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...

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

10⁹ 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? ✓ Mature Device? ✓ Development? X Development? ✓

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

Asymptotic Cost

	Time	Space	Imperfection
Mature	execution	hardware	error

How hard is it to run the part?

Developmental Cost

	Time	Space	Imperfection
Mature	execution	hardware	error
Development	growth	encoding	variation

How hard would it be to grow the part?

Developmental Cost



How delicate is this part?

Developmental Cost

	Time	Space	Imperfection
Mature	100 ms	10^11 neurons	error
Development	9 months	1GB DNA	variation

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

Primitive: Simple Program

	Time	Space	Imperfection
Mature	O(ops+bits)	O(ops+bits)	abort
Development	O(ops+bits)	O(ops+bits)	DOA

Loops, function calls handled by expansion Simple programs are cheap

Primitive: Communication Paths



	Time	Space	Imperfection
Mature	O(1) O(length)	O(bits*paths)	noise
Development	O(length)	O(bits/reuse)	extra or absent paths

Precision connections are expensive

Primitive: Set of Parts



	Time	Space	Imperfection
Mature	O(part)	O(size*part)	part
Development	O(part)	O(part)	set size & part

Can add mesh network for O(1) added cost Making copies is cheap

A growing library of parts...

Device	Mat. Time	Mat. Space	Dev. Time	Dev.Space
Competition	O(1)	O(n)	O(1)	O(1)
Random Bipartite Graph	O(1)	O(k*A)	O(A)	O(1)
Distributed Map	O(1)	O((A+B) * √(min(A,B))	O(min(A,B))	O(1)
Unidirectional Symbolic Link	O(b)	O(i(i+b)+ s(i+√s))	O(i+s√s)	O(1)
Bidirectional Symbolic Link	O(b)	O(i(i+b)+ s(i+√s))	O(i+s√s)	O(1)
Signal Map	O(b)	O(i(i+b)+ s(i+s)) ?	O(i^2+s^2) ?	O(1)

Competition



Mat. Time	Mat. Space	Dev. Time	Dev.Space
O(1) am.	O(n)	O(1)	O(1)

Random Bipartite Graph



Mat. Time	Mat. Space	Dev. Time	Dev.Space
O(1)	O(k*A)	O(A)	O(1)

Distributed Map



Mat. Time	Mat. Space	Dev. Time	Dev.Space
O(1)	O((A+B)* √min(A,B))	O(min(A,B))	O(1)

Unidirectional Symbolic Link



Bidirectional Symbolic Link



Mat. Time	Mat. Space	Dev. Time	Dev.Space
O(b)	O(i(i+b)+ s(i+√s))	O(i+s√s)	0(1)

Signal Map



O(b) O(i(i+b)+ O(i^2+s^2) O(1) s(i+s))? ? O(1)

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?