Lecture #11: Sketch Understanding
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Slides adapted from Alvarado, Multi-Domain Sketch Understanding, SIGGRAPH course #3, 2007.

Recall Pen-Based Interface Dataflow
Building Recognition Systems

- Building each system requires:
  - sketch recognition expertise
  - a lot of time (2-5 person years!)
  - built in domain assumptions to improve recognition

A Multi-Domain Sketch Recognition Engine

- General Recognition Engine
  - Shape descriptions
  - Mechanical Engineering → Domain Shapes
  - UML → Domain Shapes
  - Electrical Engineering → Domain Shapes
Enabling Natural Interaction

- **Goal:**
  - recognition engines for multiple domains
- **Core challenge:**
  - multi-domain recognition

Sketch Recognition Subtasks

- **Need a multi-domain solution!**

![Diagram of sketch recognition subtasks with labels for stroke fragmentation, symbol recognition, and stroke grouping.]
Multi-Domain Sketch Recognition Architecture

Strokes

Line, Ellipse, Arc, Polyline

Shape Descriptions

Primitive Recognizer/Fragmenter

Generalized Matching Engine

Post Processor

Recognized Objects
Family Tree Domain

- Compound:
  - Domain:

  - Domain Patterns:
    - Family Tree Domain
    - Quadrilateral

Knowledge Representation

(LADD [Hammond03])

(Define Arrow
  (Subshapes (Line shaft)
  (Line head1)
  (Line head2))

(Constraints
  (coincident shaft.p1 head1.p1)
  (coincident shaft.p1 head2.p1)
  (equalLength head1 head2)
  (smaller head1 shaft)
  (acuteAngle head1 shaft)
  (acuteAngle head2 shaft)))

Shape defined by
Subshapes
Constraints
Knowledge Representation

(Define Child-link
  (Subshapes (Arrow a)))

(Define Current-Source
  (Subshapes (Arrow a)
              (Ellipse e))
  (Constraints
   (contains e a)))

Multi-Domain Sketch Recognition Architecture

Strokes

Line, Ellipse, Arc, Polyline

Shape Descriptions

Primitive Recognizer/Fragmenter

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Recognized Objects
Recognition overview

- Task: Simultaneous fragmentation, grouping and symbol identification
- Constraint-based approach
- Generate and test

Definition

- **Hypothesis**: A shape description with associated mapping from subshapes to user’s strokes.

Arrow hypothesis 1
- shaft
- head1
- head2

Arrow hypothesis 2
- head2
- shaft
- head1
Hypothesis-based recognition

- Given a hypothesis, determine if it matches a shape description by testing constraints

\[
\text{Define Arrow} \\
\text{(Subshapes} \\
\text{Line shaft)} \\
\text{Line head1)} \\
\text{Line head2))} \\
\text{(Constraints} \\
\text{coincident shaft.p1 head1.p1)} \\
\text{coincident shaft.p1 head2.p1)} \\
\text{equalLength head1 head2)} \\
\text{smaller head1 shaft)} \\
\text{acuteAngle head1 shaft)} \\
\text{acuteAngle head2 shaft))}
\]
Hypothesis-based recognition: Issues

- Too many hypotheses to try them all

\[ \sum_{i \in S} \binom{n}{k_i} = \text{n = number of strokes;} \]
\[ \binom{n}{k_i} = \text{set of shapes;} \]
\[ k_i = \text{subcomponents in shape } S_i; \]

- Constraints depend on context

And this only considers shapes independently!

Definition

- **Partial Hypothesis**: A hypothesis with unbound subshapes

Quadrilateral partial hypothesis

L1  L2  L3

L4 is unbound
Recognition Using Partial Hypotheses

- Generating Hypotheses (rule-based)
  - generate partial hypotheses (PHs) based on easily recognizable low-level shapes
  - fill in strong PHs with unrecognized strokes
  - prune weak PHs

- Evaluating Hypotheses (probabilistic)
  - how well do user’s strokes fit low level shapes?
  - how well are constraints satisfied?

