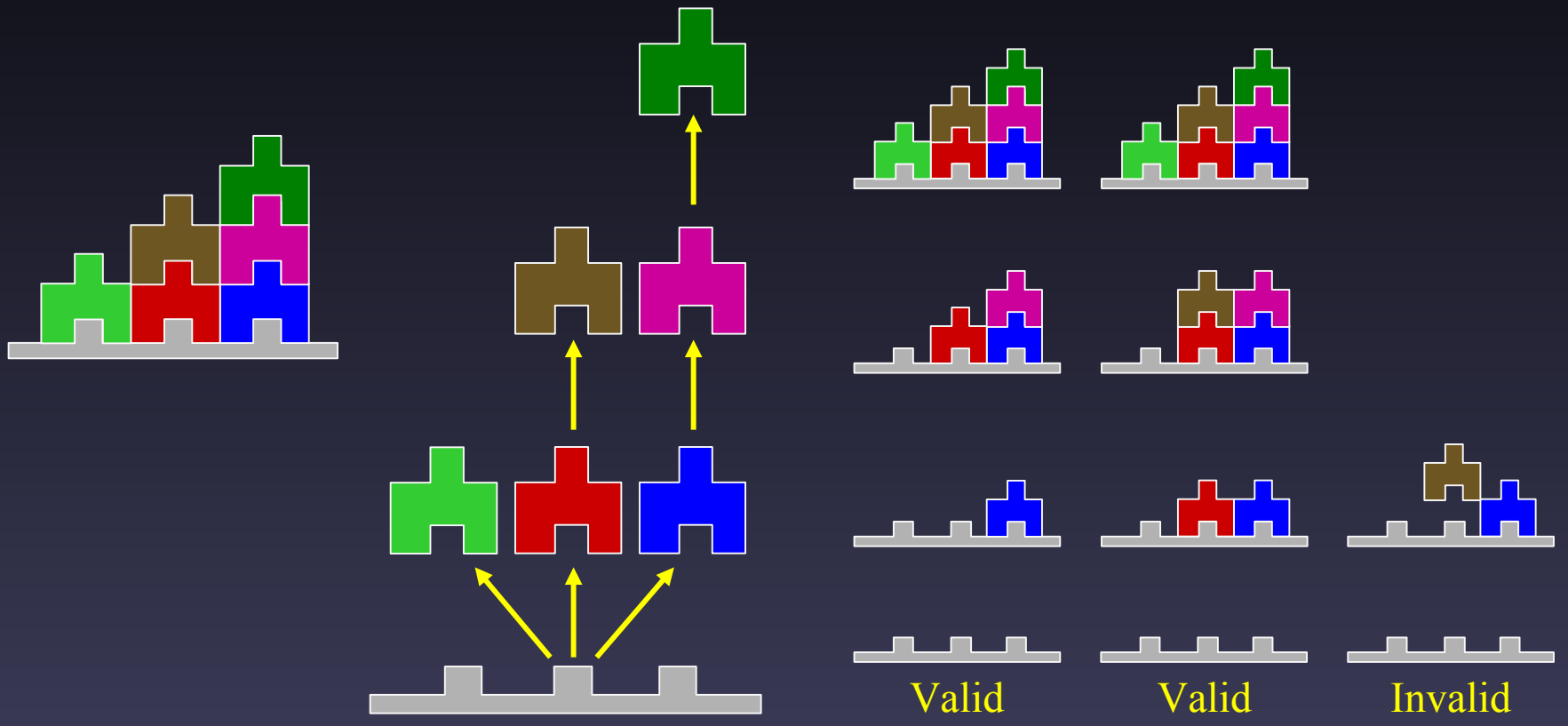


Goal: Create step-by-step instructions from 3D model

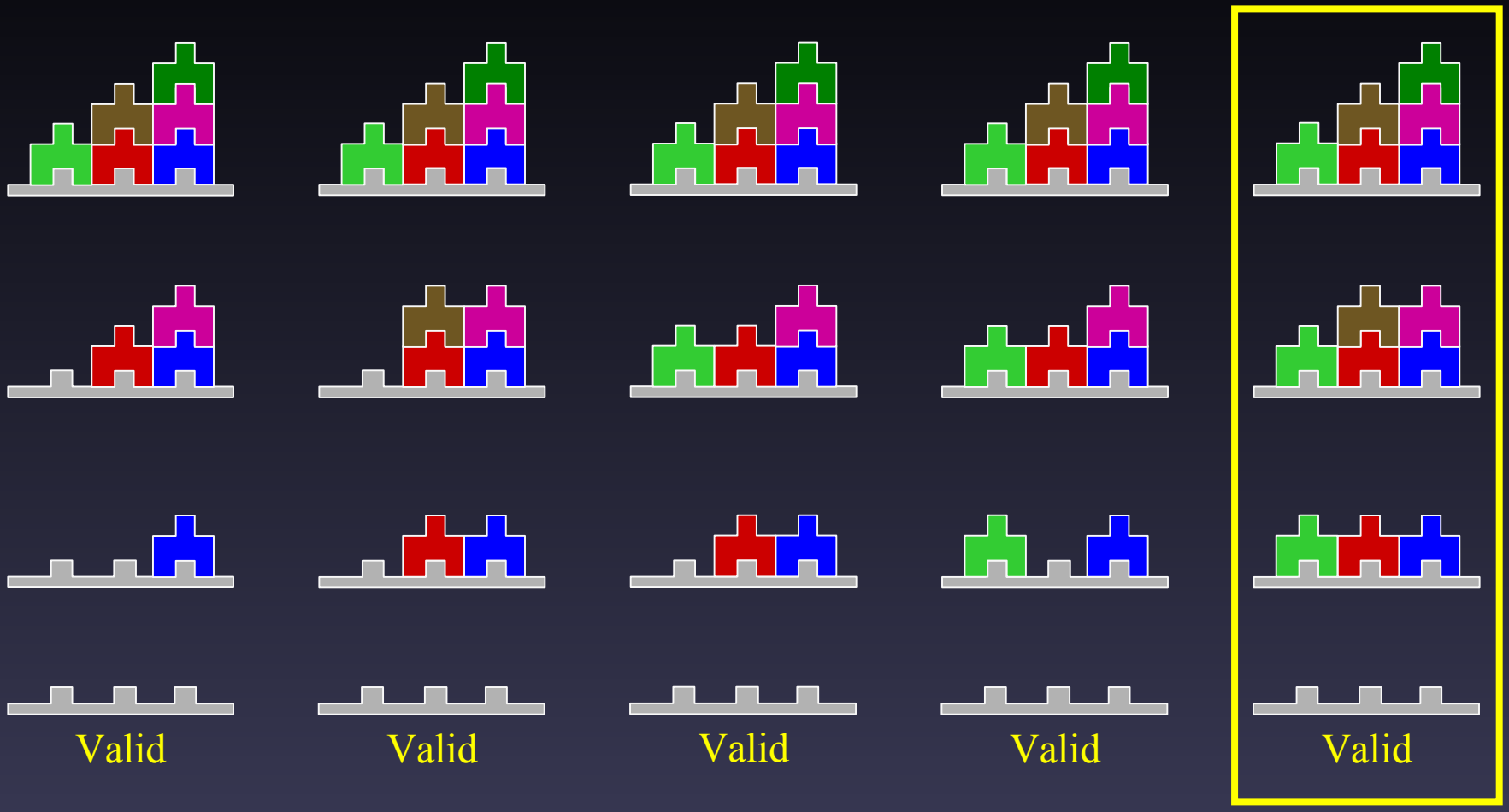

Geometric model in assembled configuration
Compute geometrically valid assembly sequences
Evaluate effectiveness of sequences and choose most *effective* assembly sequence
Assembly instructions

