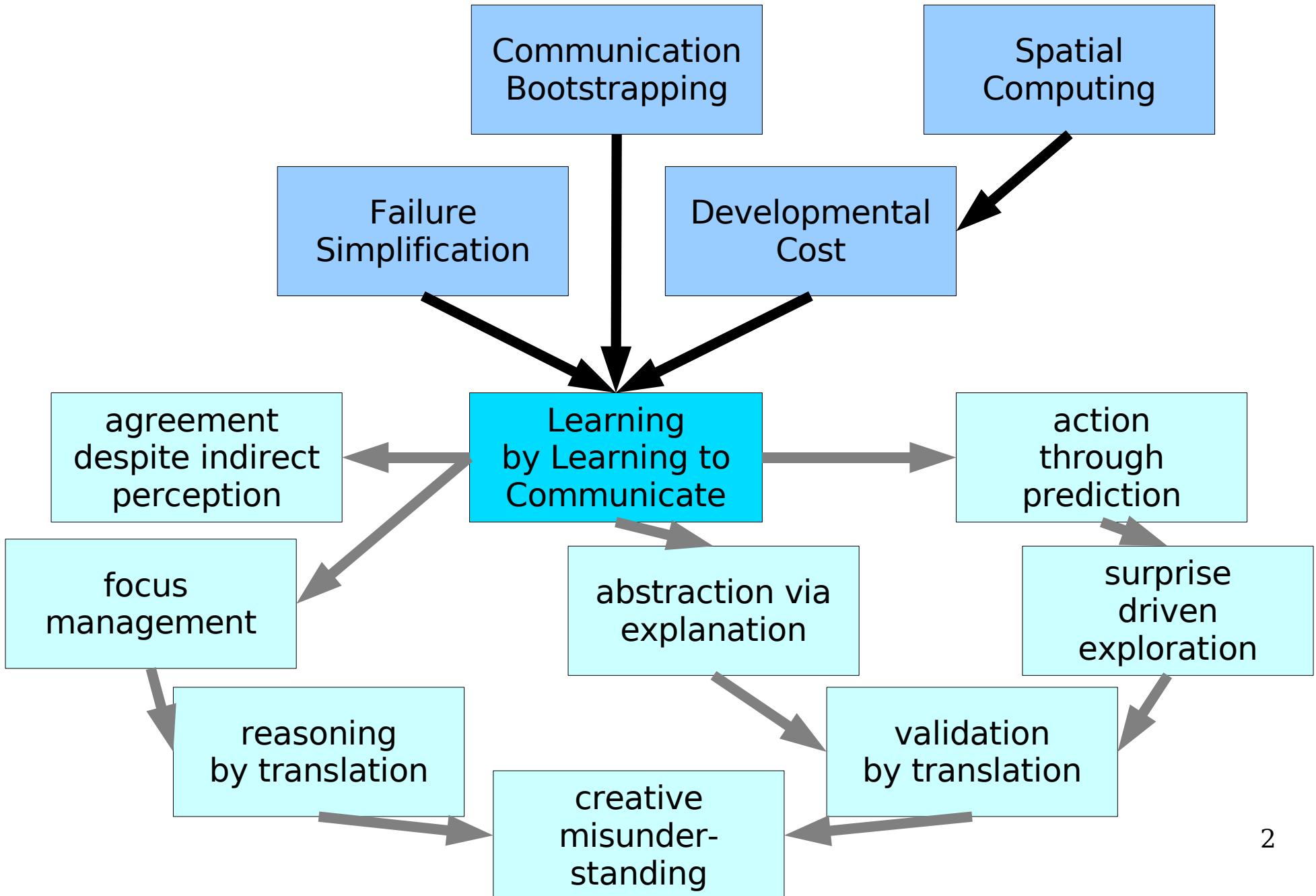


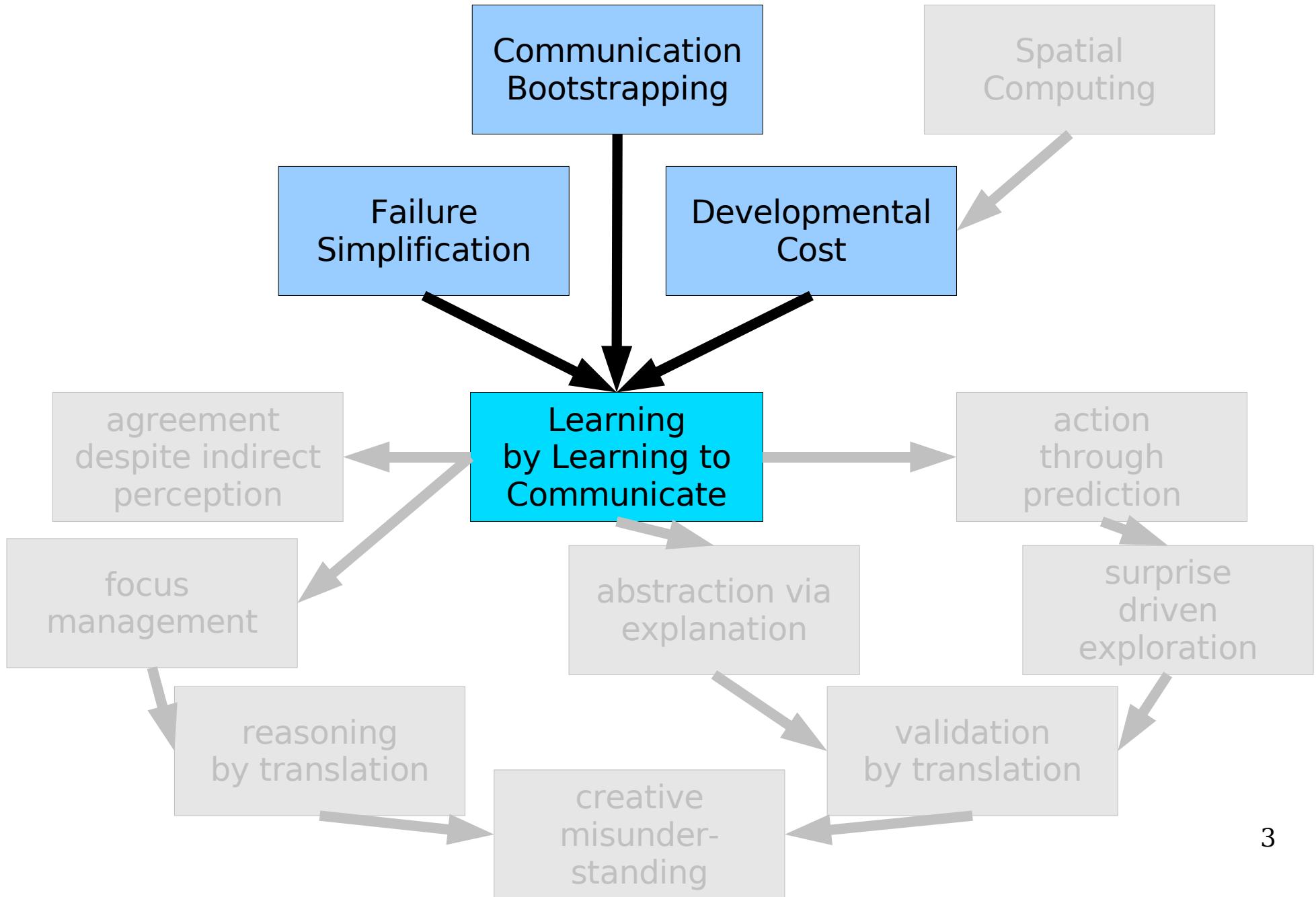
Learning by Learning to Communicate

Jacob Beal

Jake's Quest for Intelligence



Jake's Quest for Intelligence



METROPOLITAN STAGE FIRE RO OF WAREHOUS

METROPOLITAN

TOPAC

EBO

ESCO'S GRILL

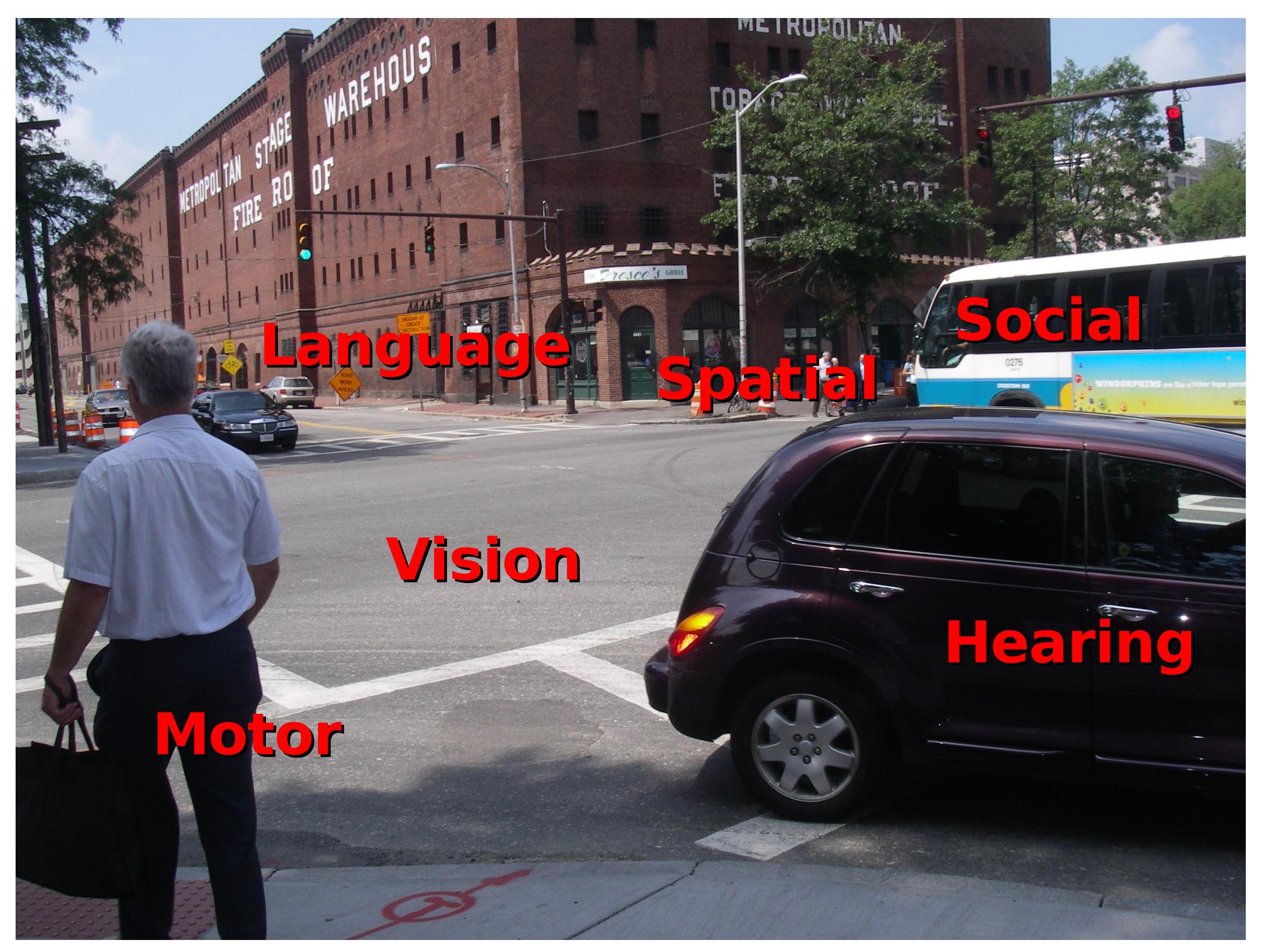
ROAD WORK AHEAD

ROAD WORK AHEAD

0276

WINDORPHINS are like a ticket to a par-





Motor

Vision

Language

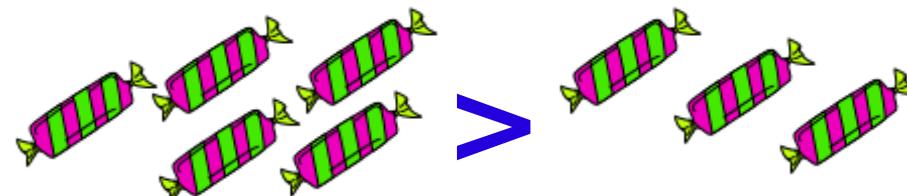
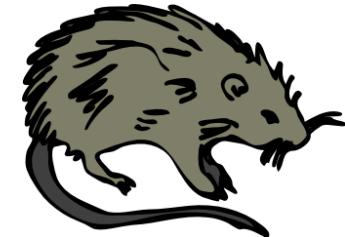
Spatial

Hearing

Social

Human intelligence comes from integrating specialists

- Infants = Rats (Spelke)
 - Orienting from geometry + color
 - “Left” and “Right,” language vs. rhythm
- Counting numbers (Carey)
 - Numerosity + tracking + sequence
 - Four stages



