Developmentally Inspired Cognitive Architectures

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Not from Zeus's Forehead

• Human intelligence is fundamentally shaped by the challenges of growing a complete organism from a single cell.

• Developmental Cost captures these challenges and invalidates many possible cognitive models.
Popular Constraints

• Anatomy
  – Brodmann areas, fMRI, injury studies, ...

• Cellular Biology
  – Neurons, synapses, transmitters, glia, ...

• Behavior
  – Reflexes, infant cognition, illusions, ...
Popular Constraints

- **Anatomy**  How do parts cooperate?
  - Brodmann areas, fMRI, injury studies, ...
- **Cellular Biology**  1K+ neurons do anything
  - Neurons, synapses, transmitters, glia, ...
- **Behavior**  How do we debug?
  - Reflexes, infant cognition, illusions, ...

*These do not constrain our models much!*
Two Hurdles of Development

Notice I'm not talking about evolution...
Encoding

$\sim 10^{10}$ neurons
$\sim 10^{14}$ synapses

$10^9$ bytes DNA
Variation

- Centimeters are huge to cells!
- Anatomical features vary at every level
Development is *Different*

- Human intelligence is fundamentally shaped by the challenges of growing a complete organism from a single cell.
- Are we missing key organizational ideas?

*Why should we accept a cognitive model if nobody knows how to grow it?*
Engineering for Development

Mature Device? ✓
Development? X

Mature Device? ✓
Development? ✓

Just because you know how to grow it doesn't mean you're forced to...
Asymptotic Cost

<table>
<thead>
<tr>
<th>Mature</th>
<th>Time</th>
<th>Space</th>
<th>Imperfection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>execution</td>
<td>hardware</td>
<td>error</td>
</tr>
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</table>

How hard is it to run the part?
## Developmental Cost

<table>
<thead>
<tr>
<th>Development</th>
<th>Time</th>
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<tr>
<td>Development</td>
<td>growth</td>
<td>encoding</td>
<td>variation</td>
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</table>

*How hard would it be to grow the part?*
How delicate is this part?
## Developmental Cost

<table>
<thead>
<tr>
<th>Mature</th>
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</tr>
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<tbody>
<tr>
<td>Time</td>
<td>100 ms</td>
</tr>
<tr>
<td>Space</td>
<td>9 months</td>
</tr>
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</table>

Does this part cost too much? 

... but only asymptotically
Example Application: Communication Bootstrapping

- How might our eyes and ears learn to understand one another?
Calculating Cost

• Three building blocks:
  – Simple program
  – Communication paths
  – Set of parts

• Building block costs come from neuroscience & synthetic biology

Problems with building block assumptions are likely to change cost constants only
(defun hypotenuse (leg1 leg2) 
  (sqrt (+ (* leg1 leg1) 
          (* leg2 leg2))))

Loops, function calls handled by expansion

Simple programs are cheap
Primitive: Communication Paths

Mature

Development

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<thead>
<tr>
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<tbody>
<tr>
<td>Mature</td>
<td>O(1)</td>
<td>O(bits*paths)</td>
<td>noise</td>
</tr>
<tr>
<td></td>
<td>O(length)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development</td>
<td>O(length)</td>
<td>O(bits/reuse)</td>
<td>extra or absent paths</td>
</tr>
</tbody>
</table>

Precision connections are expensive
Can add mesh network for $O(1)$ added cost

Making copies is cheap
A growing library of parts...

<table>
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<tr>
<th>Device</th>
<th>Mat. Time</th>
<th>Mat. Space</th>
<th>Dev. Time</th>
<th>Dev. Space</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Competition</strong></td>
<td>(O(1))</td>
<td>(O(n))</td>
<td>(O(1))</td>
<td>(O(1))</td>
</tr>
<tr>
<td><strong>Random Bipartite Graph</strong></td>
<td>(O(1))</td>
<td>(O(k*A))</td>
<td>(O(A))</td>
<td>(O(1))</td>
</tr>
<tr>
<td><strong>Distributed Map</strong></td>
<td>(O(1))</td>
<td>(O((A+B) \times \sqrt{\min(A,B)}))</td>
<td>(O(\min(A,B)))</td>
<td>(O(1))</td>
</tr>
<tr>
<td><strong>Unidirectional Symbolic Link</strong></td>
<td>(O(b))</td>
<td>(O(i(i+b)+s(i+\sqrt{s})))</td>
<td>(O(i+s\sqrt{s}))</td>
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<td>(O(b))</td>
<td>(O(i(i+b)+s(i+s))\ ?)</td>
<td>(O(i^2+s^2)\ ?)</td>
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Competition

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<td>O(1) am.</td>
<td>O(n)</td>
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Random Bipartite Graph

$\begin{array}{cccc}
\text{Mat. Time} & \text{Mat. Space} & \text{Dev. Time} & \text{Dev. Space} \\
O(1) & O(k*A) & O(A) & O(1)
\end{array}$
Distributed Map

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<tr>
<td>$O(1)$</td>
<td>$O((A+B)\sqrt{\min(A,B)})$</td>
<td>$O(\min(A,B))$</td>
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Unidirectional Symbolic Link

AGT = JOHN
DST = JOHN
PAT = RED BALL
VRB = THREW

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### Signal Map

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Symbols send?

Relation & IISE map

Inflection coders

Crossbar

Symbol coders

Random bipartite graph

Listener

Unidirectional symbolic link

Bidirectional symbolic link

Message arrived

Channel

Cable heads
Contributions

• Defined *Developmental Cost*
  – adds needed constraint
  – has low sensitivity to biological details
  – can measure parts in isolation

• Built development-aware parts for Communication Bootstrapping project
  – three building block assumptions
  – beginning of a library of parts
Open Questions

• What is the developmental cost of existing models?
  – SOAR, ACT-R, EPIC, PolyScheme, etc.
• What makes a good toolbox of parts?
• What other building blocks are useful?
• Is it ever reasonable to ignore development?