Geometrically Valid Sequences

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



Many Geometrically Valid Sequences



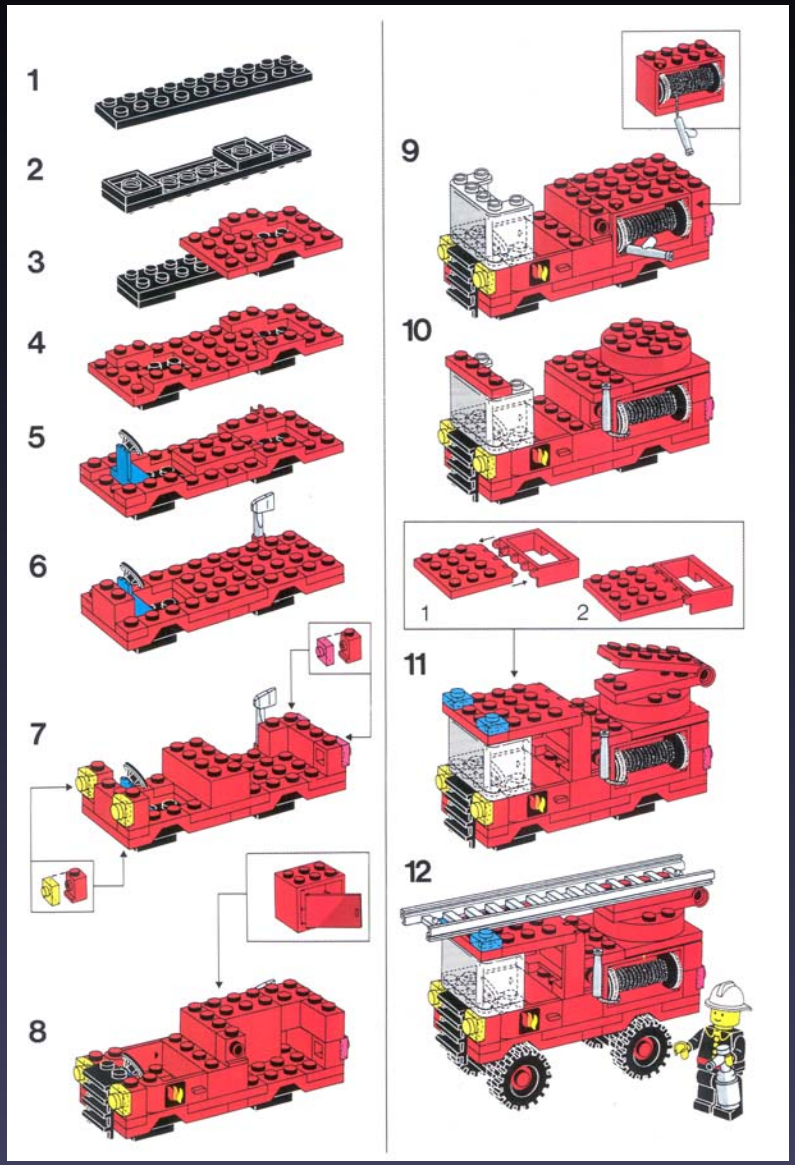
- **How do we choose most effective sequence?**

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

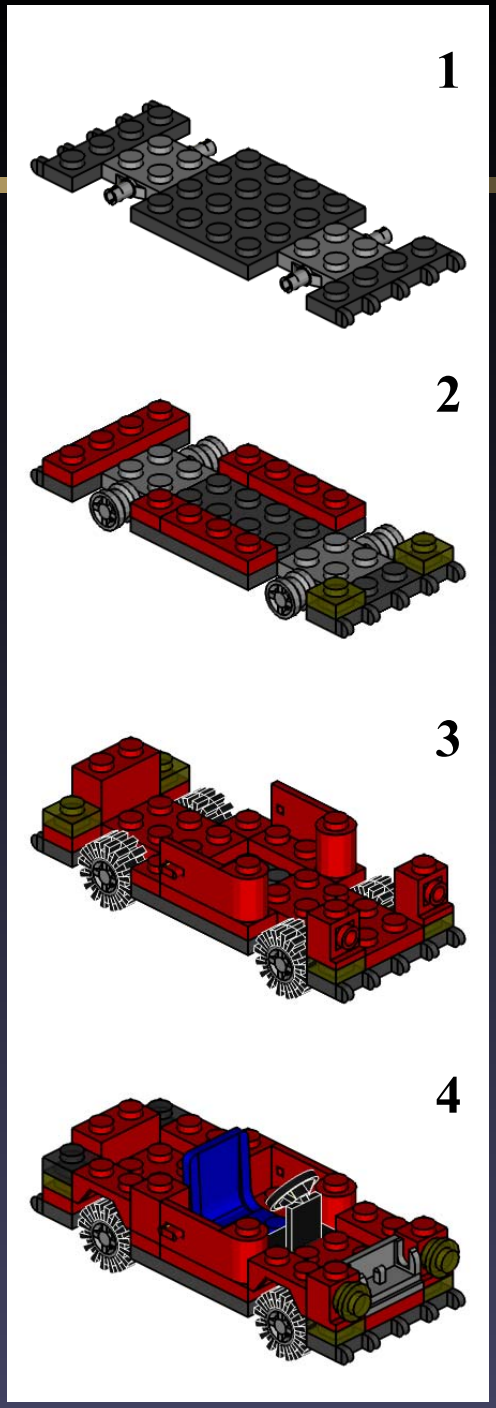
- **Visibility**: If part *A* occludes *B*

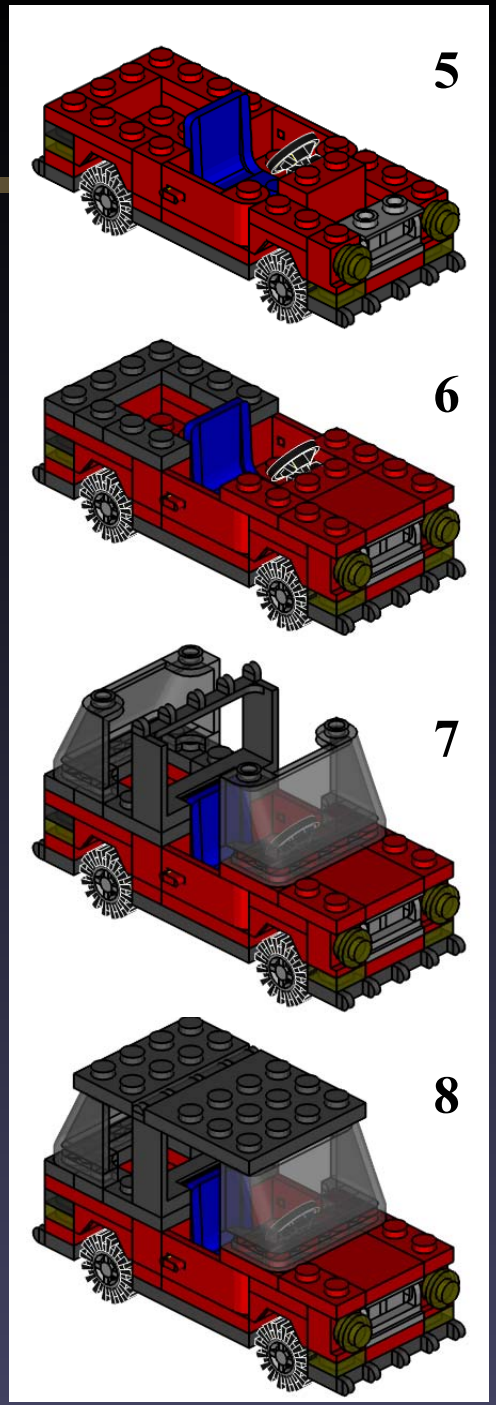
  Penalty = Occlusion (*A*, *B*) * $W_{visibility}$