Integration takes communication

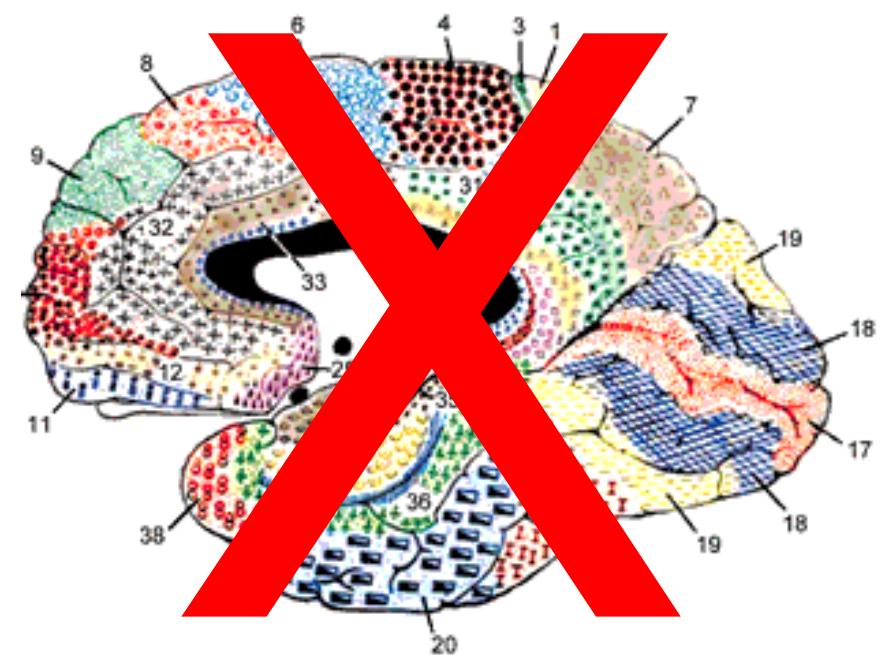
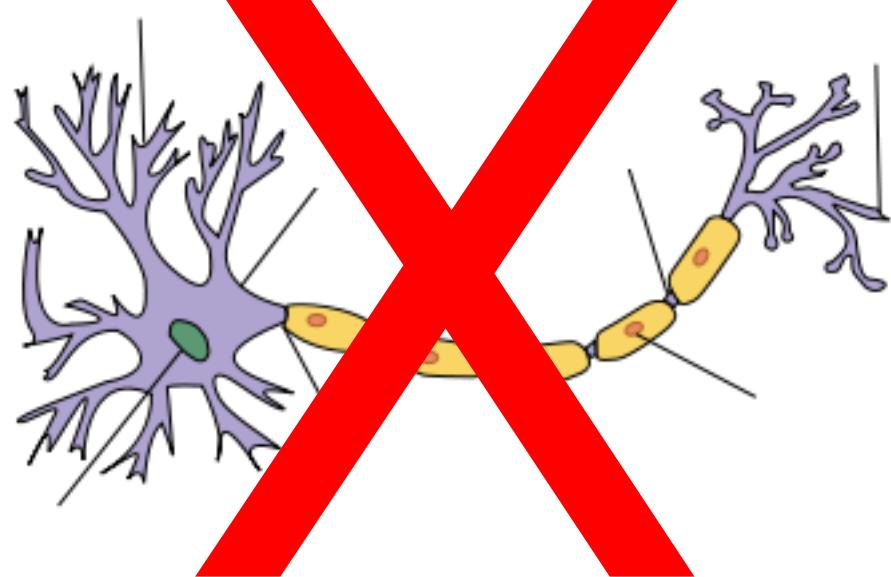
Novel situations need **combinatoric** signals

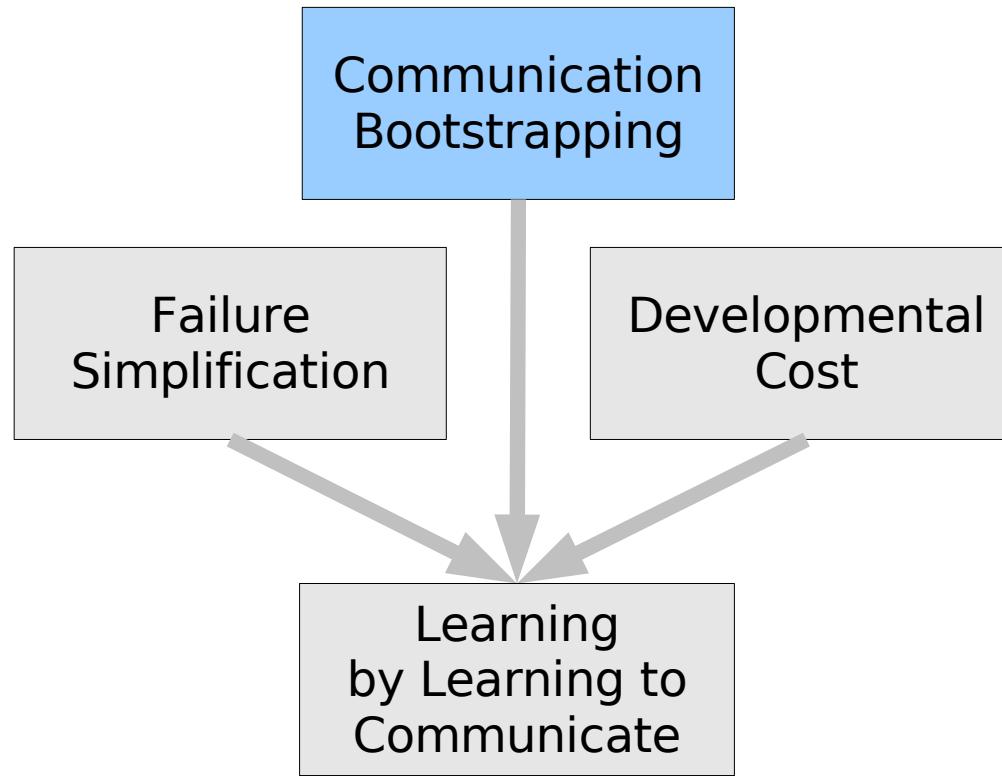
Architectural Approaches

	Hard-Wired Communication	Learned Communication
Hard-Wired Integration	Cognitive Architectures SOAR, ACT-R, EPIC, ICARUS, ...	Synthetic Language Kirby, Steels, Batali, Yanco, ...
Learned Integration	Multi-Modal Learning Kohonen, Coen, Singh, Minsky, Roy,...	(this work)

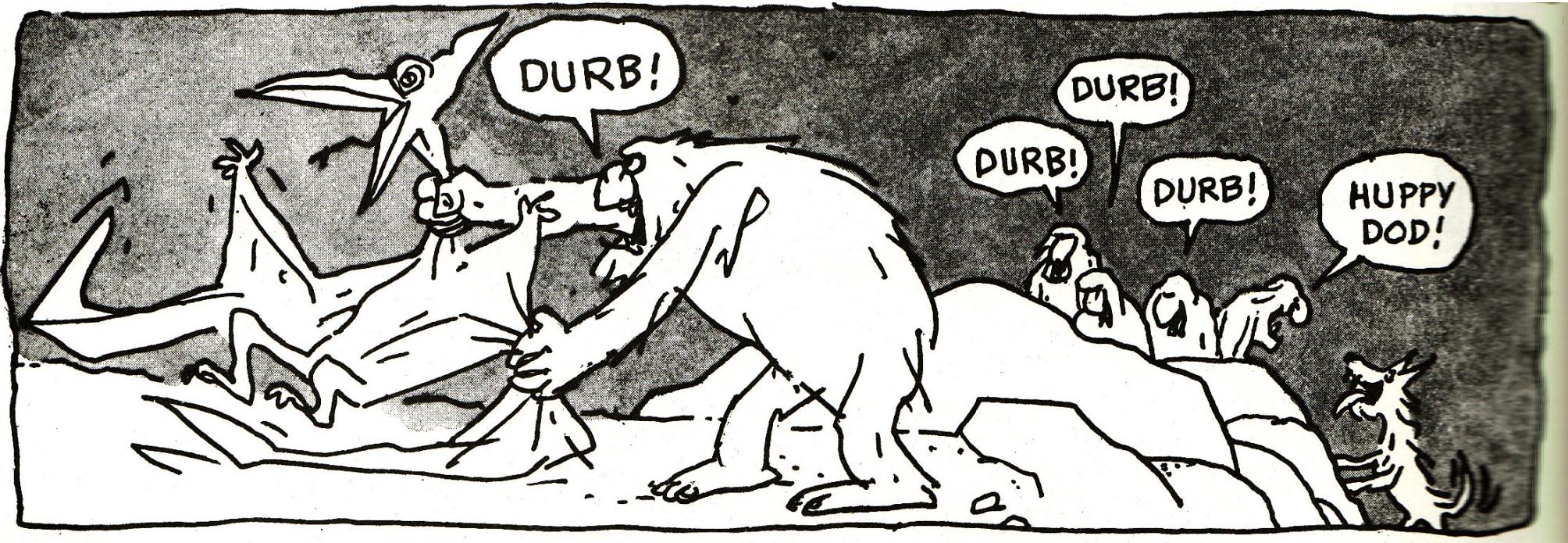
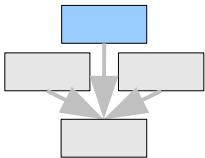
Communication = Integration

- Specialists agree on signals, but may disagree on their interpretation
- Differences can capture information
- Exchanging messages can *be* reasoning



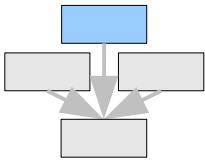


Shared experiences → agreement on signals

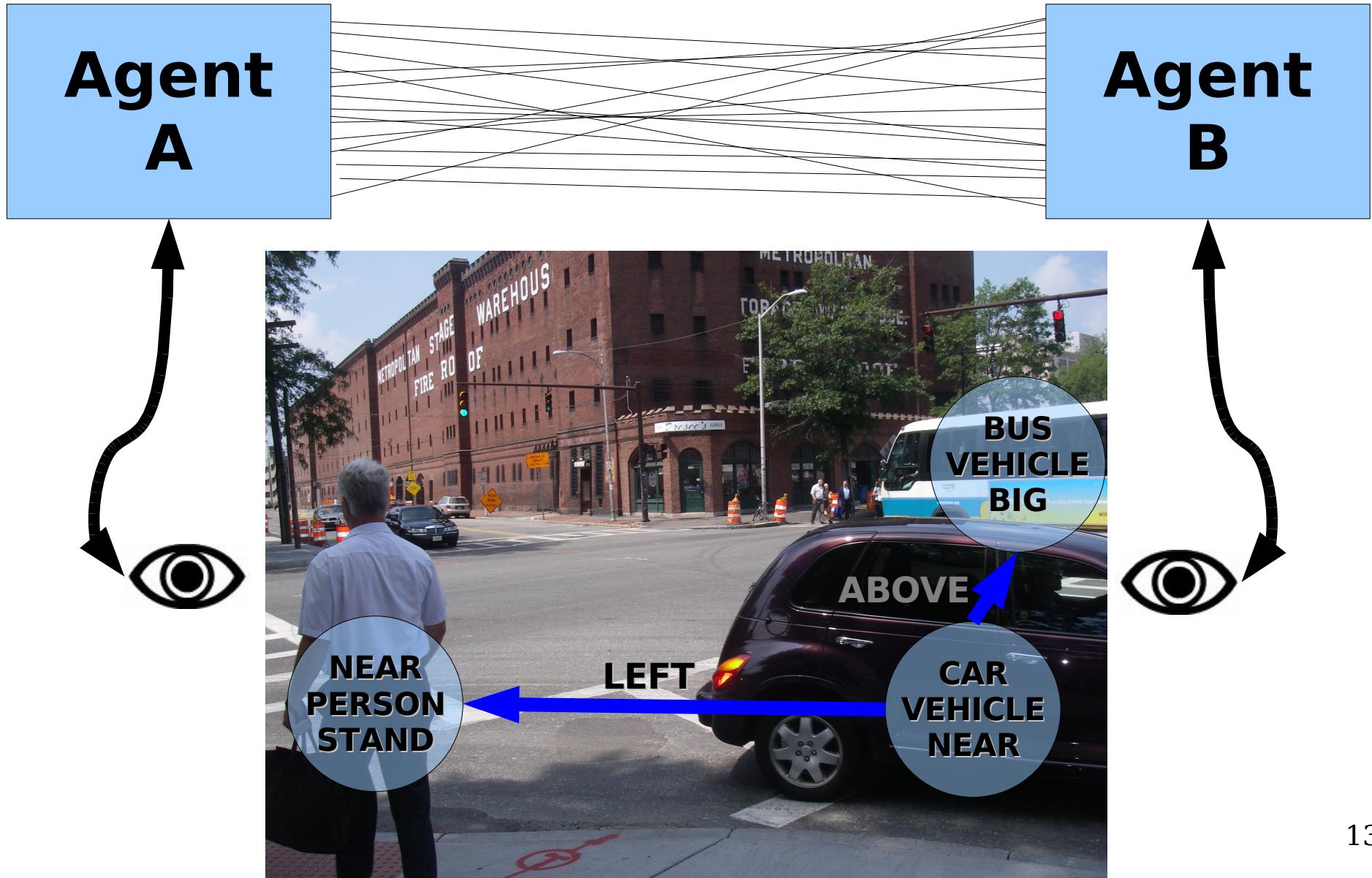


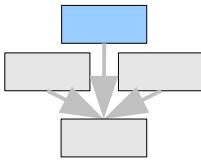
(cartoon by Booth)

