Recall Pen-Based Interface Dataflow

- Raw Stroke Data
- Preprocessing
- Segmentation
- Ink Parsing
- Classification
- Feature Extraction and Analysis
- Sketch Understanding
- Make Inferences
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

- Strokes
- Mechanical Engineering → Domain Shapes
- Strokes
- UML → Domain Shapes
- Strokes
- Electrical Engineering → Domain Shapes
- Strokes
- General Recognition Engine → 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 showing subtasks: Stroke Fragmentation, Symbol recognition, Stroke grouping]
Family Tree Domain

- **Compound:**
- **Domain:**

<table>
<thead>
<tr>
<th>Domain Patterns:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
</tr>
<tr>
<td>Quadrilateral</td>
</tr>
</tbody>
</table>

- **Domain Patterns:**

<table>
<thead>
<tr>
<th>Marriage</th>
<th>Partnership</th>
<th>Parent-Child</th>
<th>Divorce</th>
</tr>
</thead>
</table>

Knowledge Representation

**LADDER [Hammond03]**

Shape defined by

<table>
<thead>
<tr>
<th>Subshapes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line shaft</td>
</tr>
<tr>
<td>Line head1</td>
</tr>
<tr>
<td>Line head2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>coincident shaft.p1 head1.p1</td>
</tr>
<tr>
<td>coincident shaft.p1 head2.p1</td>
</tr>
<tr>
<td>equalLength head1 head2</td>
</tr>
<tr>
<td>smaller head1 shaft</td>
</tr>
<tr>
<td>acuteAngle head1 shaft</td>
</tr>
<tr>
<td>acuteAngle head2 shaft</td>
</tr>
</tbody>
</table>
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

Generalized Matching Engine

Post Processor

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.

![Diagram](image-url)
Hypothesis-based recognition

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

(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])))
Hypothesis-based recognition: Issues

- Too many hypotheses to try them all
  \[ \sum_{i \in S} \binom{n}{k_i} (k_i)! \]
  \( n \) = number of strokes;
  \( S \) = set of shapes;
  \( k_i \) = 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

  \( L_1 \) \( L_2 \) \( L_3 \) \( L_4 \)

  \( L_4 \) 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
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

Squared error between stroke and best fit line

Distance between shaft.p1 head.p1

Shape Fragments: Measurement Nodes

(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)))

Squared error between stroke and best fit line

Distance between shaft.p1 head.p1
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)))

shaft = s₂
head₁ = s₃
head₂ = s₄

Arrow Hypothesis

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)))

shaft = s₃
head₁ = s₁
head₂ = s₂

Arrow Hypothesis #2
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))

Each node represents a hypothesis

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 (e1)
- Stroke (s1)
- Stroke (s2)
- Line (l1)
- Line (l2)
- Arrow
- Female (f1)
- Female (f2)
- Ellipse (e2)
- Connects (l1, l3)
- Connects (l1, l2)
- Same-length (l3, l2)
- 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