- **Context**: If < 25% of step *N-1* parts visible

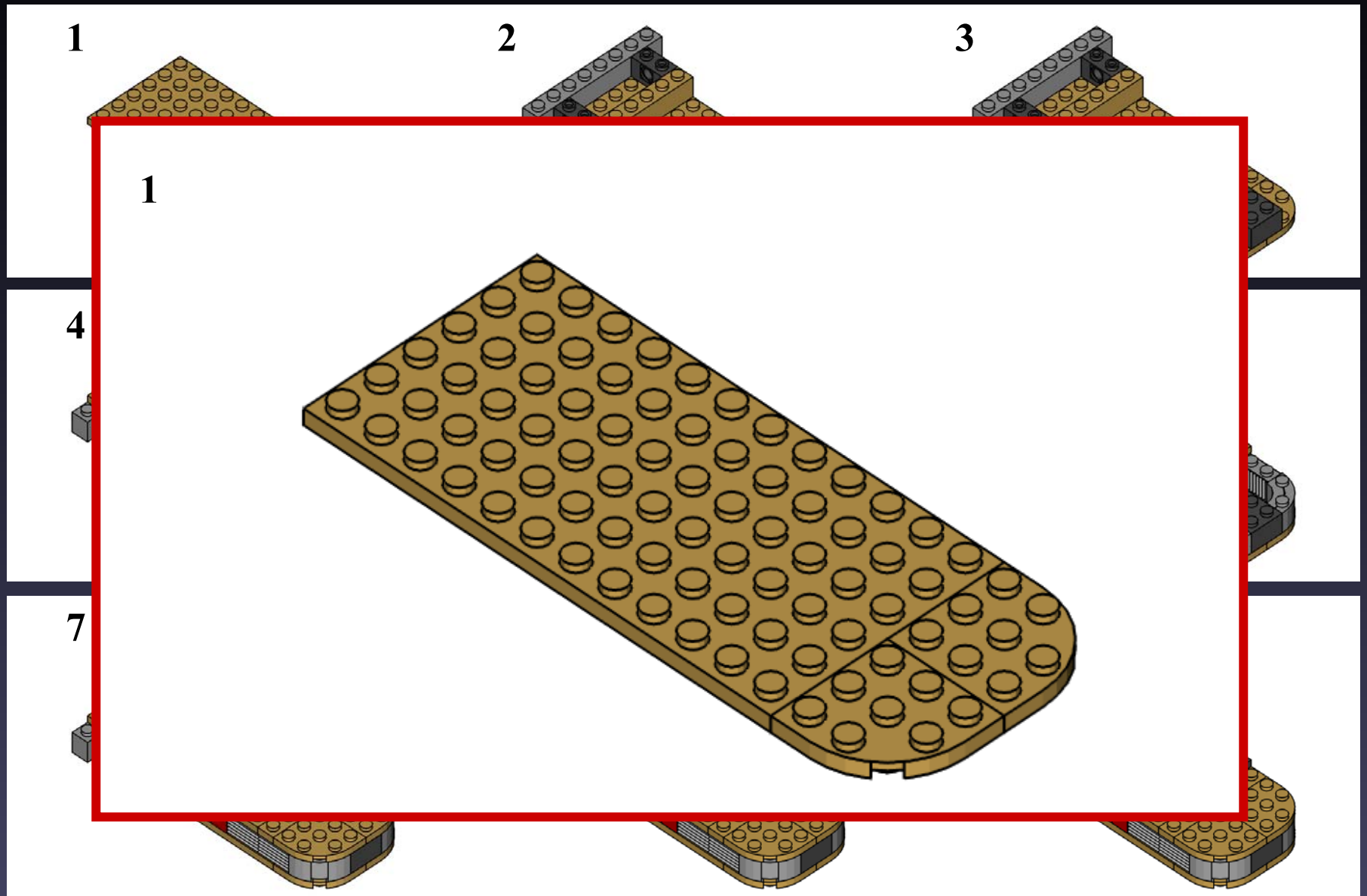
  Penalty = Occlusion (Step *N*, Step *N-1*) * $W_{context}$

Lego Car





Landspeeder

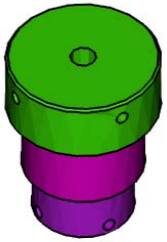


Mechanical Assembly

1

2

3



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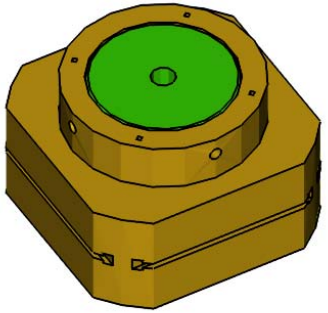

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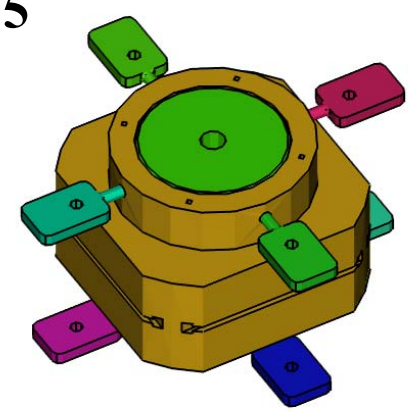

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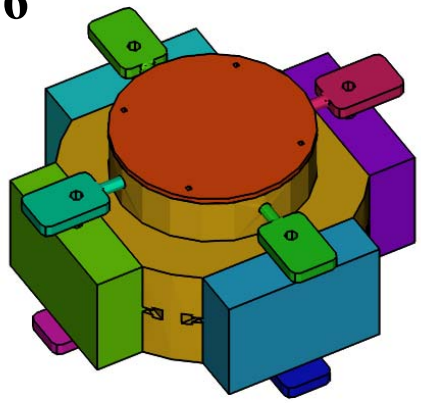