Communication Bootstrapping

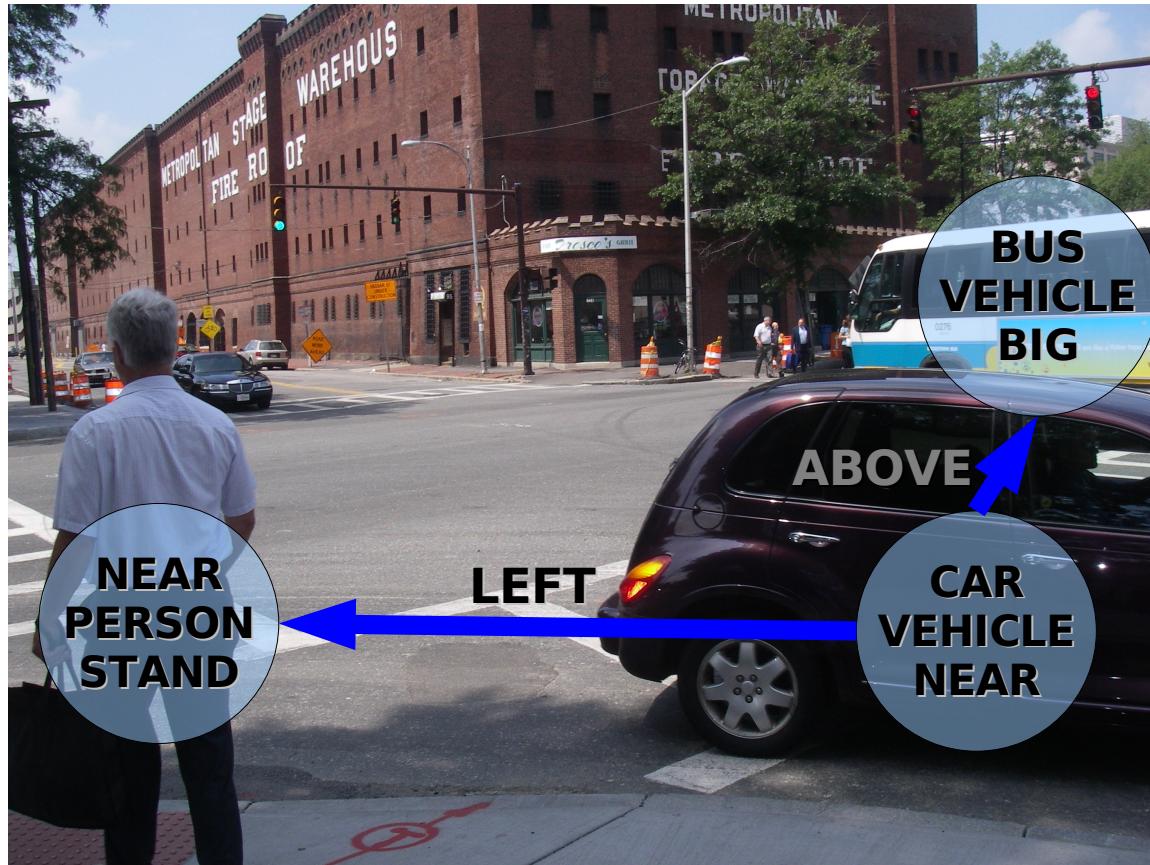


Bootstrapping v1.0





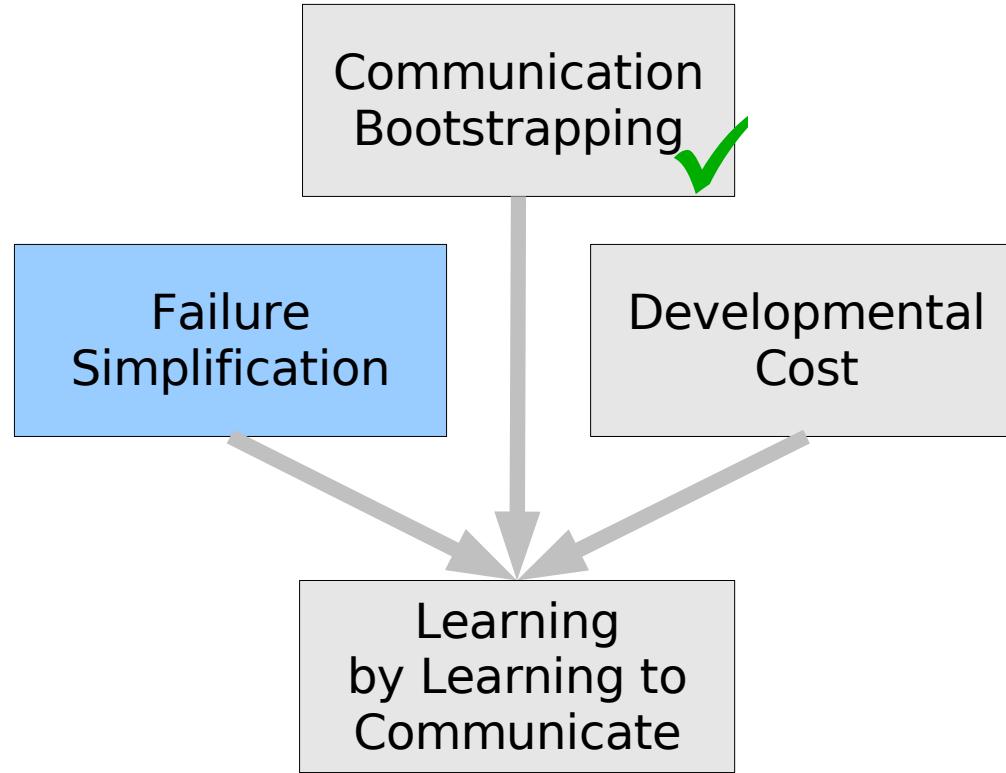
Agreed Combinatoric Signals



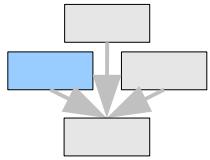
Symbols & Inflections

PERSON	= LEFT
STAND	= LEFT
NEAR	= FOCUS+LEFT
CAR	= FOCUS
VEHICLE	= FOCUS+ABOVE
BUS	= ABOVE
BIG	= ABOVE

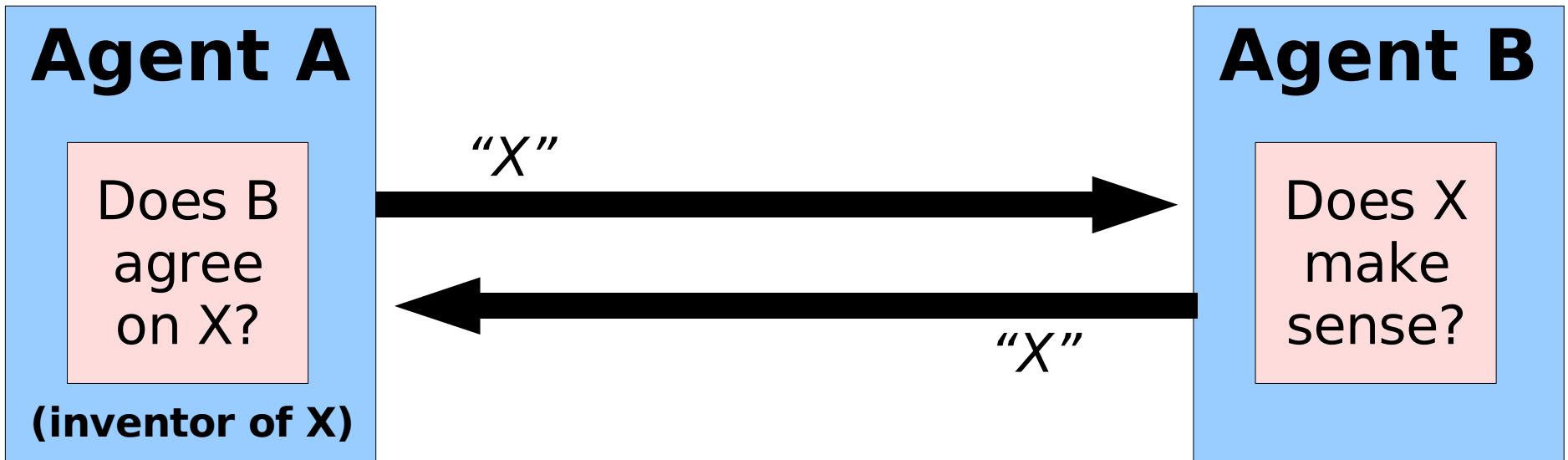
Can this work for different specialists?

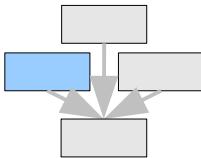


How do we make the engineering tractable?

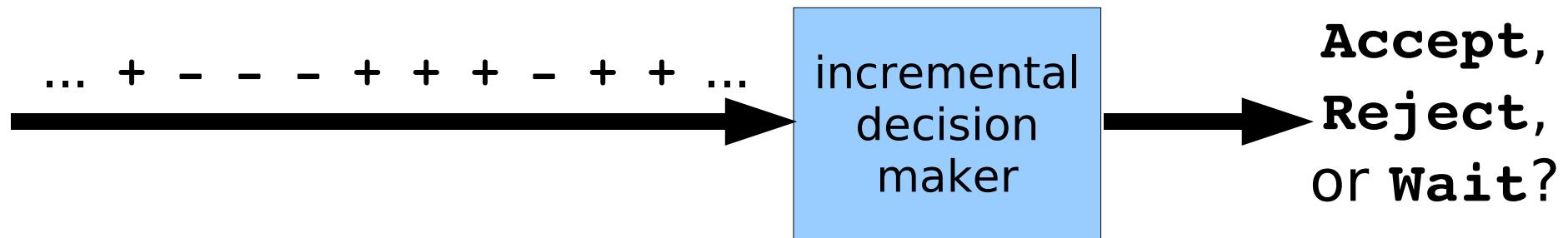


Example: Deciding on Coupled Proposals



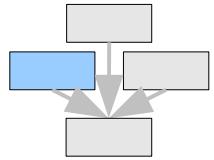


Unsatisfiable Specifications

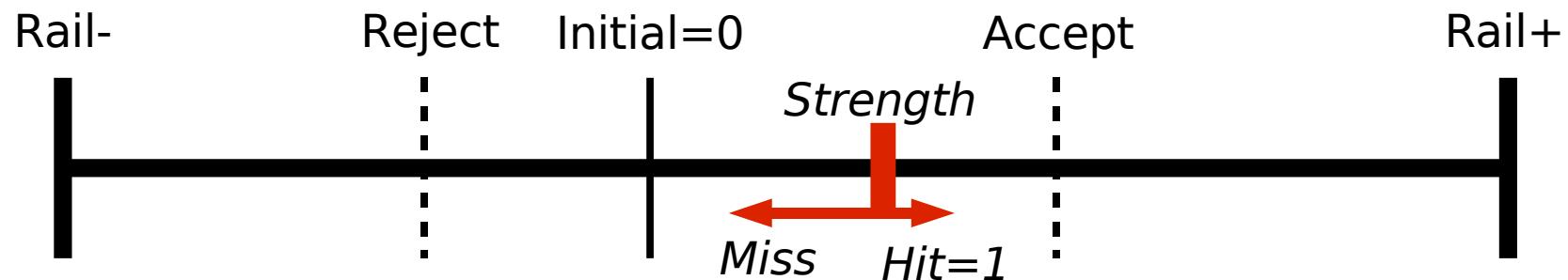
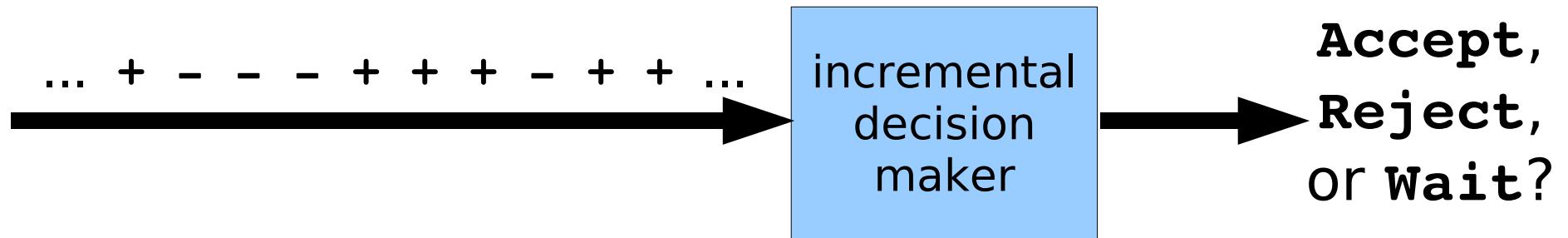


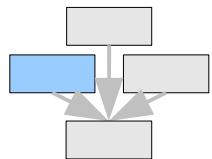
- Fast
- Follow evidence
- Firm
- Revisable

We must accept misbehavior!