Bayesian Networks [Pearl88]

- Reason about events/entities
- Two parts
  - directed Acyclic Graph:
    - assign meaning to nodes
    - specify which variables influence one another
  - conditional Probability Tables
    - specify how variables influence one another

Use Bayes Rule to reason about the certainty of each variable
Bayesian Networks [Pearl88]

- Observations give evidence for other variables
  Say we observe $A = t$, then
  $P(E|A) = 0.0056$
  $P(B|A) = 0.49$

Important Phenomenon: Explaining away
If we also hear there has been an earthquake (i.e., $E = t$), then
$P(B|A, E) = 0.001$
Shape Fragments

(Define Arrow
(Subshapes
L_1: (Line shaft)
L_2: (Line head1)
L_3: (Line head2))
(Constraints
C_1: (coincident shaft.p1 head1.p1)
C_2: (coincident shaft.p1 head2.p1)
C_3: (equalLength head1 head2)
C_4: (smaller head1 shaft)
C_5: (acuteAngle head1 shaft)
C_6: (acuteAngle head2 shaft)))

Arrow Hypothesis

User's intention to draw an Arrow \([t, f]\)

Squared error between stroke and best fit line

Distance between shaft.p1 head.p1

Shape Fragments: Measurement Nodes

(Define Arrow
(Subshapes
L_1: (Line shaft)
L_2: (Line head1)
L_3: (Line head2))
(Constraints
C_1: (coincident shaft.p1 head1.p1)
C_2: (coincident shaft.p1 head2.p1)
C_3: (equalLength head1 head2)
C_4: (smaller head1 shaft)
C_5: (acuteAngle head1 shaft)
C_6: (acuteAngle head2 shaft)))

User's intention to draw needed lines and constraints \([t, f]\)

Arrow Hypothesis

shaft = s2
head1 = s3
head2 = s4

User's intention to draw an Arrow \([t, f]\)
Shape Fragments

(Define Arrow
(Subshapes
  L1: (Line shaft)
  L2: (Line head1)
  L3: (Line head2))
(Constraints
  C1: (coincident shaft.p1 head1.p1)
  C2: (coincident shaft.p1 head2.p1)
  C3: (equalLength head1 head2)
  C4: (smaller head1 shaft)
  C5: (acuteAngle head1 shaft)
  C6: (acuteAngle head2 shaft)))

Arrow Hypothesis
shaft = s2
head1 = s3
head2 = s4

Shape Fragments: Another Hypothesis

(Define Arrow
(Subshapes
  L1: (Line shaft)
  L2: (Line head1)
  L3: (Line head2))
(Constraints
  C1: (coincident shaft.p1 head1.p1)
  C2: (coincident shaft.p1 head2.p1)
  C3: (equalLength head1 head2)
  C4: (smaller head1 shaft)
  C5: (acuteAngle head1 shaft)
  C6: (acuteAngle head2 shaft)))

Arrow Hypothesis #2
shaft = s3
head1 = s1
head2 = s2
Shape Fragments: Partial Hypothesis

(Define Arrow
(Subshapes
L₁: (Line shaft)
L₂: (Line head1)
L₃: (Line head2))
Constraints
C₁: (coincident shaft.p₁ head1.p₁)
C₂: (coincident shaft.p₁ head2.p₁)
C₃: (equalLength head1 head2)
C₄: (smaller head1 shaft)
C₅: (acuteAngle head1 shaft)
C₆: (acuteAngle head2 shaft)))

shaft = s₁
head1 = s₂
head2 = ??

Composing Shape Fragments

Each node represents a hypothesis
Hypothesis Generation

- **Bottom Up**
  - partial hypotheses generated based on rough classification for objects and constraints

- **Top Down**
  - strokes possibly reclassified to fit into PHs

- **Pruning**
  - keep number of hypotheses manageable

An Illustration

- Ellipse(e2)
- Stroke(s3)
- Stroke(s1)
- Stroke(s4)
- Stroke(s5)
- Parent-child
- Female(f1)
- Female(f2)
- Domain patterns
- Domain shapes
- Compound shapes
- Primitive shapes
- Connects(I1, I3)
- Connects(I1, I2)
- Same-length(I3, I2)
- Line(I1)
- Line(I2)
- Line(I3)
- Female(f1)
- Female(f2)
- Ellipse(e1)
- Stroke(s1)
- Stroke(s2)
- Stroke(s3)
- Stroke(s4)
- Stroke(s5)
Results: Trees

Overall: SketchREAD: 77% Precision (F=0.83)
Baseline: 50% Precision (F=0.65)

Results: Circuits

Overall: SketchREAD: 62% Precision (F=0.65)
Baseline: 54% Precision (F=0.57)
Readings