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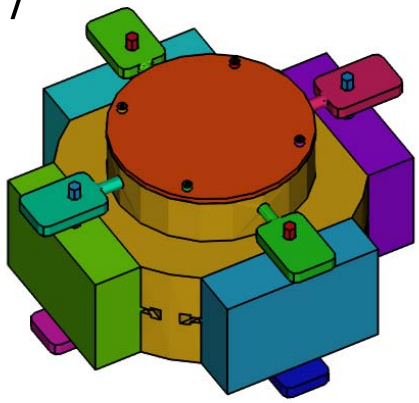
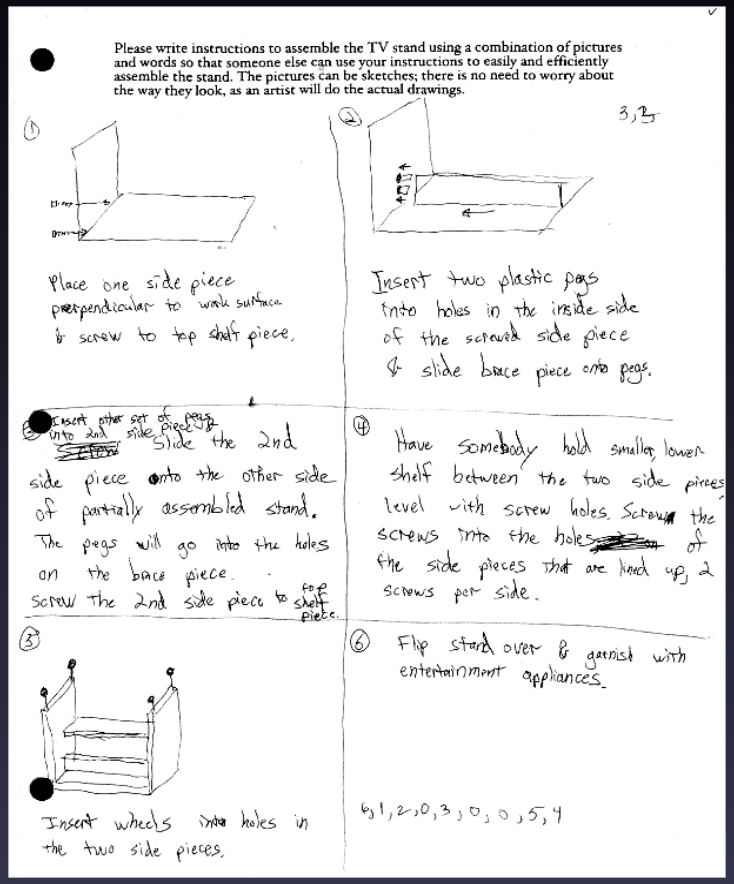


Assembling TV Stand



Please write instructions to assemble the TV stand using a combination of pictures and words so that someone else can use your instructions to easily and efficiently assemble the stand. The pictures can be sketches; there is no need to worry about the way they look, as an artist will do the actual drawings.

3,2

① Place one side piece perpendicular to work surface & screw to top shelf piece.

② Insert two plastic pegs into holes in the inside side of the screwed side piece & slide brace piece onto pegs.

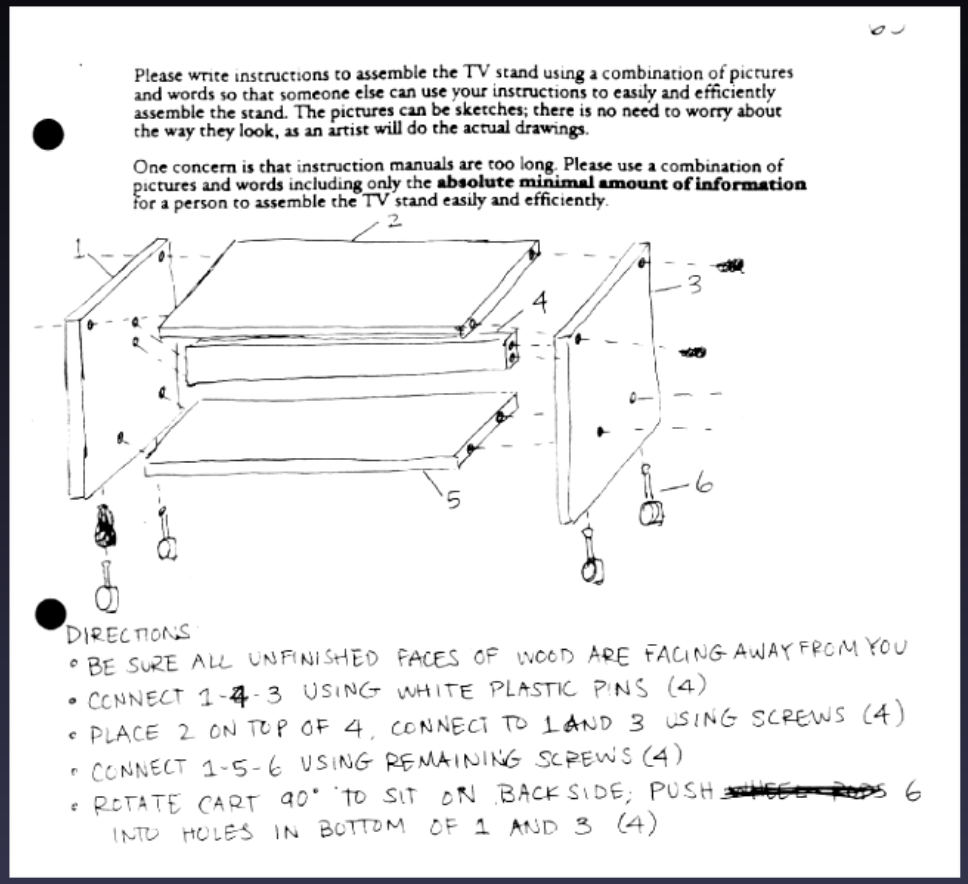
~~Insert other set of pegs into 2nd side piece~~ ③ Slide the 2nd side piece onto the other side of partially assembled stand. The pegs will go into the holes on the brace piece. Screw the 2nd side piece to top shelf piece.

④ Have somebody hold smaller lower shelf between the two side pieces level with screw holes. Screw the screws into the holes of the side pieces that are lined up, 2 screws per side.

③ Insert wheels into holes in the two side pieces.

⑥ Flip stand over & garnish with entertainment appliances.

6, 1, 2, 0, 3, 0, 0, 5, 4



Please write instructions to assemble the TV stand using a combination of pictures and words so that someone else can use your instructions to easily and efficiently assemble the stand. The pictures can be sketches; there is no need to worry about the way they look, as an artist will do the actual drawings.

One concern is that instruction manuals are too long. Please use a combination of pictures and words including only the **absolute minimal amount of information** for a person to assemble the TV stand easily and efficiently.