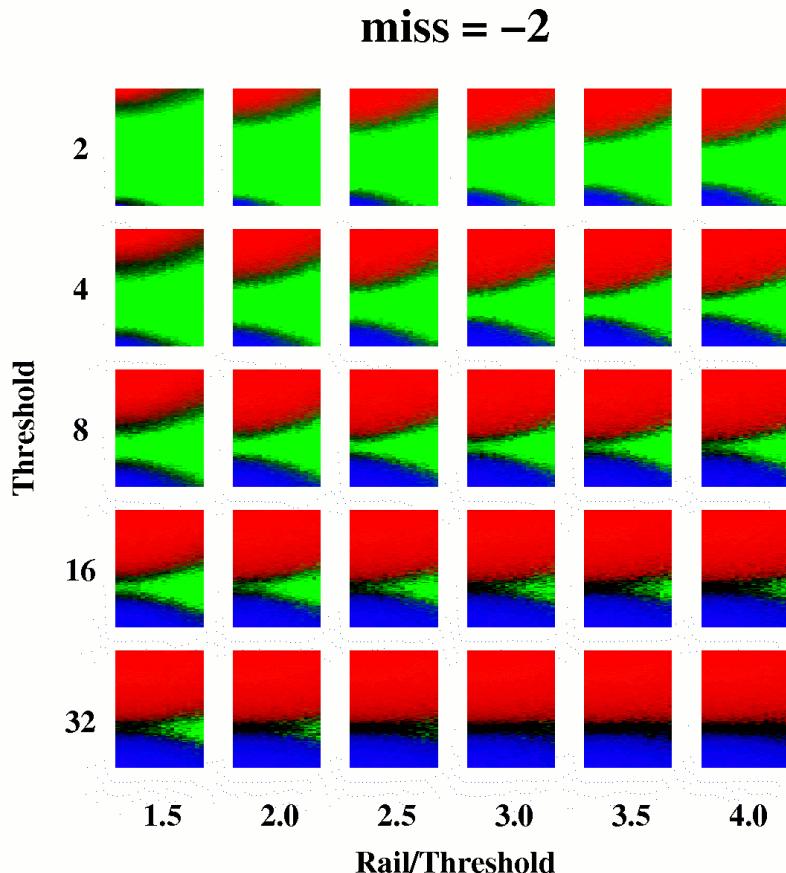


Nonlinear analysis is hard

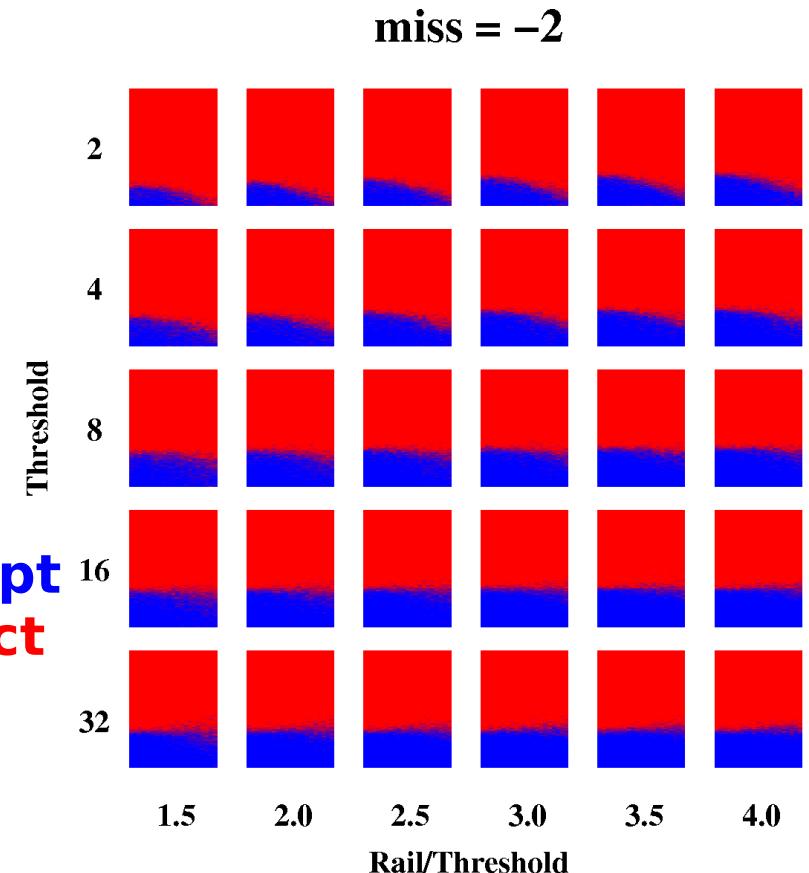




Choose the lesser evil

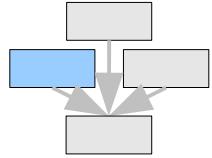


Dossier reveals
major behaviors

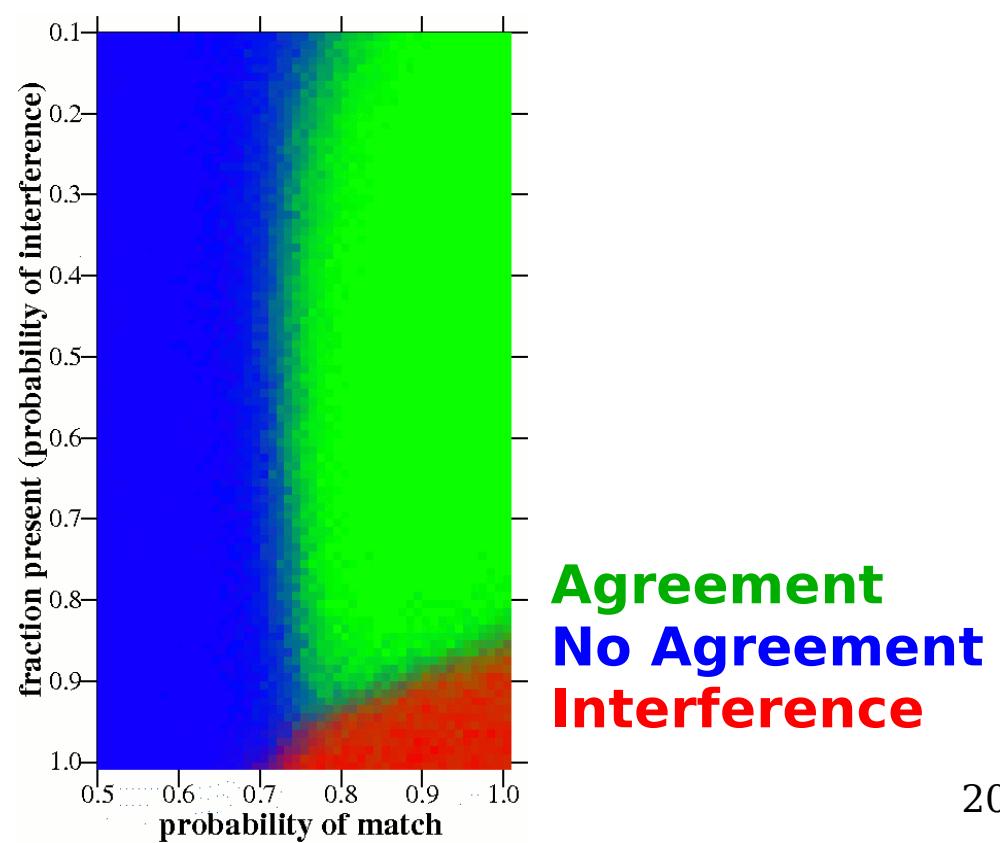
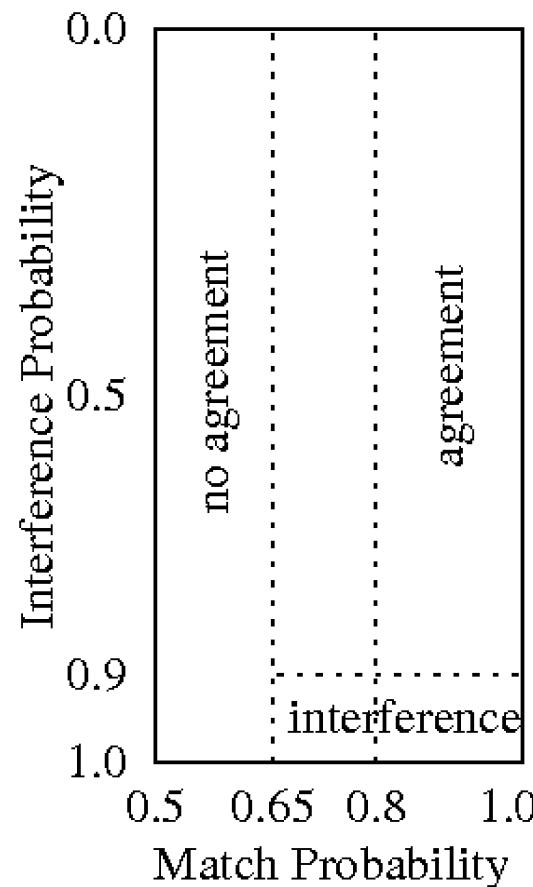
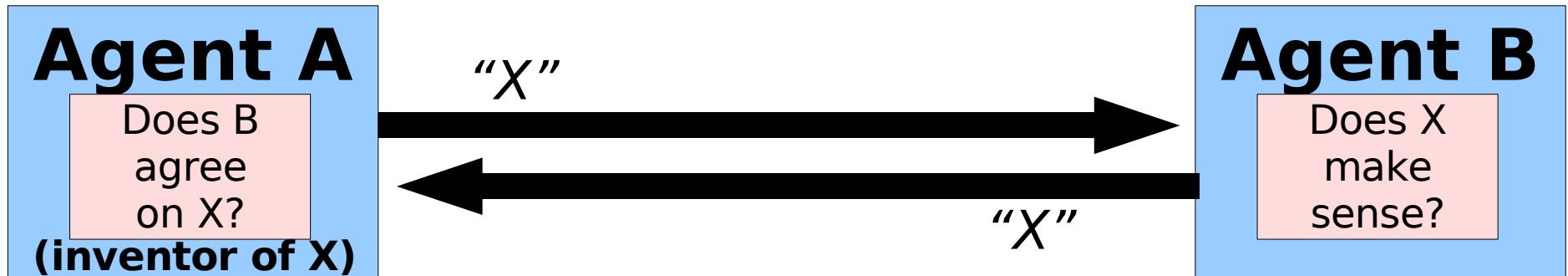


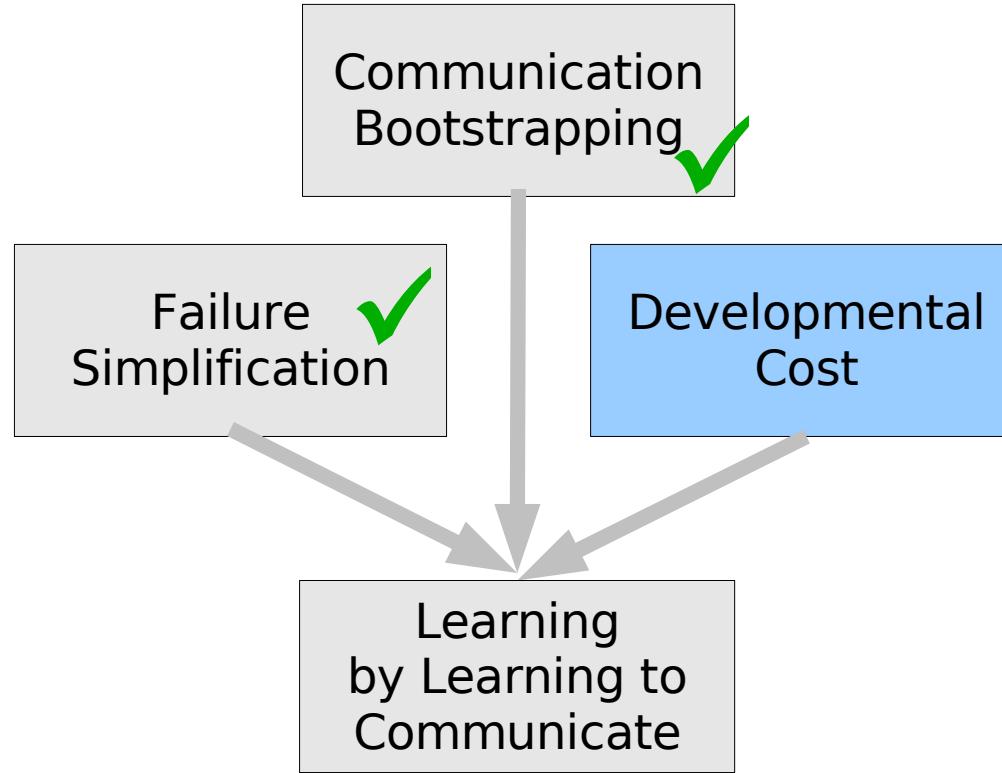
Fast Accept
Fast Reject
Hesitate
Oscillate

Failure Simplification:
choose easy cases,
lengthen time scale

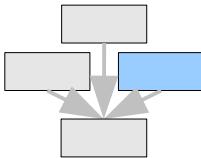


Predictable Composition

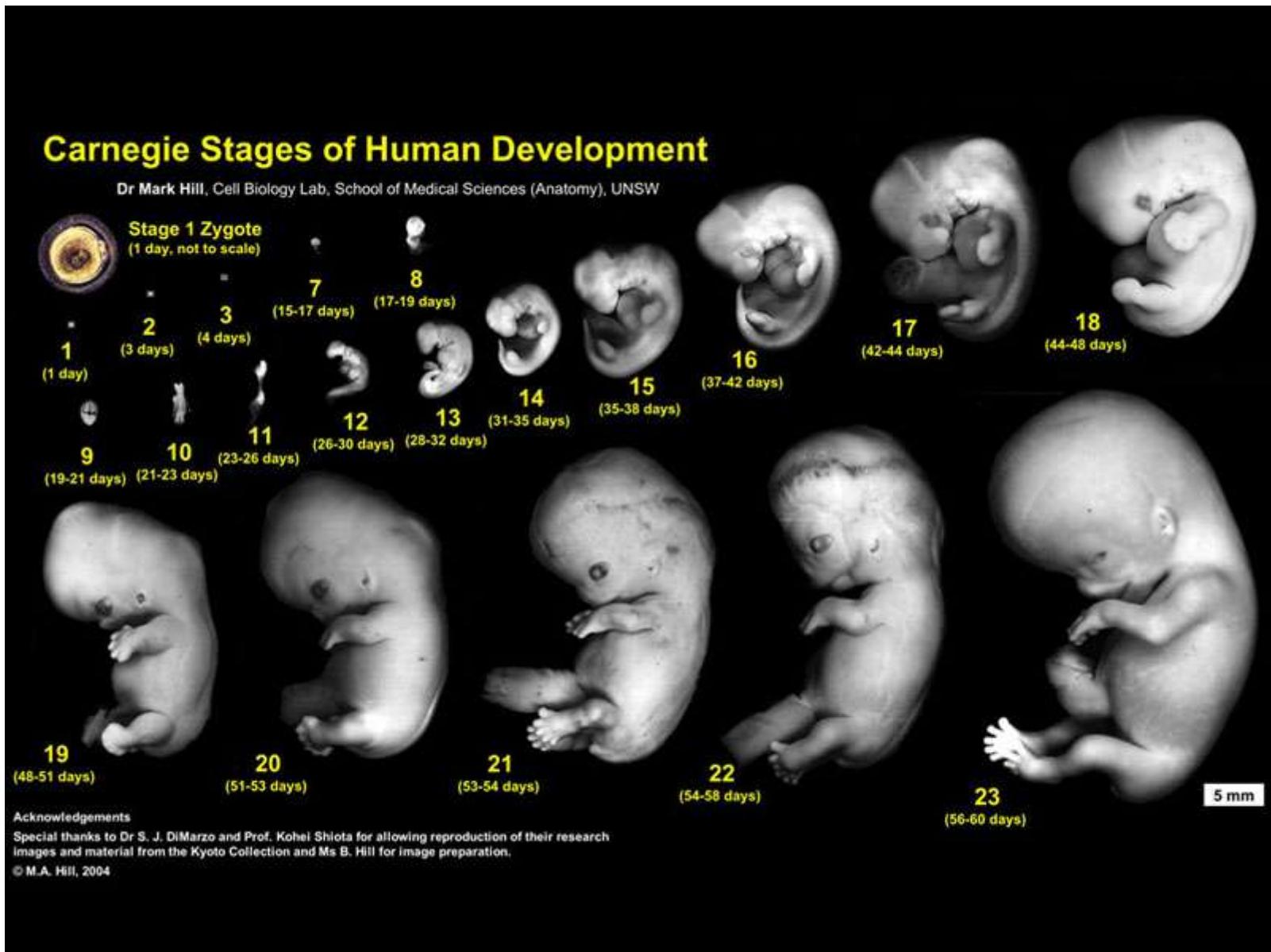


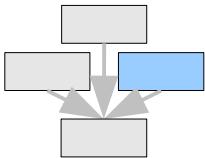


Is a part within the envelope of plausibility?



Not from Zeus's Forehead

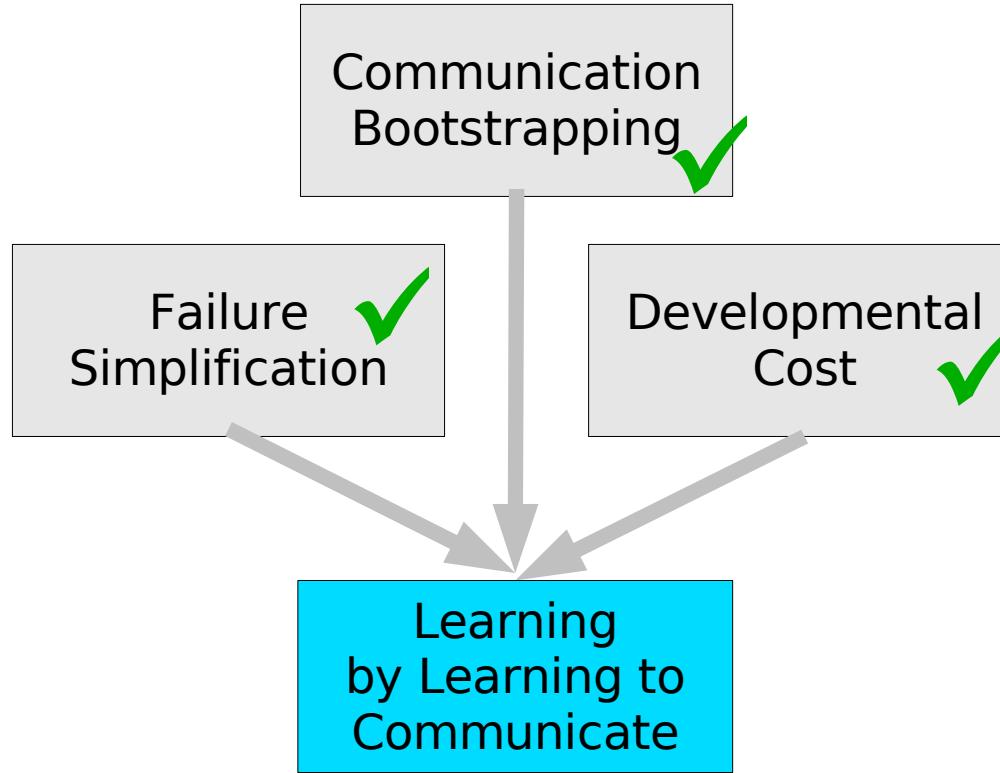




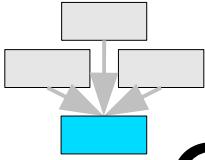
Plausibility

- Asymptotic cost vs. budget
 - Hunger can be pricy, words must be cheap
 - Synthetic biology gives upper bounds
- Variation during development means frequent hardware faults

Development			Mature		
Time	Space	Imperfection	Time	Space	Imperfection
growth	encoding	variation	execution	hardware	error



Can vocabulary capture world dynamics?



Environment for Easy

Communication Bootstrapping

- Strong input correlations



- Sparse usage in examples

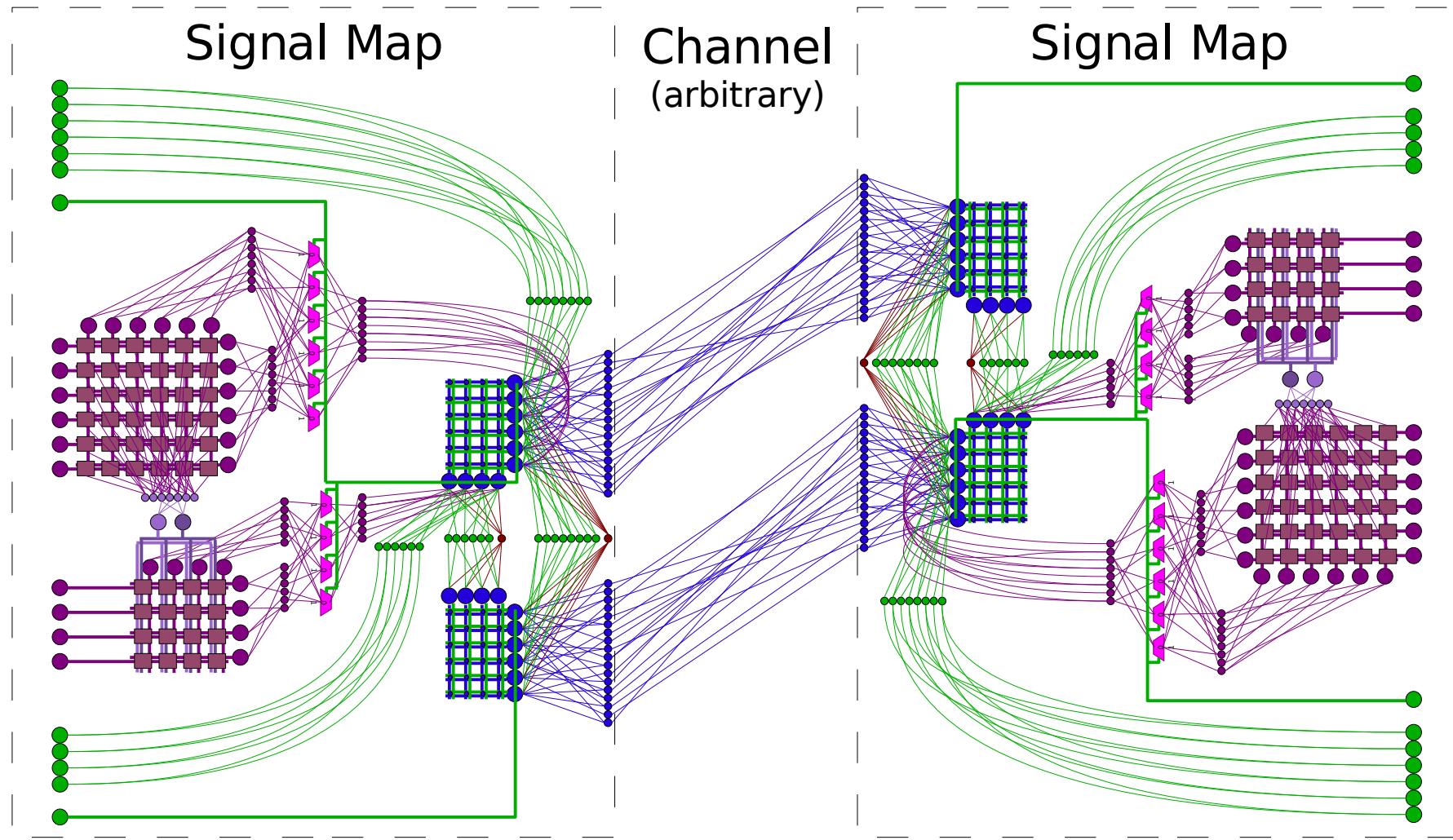


- **Independent examples**



- **Sparse signal encodings**





Key: Messages Signals Interpretation Self-Organization

Development

Time

Space

Imperfection

$O(s)$

$O(1)$

usable
symbols/
inflections

Mature

Time

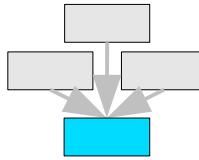
Space

Imperfection

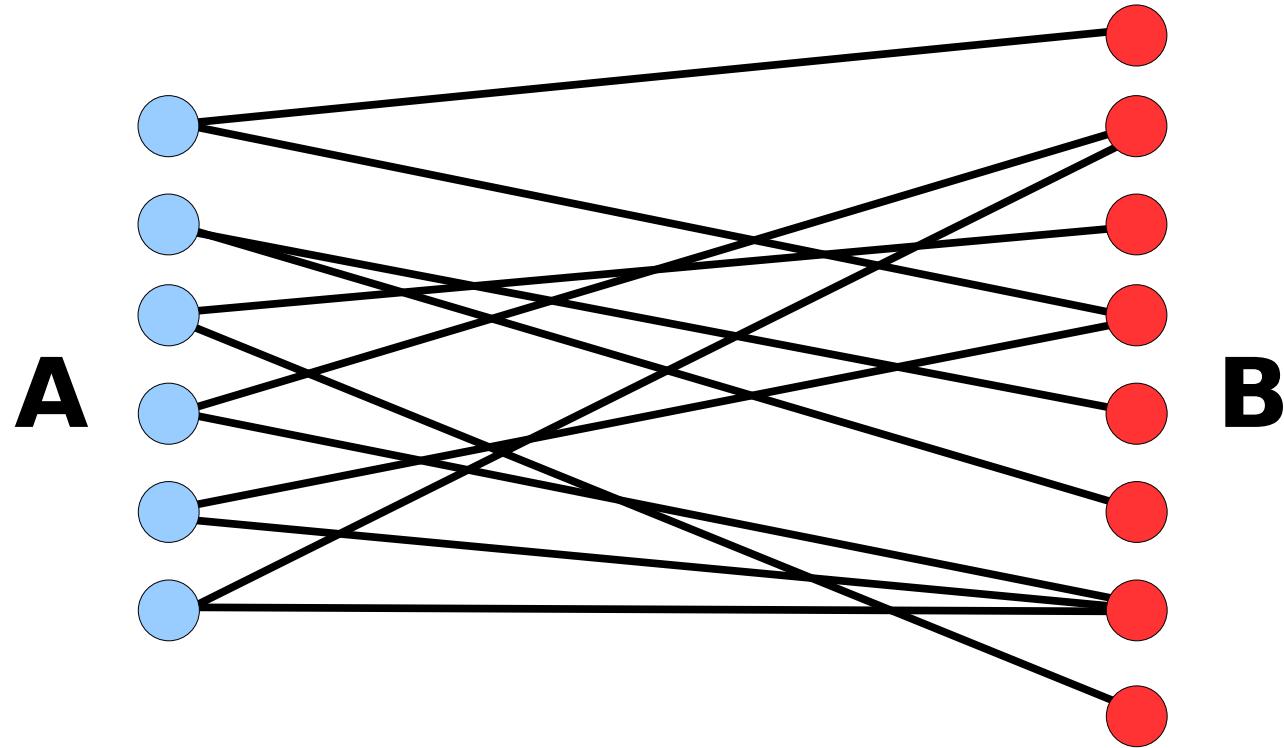
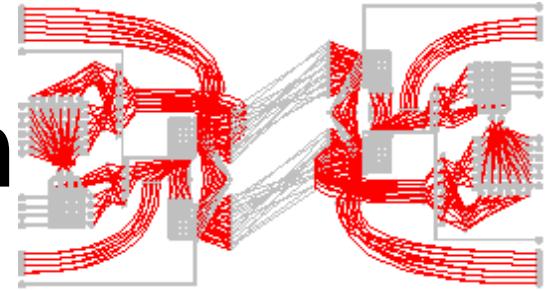
$O(b)$