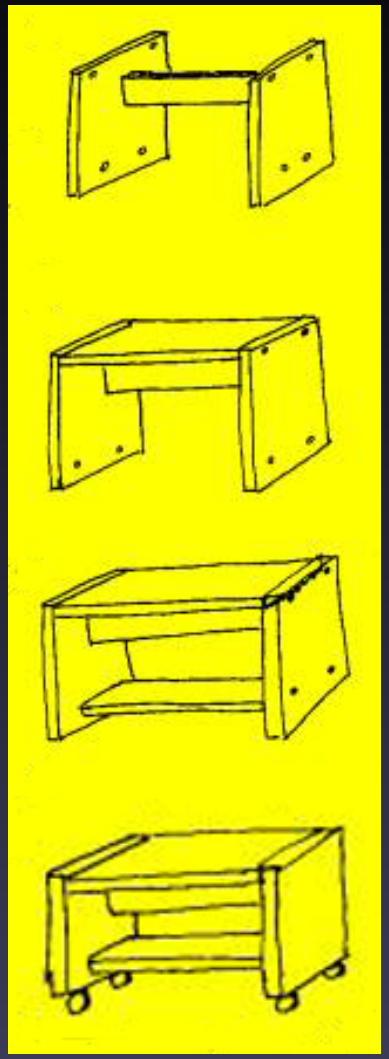
DIRECTIONS

- BE SURE ALL UNFINISHED FACES OF WOOD ARE FACING AWAY FROM YOU
- CONNECT 1-~~4~~-3 USING WHITE PLASTIC PINS (4)
- PLACE 2 ON TOP OF 4, CONNECT TO 1 ~~AND~~ 3 USING SCREWS (4)
- CONNECT 1-5-6 USING REMAINING SCREWS (4)
- ROTATE CART 90° TO SIT ON BACK SIDE; PUSH ~~WHEELS INTO~~ 6 INTO HOLES IN BOTTOM OF 1 AND 3 (4)

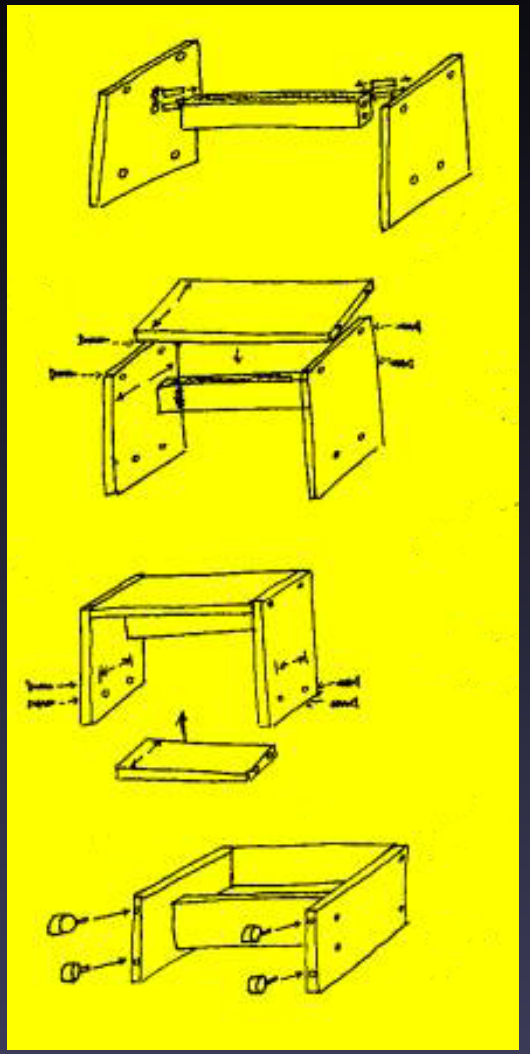
- Subjects assemble TV stand without instructions
- Then asked to produce clear set of assembly instructions