$O(s^2)$

lost/extr
message
elements



Random Bipartite Graph



Development

Time

Space

Imperfection

Mature

Space

Imperfection

$O(A)$

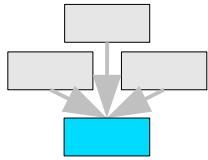
$O(1)$

more/less
links

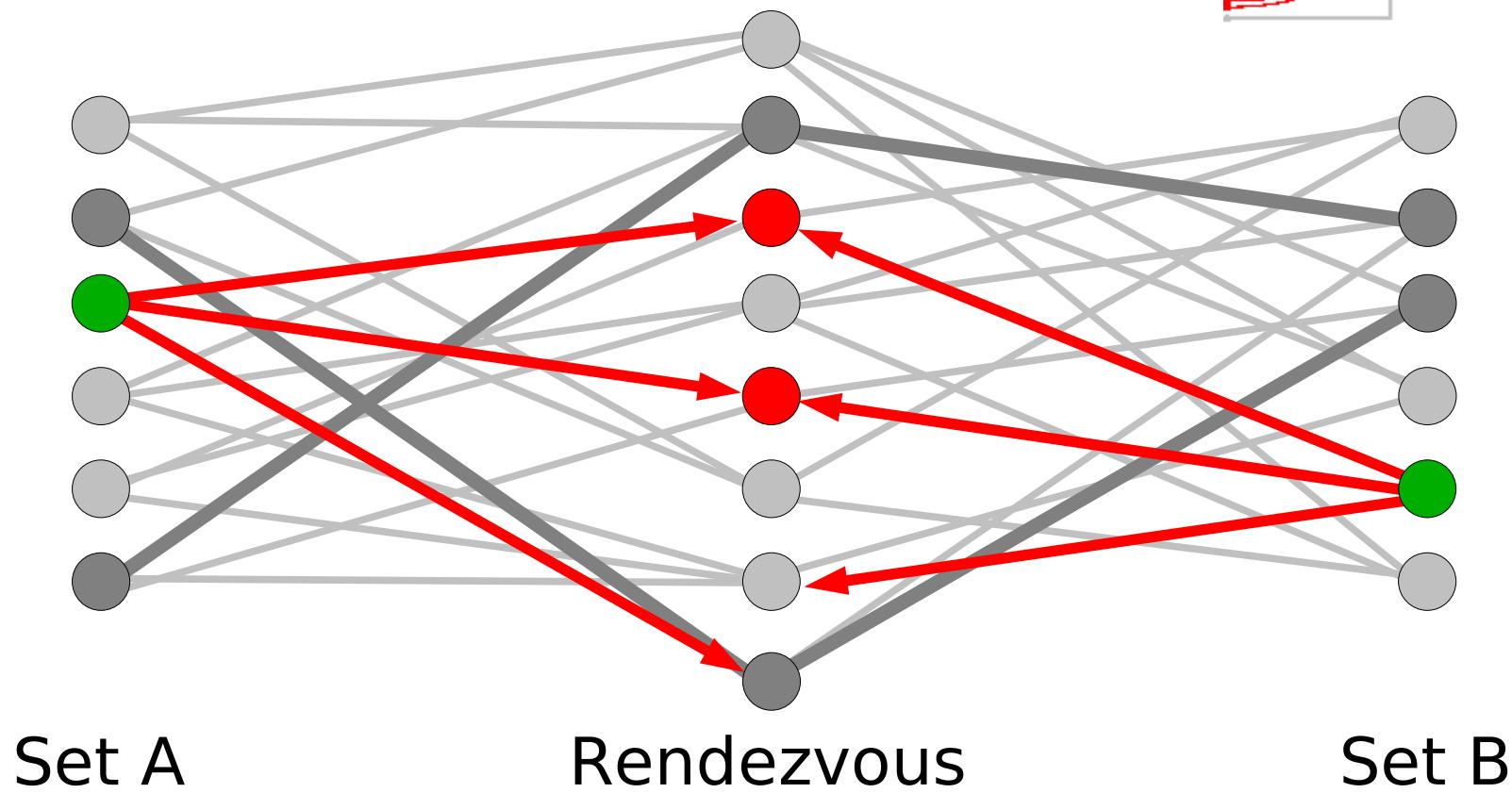
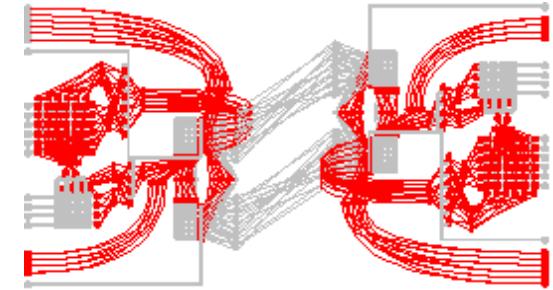
$O(1)$ am.

$O(k^*A)$

noise



Distributed Map



Set A

Rendezvous

Set B

Development

Time

Space

Imperfection

$O(\min(A,B))$

$O(1)$

more/less elements

Mature

Time

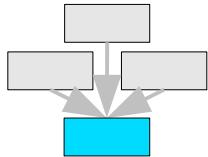
Space

Imperfection

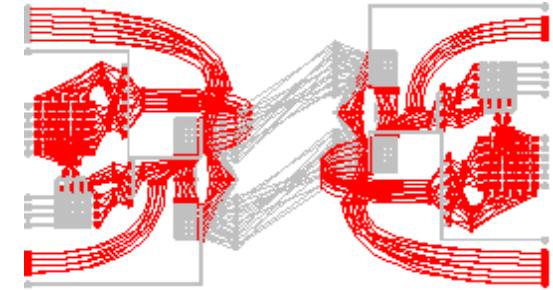
$O(1)$ am.

$O((A+B)^* \sqrt{\min(A,B)})$

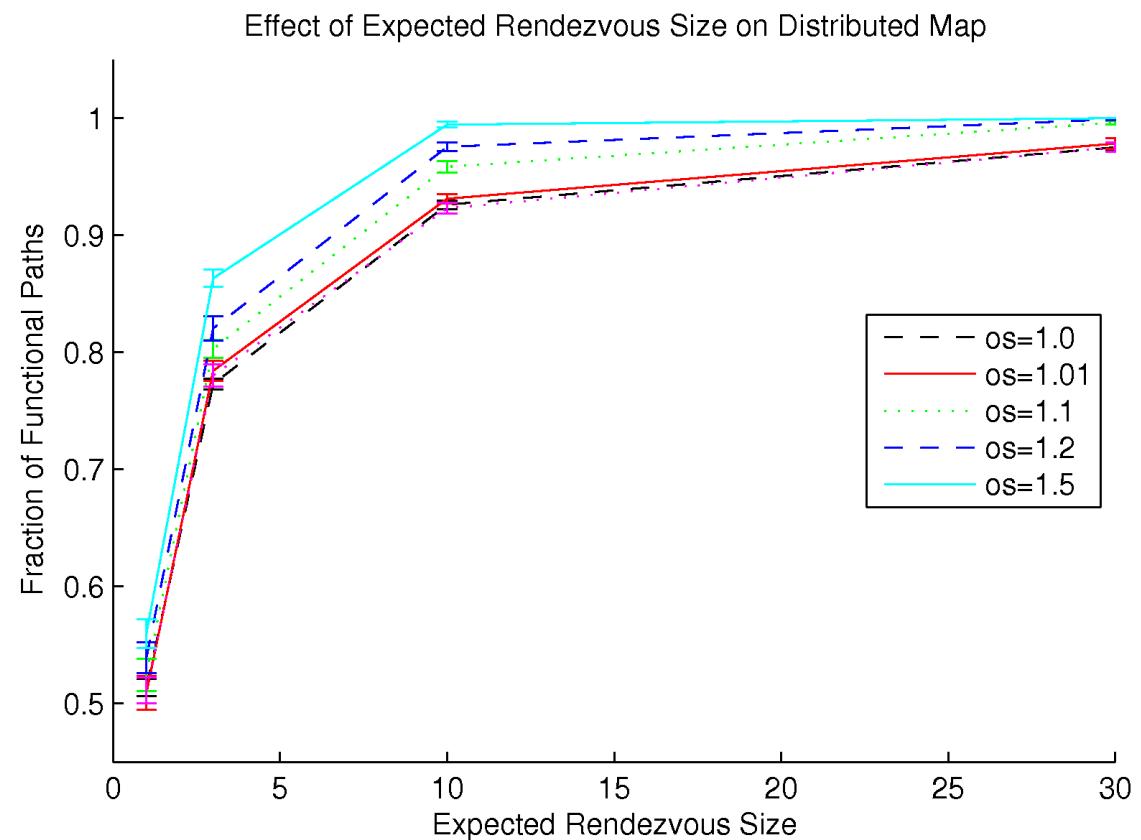
noise,
dropped
mappings

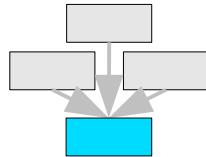


Distributed Map

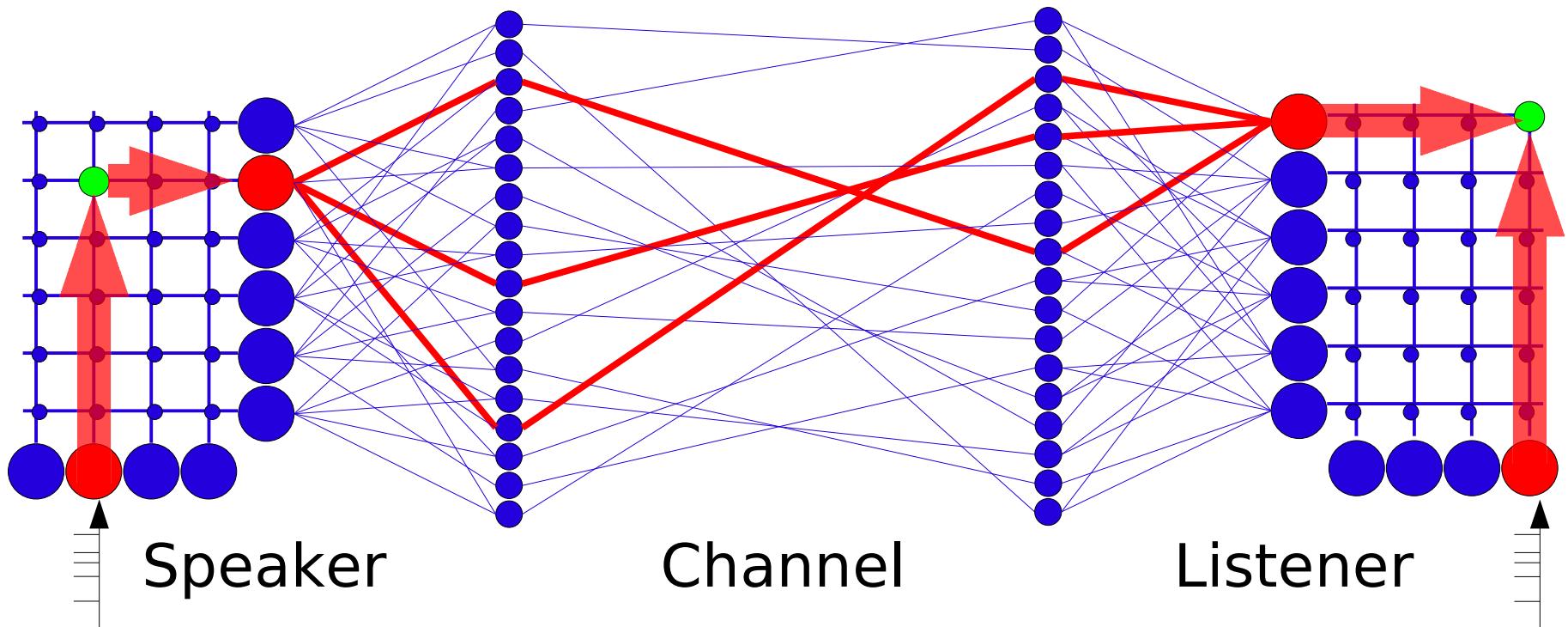
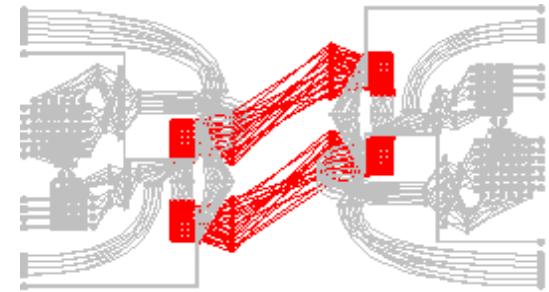


- Connections fail, snap others
- A few spare parts = almost no misbehavior





Unidirectional Link



Development

Time

$O(s)$

Space

$O(1)$

Imperfection

more/less
links, coders

Mature

Time

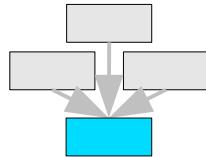
$O(b)$

Space

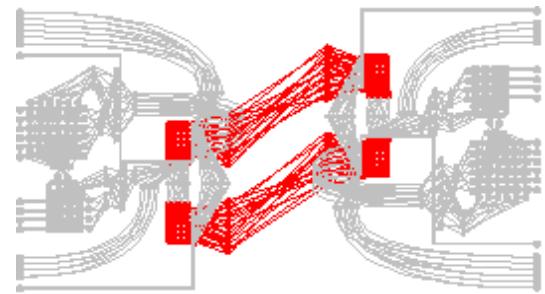
$O(ib + s(i + \sqrt{s}))$

lost/extr
message
elements

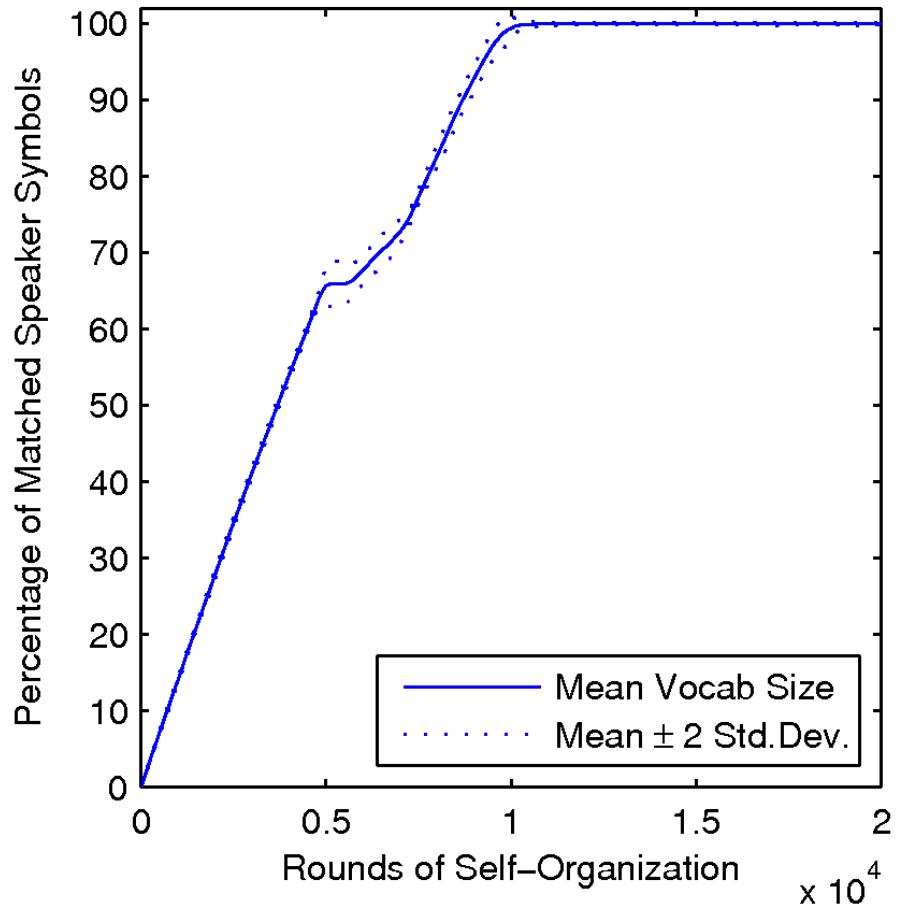
Time	Space	Imperfection	Time	Space	Imperfection
$O(s)$	$O(1)$	more/less links, coders	$O(b)$	$O(ib + s(i + \sqrt{s}))$	lost/extr message elements

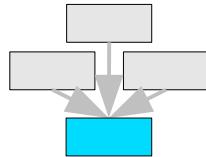


Unidirectional Link



- Coders align very quickly (~10 rounds each)

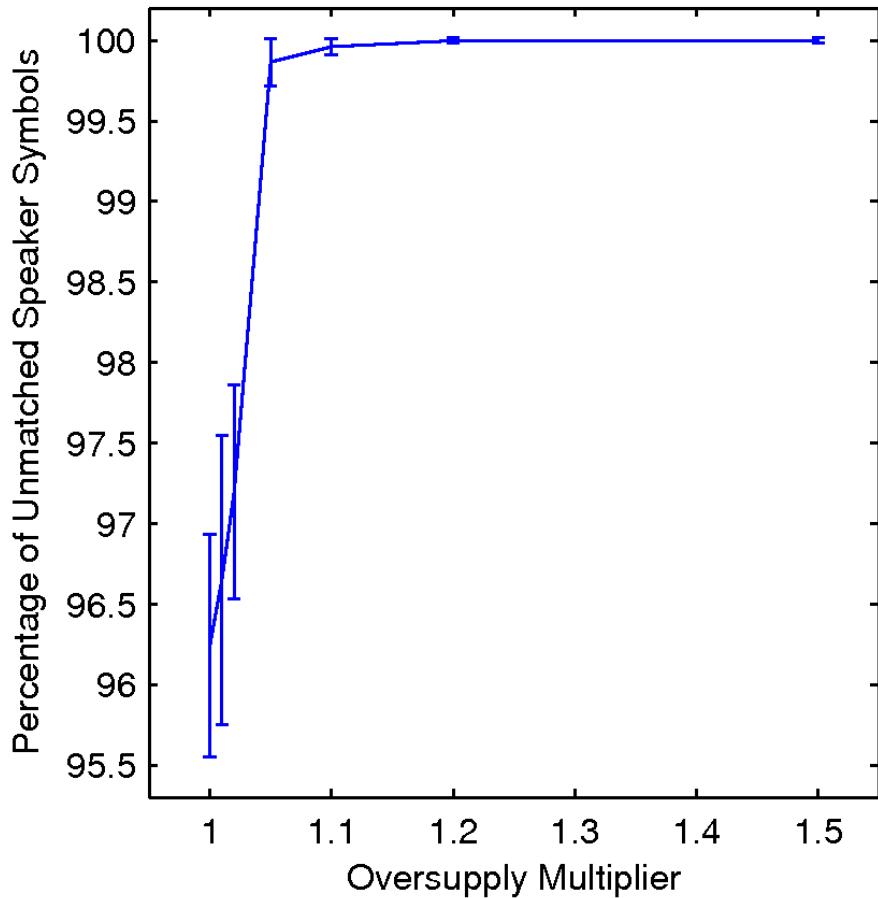


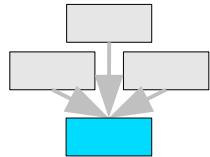


Unidirectional Link

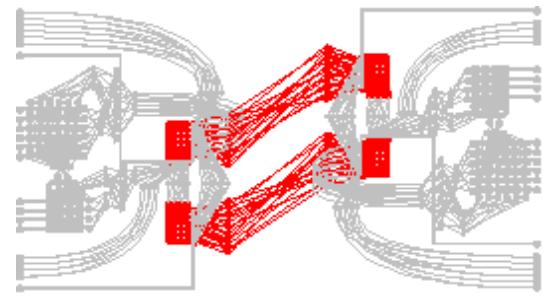


- Reallocation can cause thrashing
- A few spare parts = almost no misbehavior

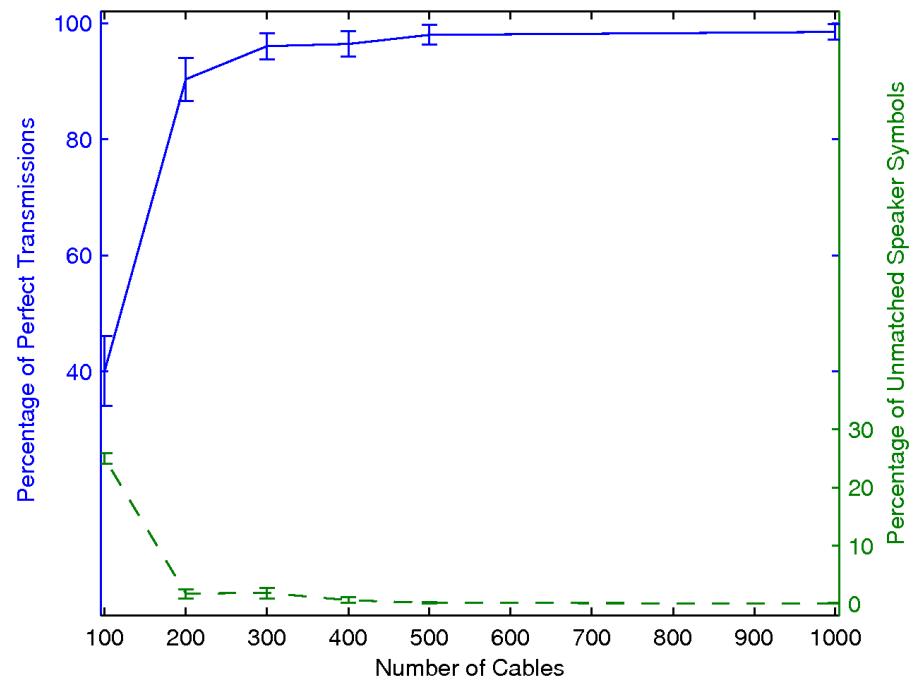


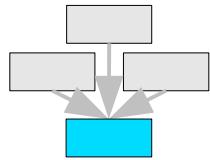


Unidirectional Link

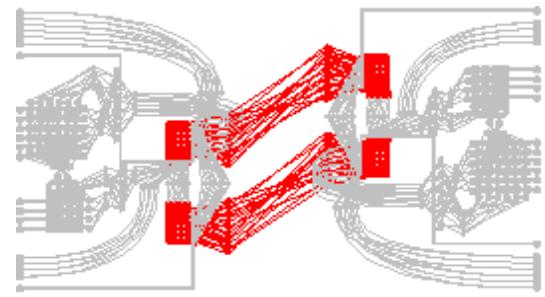


- Interference causes gradual degradation

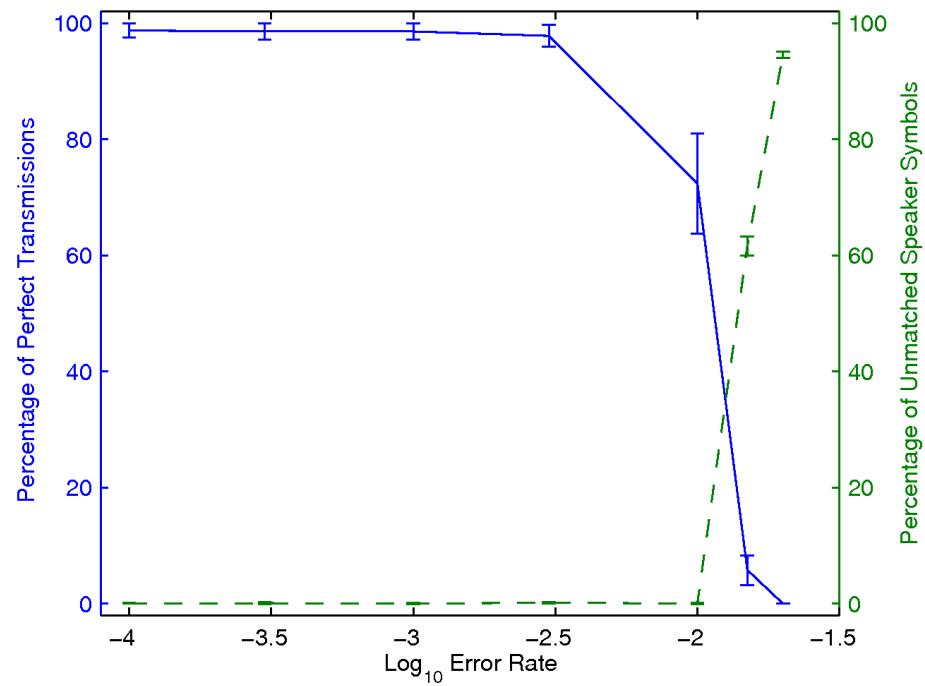


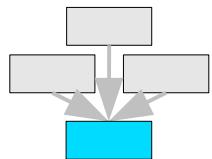


Unidirectional Link

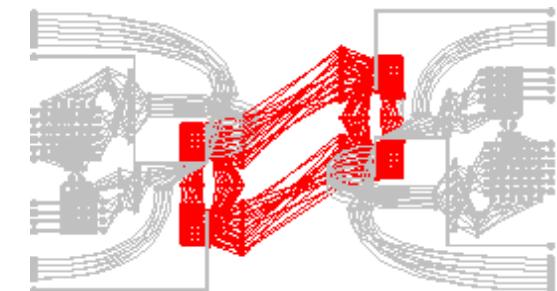


- Noise also causes gradual degradation

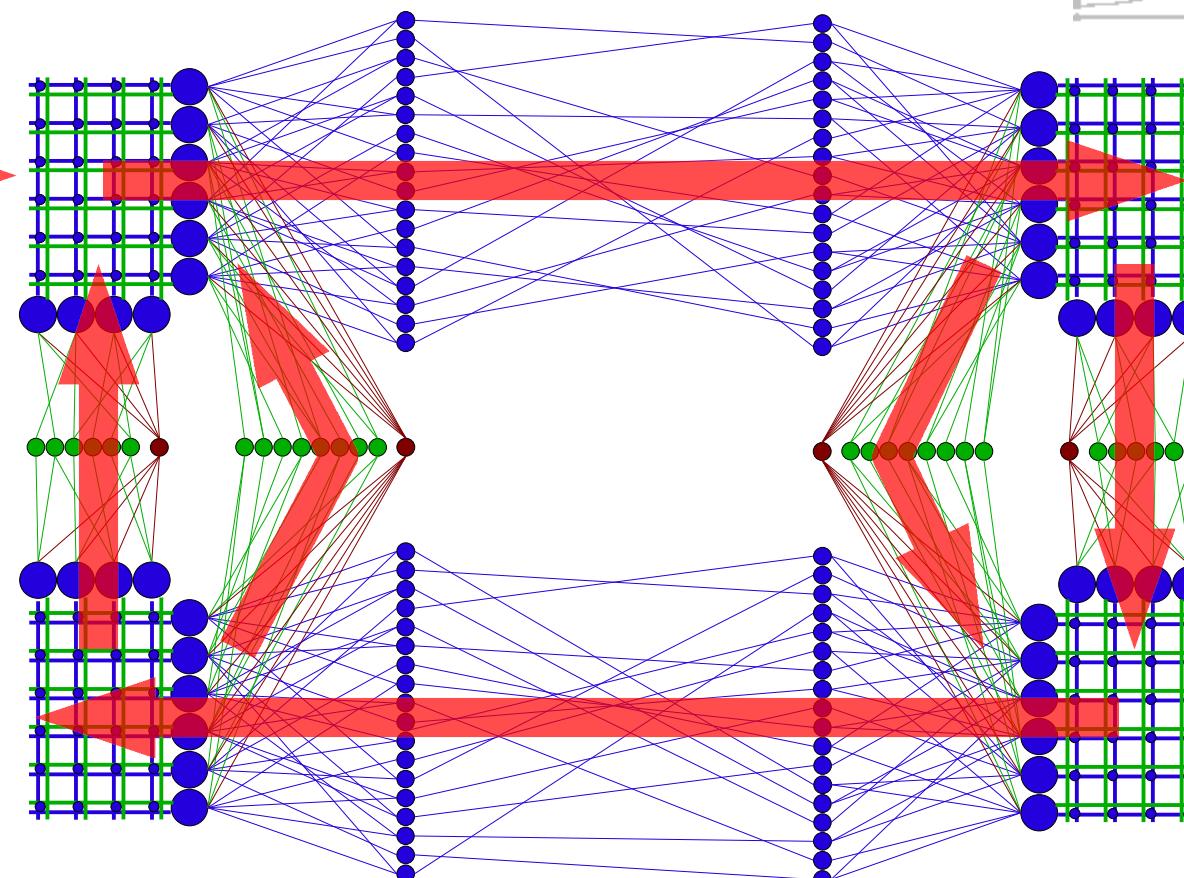
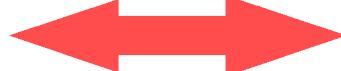