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

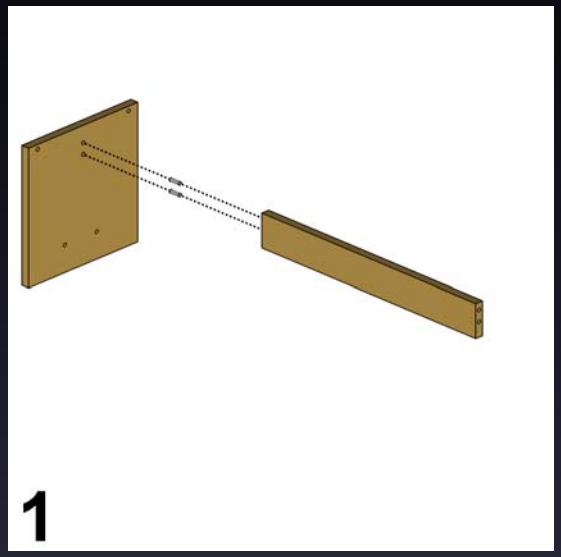


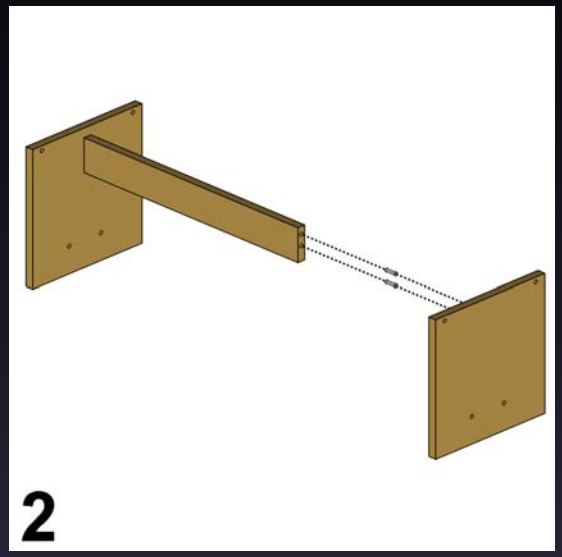
Static Diagrams

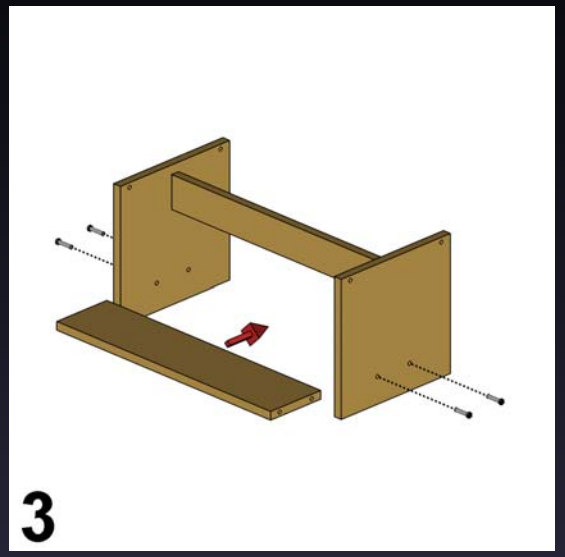


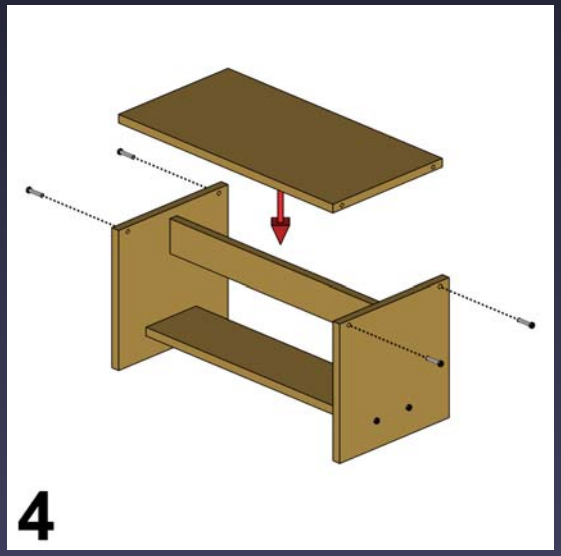
Action Diagrams

Computer-Generated Instructions





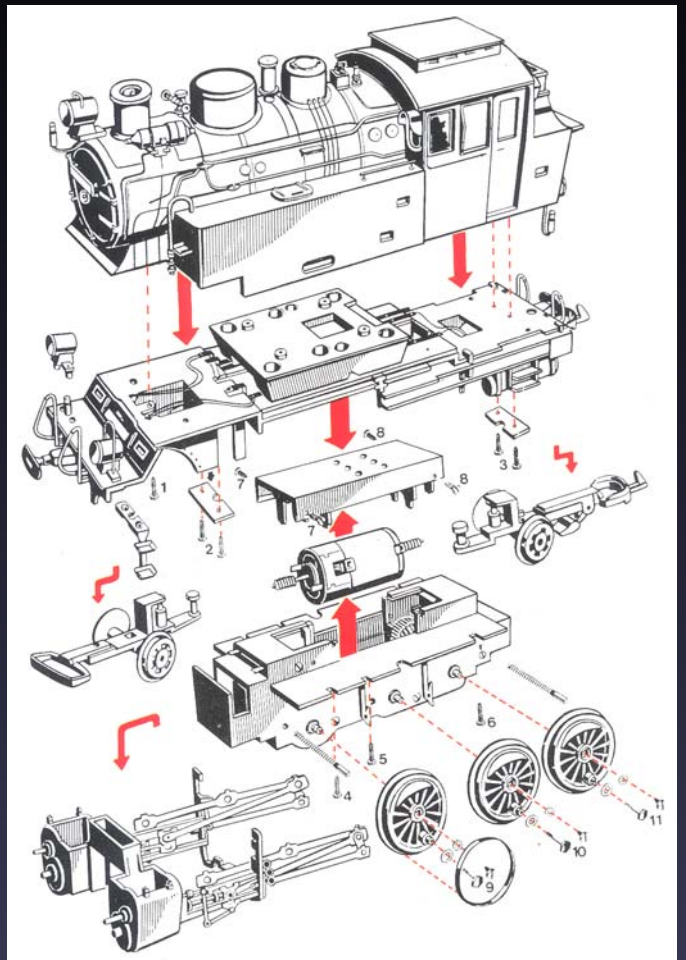




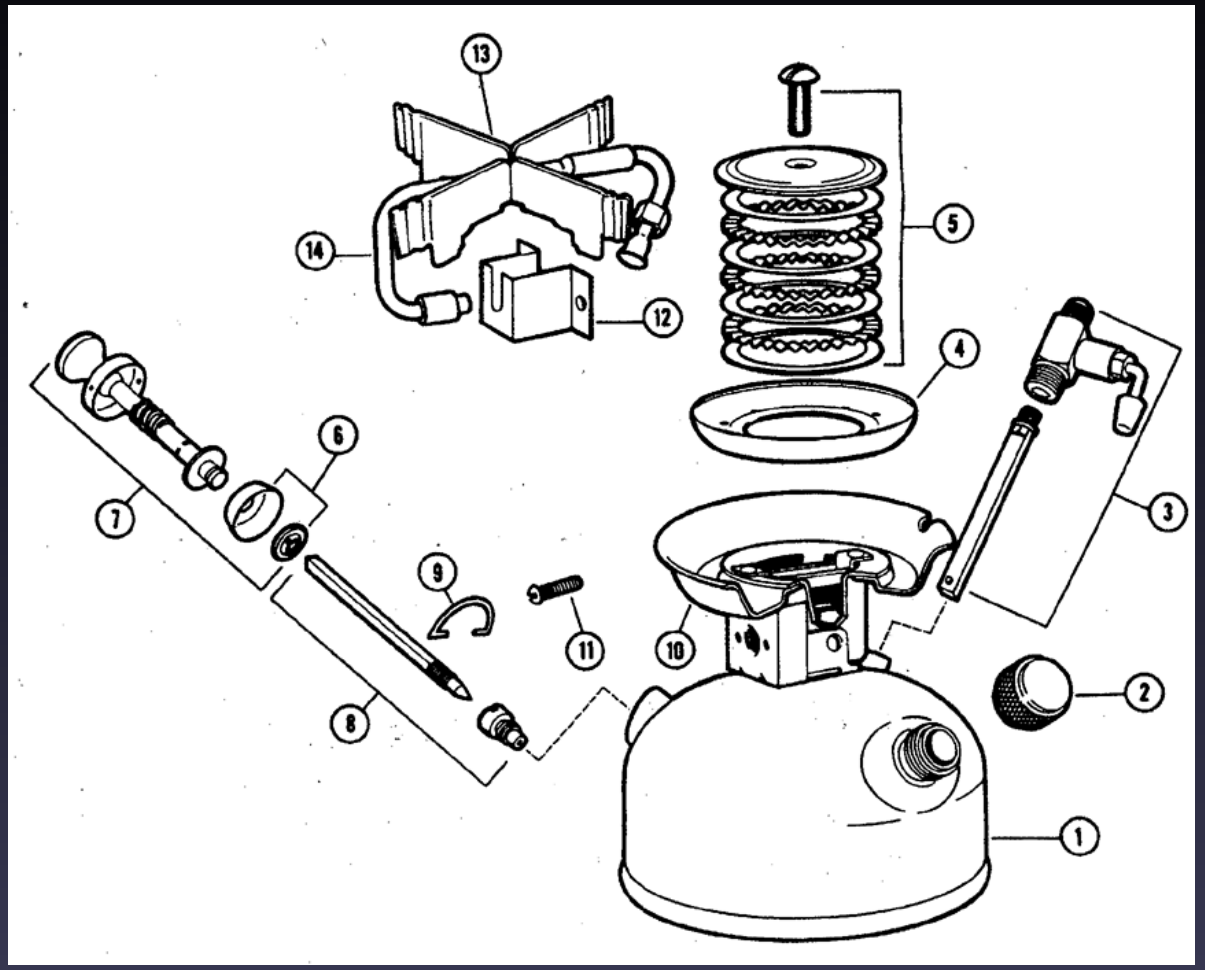
Current Agenda

- 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]



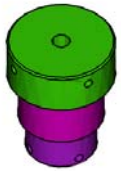
Camping Stove [from Mijksenaar 99]

Initial Results

1

2

3



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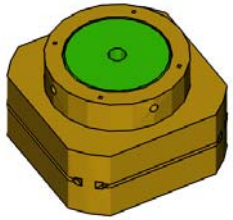

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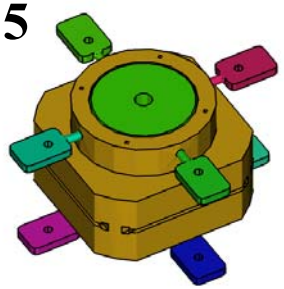

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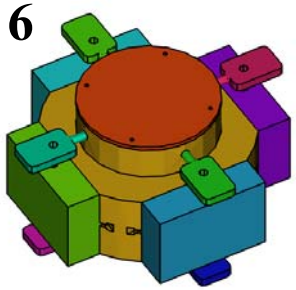

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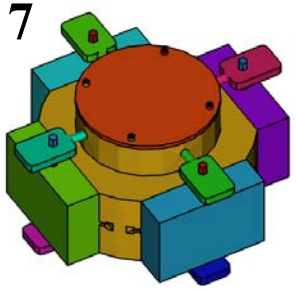
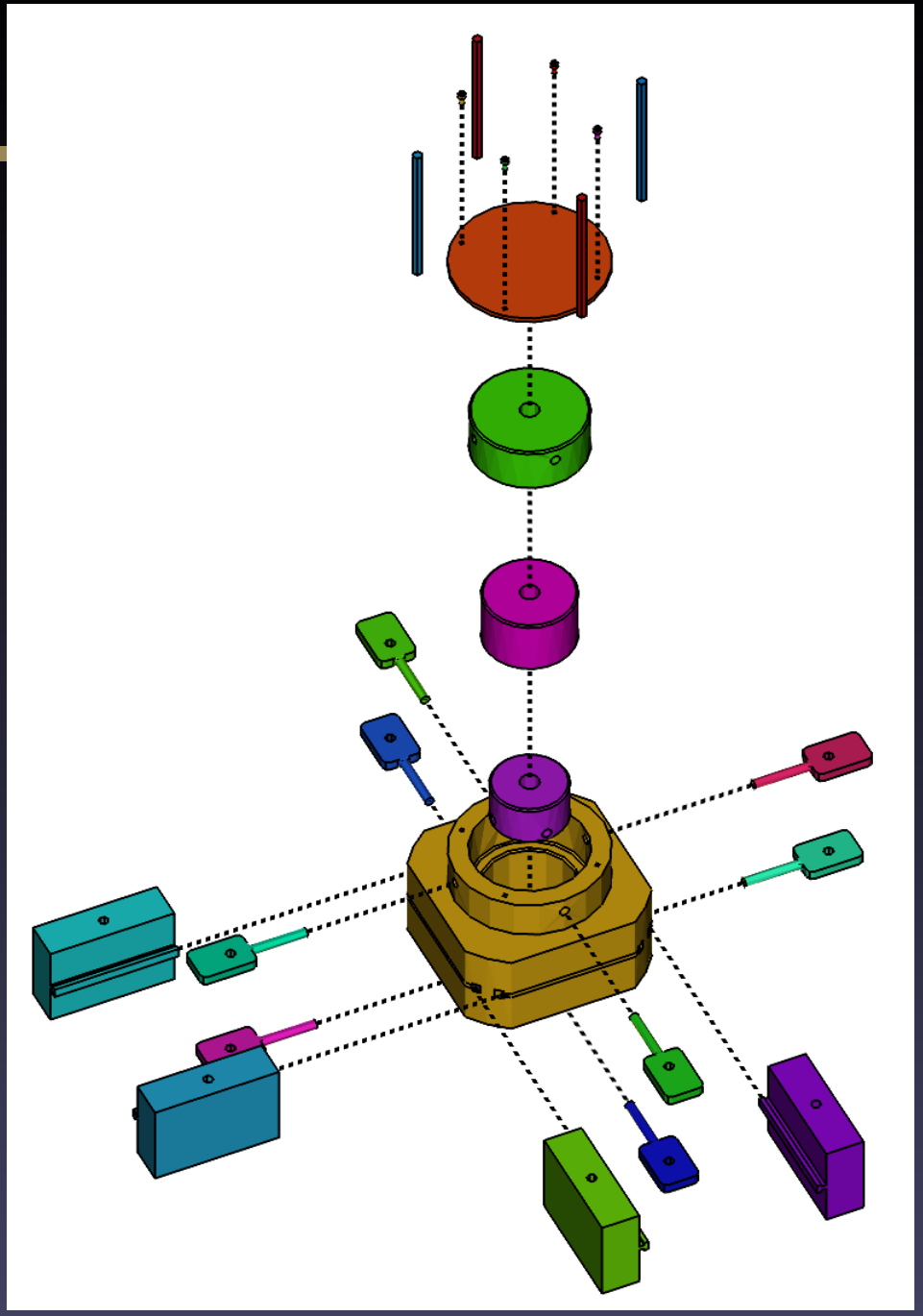
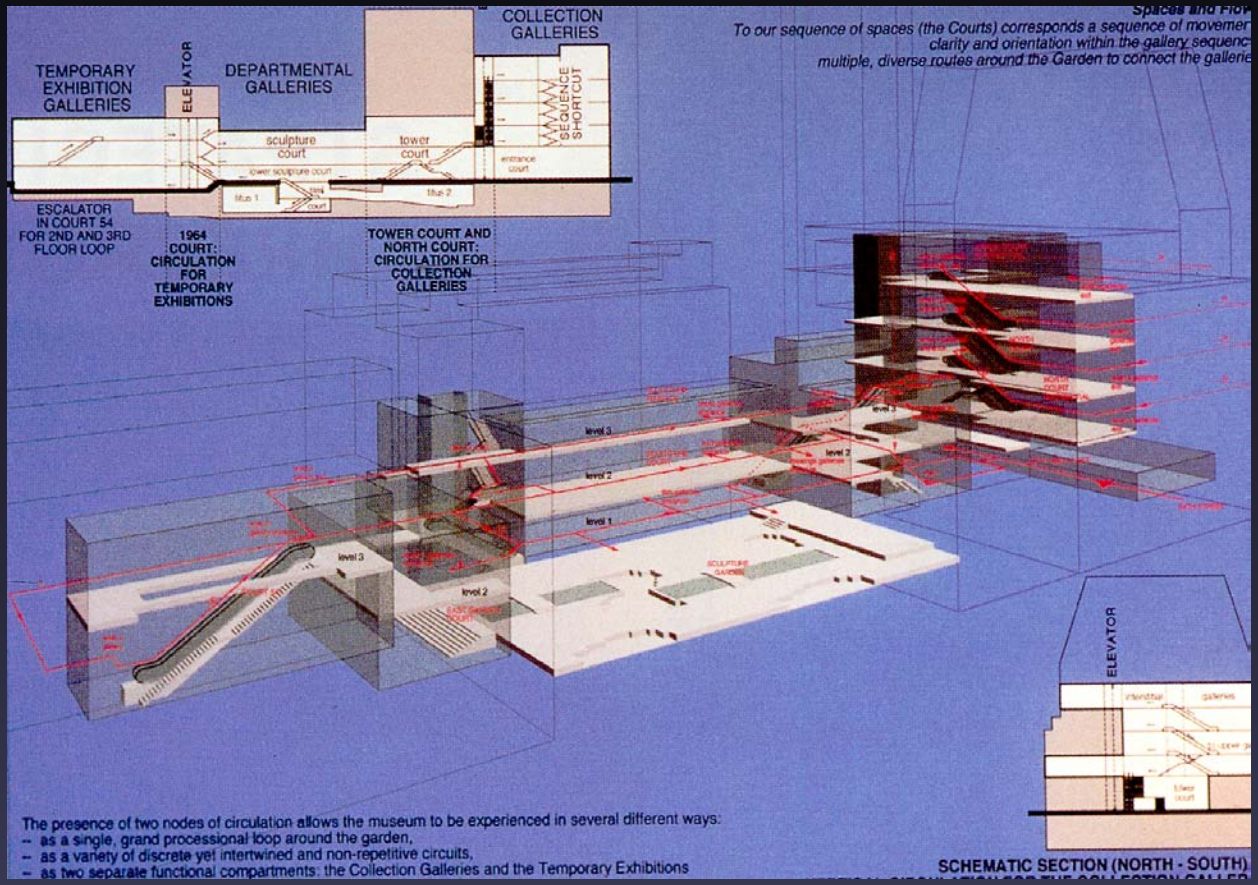
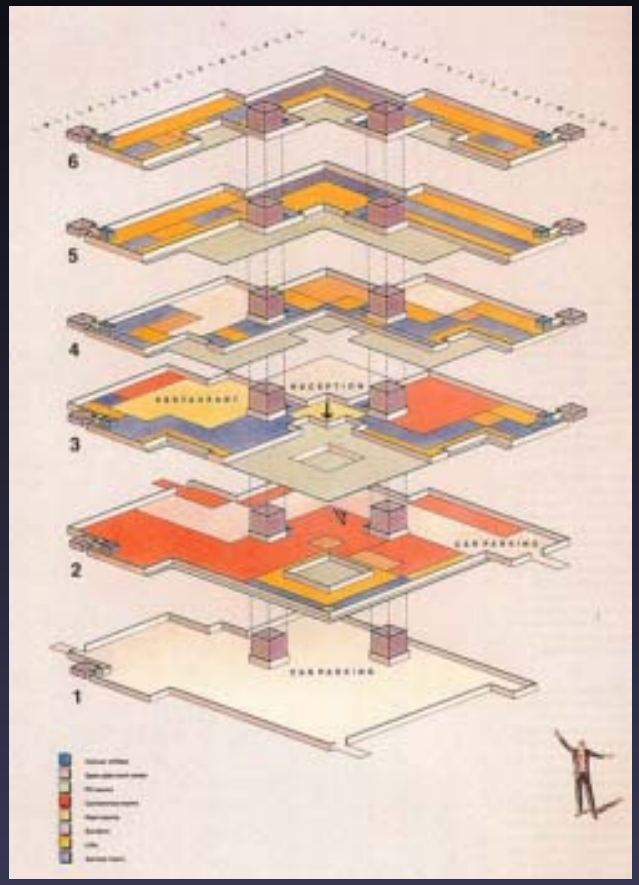




Future: 3D Environments



MoMA Design Entry [Tschumi 99]



IBM Building Plan
[from Holmes 93]

Summary

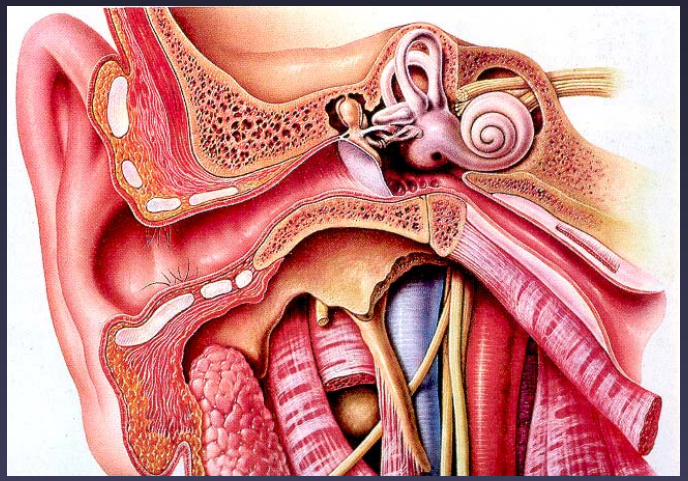
- General two-step approach
  - Step 1: Identify cognitive design principles
  - Step 2: Encode principles as constraints and find most effective visualization
- Automated design systems
  - Route maps
  - Assembly instructions
- Benefits
  - Novices can leverage skills of experts
  - Deal with data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

Outline

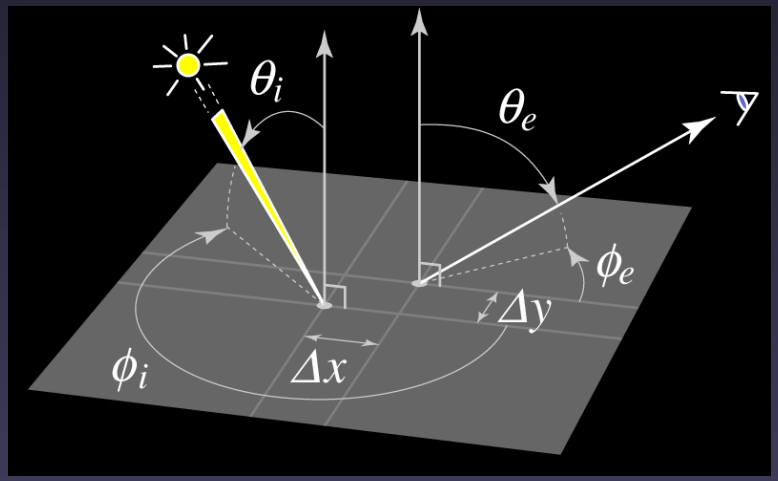
- Motivation
- Automated Route Map Design
- Framework for Automated Design
- Automated Assembly Instruction Design
- Future Directions

Many Other Domains To Consider

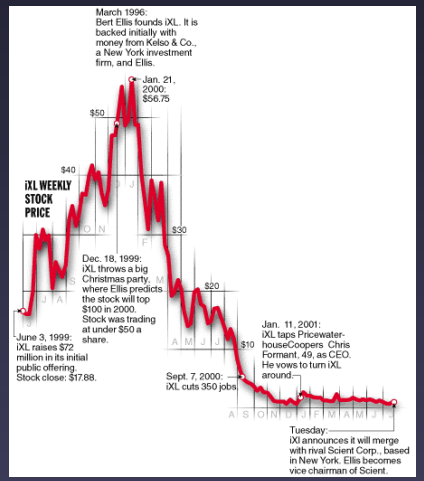
- Medical illustration: Complex biological organisms
- Scientific diagrams: Depict scientific concept
- Graphs and charts: Scatter plots, bar charts, etc.
- Architectural plans: Room and furniture layout
- Proof visualization: Depict complex logical statements



Medical Illustration



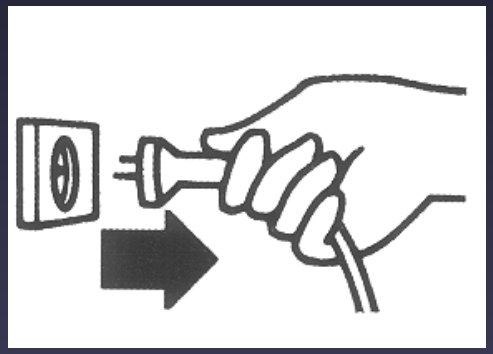
Scientific Diagram



Graphs and Charts

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**

Acknowledgements

- Pat Hanrahan
- Chris Stolte
- Barbara Tversky
- Boris Yamrom
- Vicinity Corporation