Bidirectional Link



Messages



Messages

Development

Time

Space

Imperfection

Mature

Time

Space

Imperfection

$O(s)$

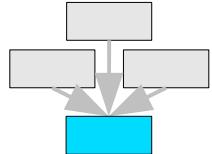
$O(1)$

more/less
links, coders

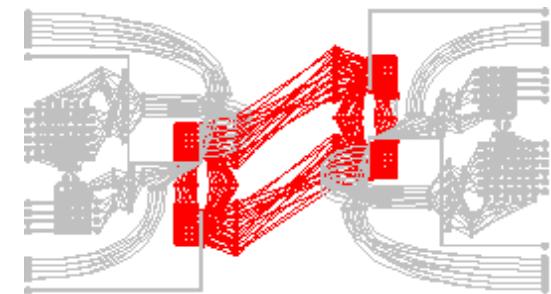
$O(b)$

$O(ib + s(i + \sqrt{s}))$

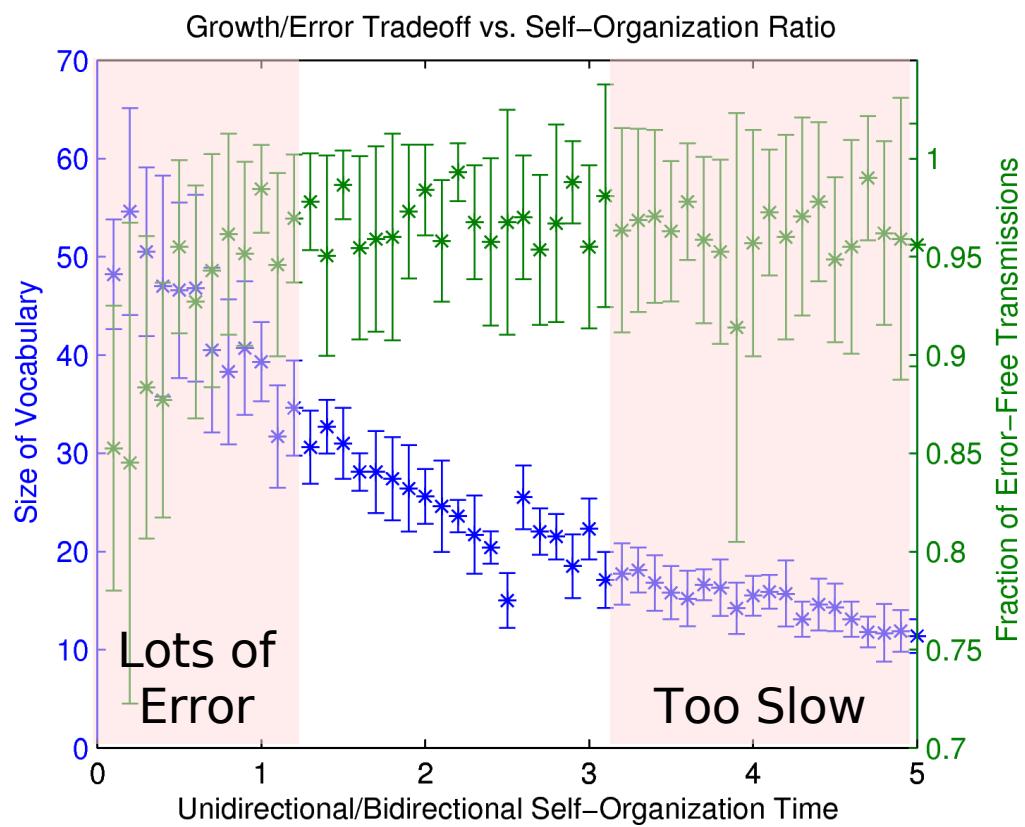
lost/extra
message
elements

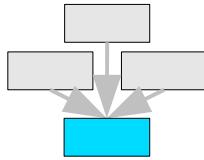


Bidirectional Link

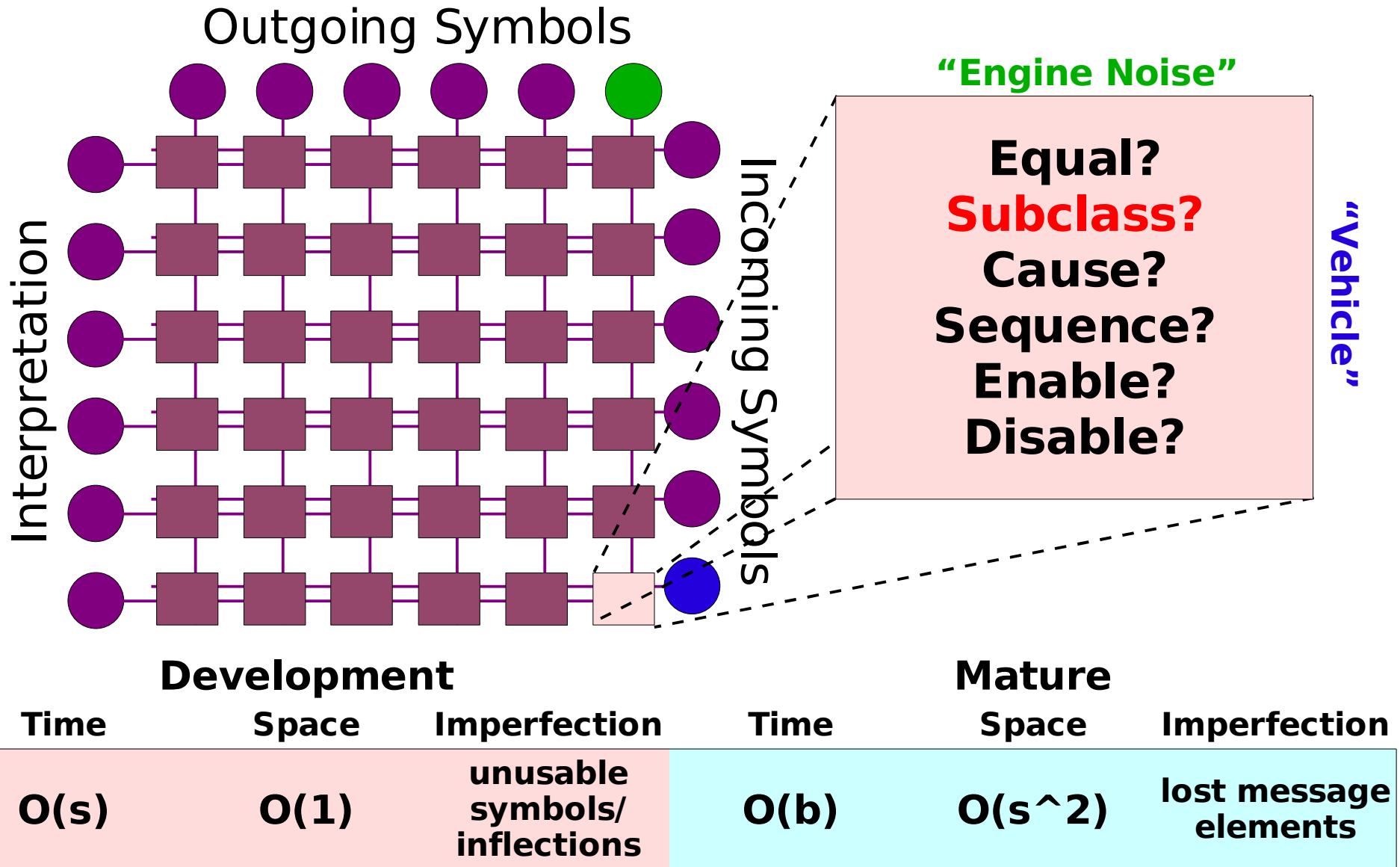
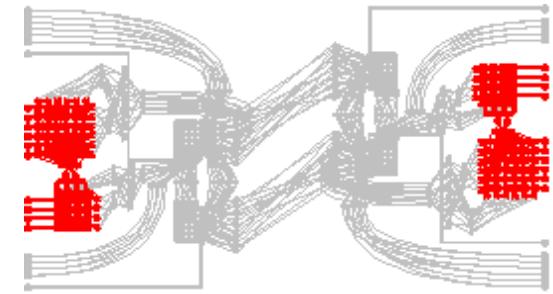


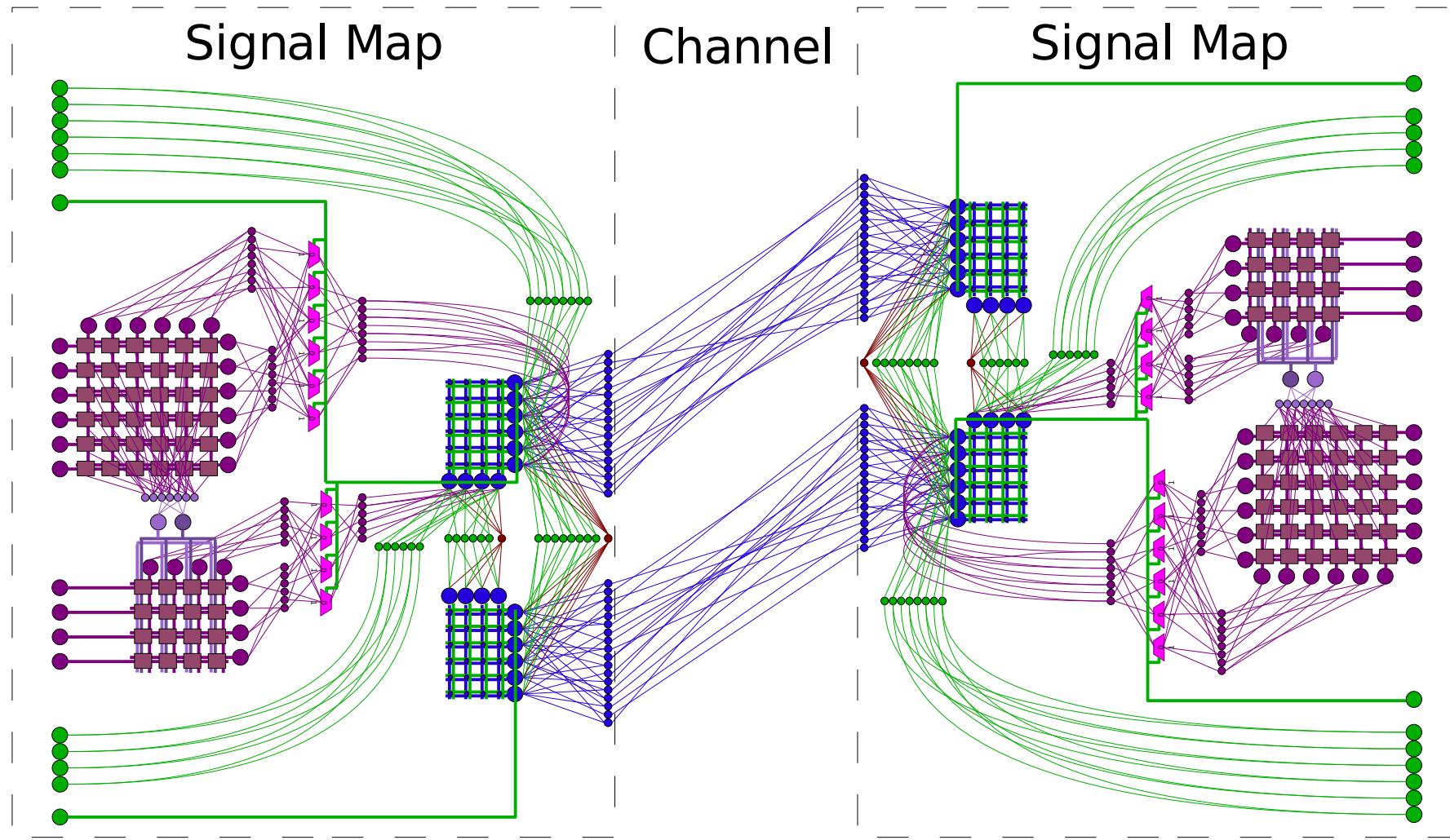
- Tradeoff: pairing speed vs. error
- A broad sweet spot exists





Relation Maps





Key: Messages Signals Interpretation Self-Organization

Development

Time

Space

Imperfection

$O(s)$

$O(1)$

unable
symbols/
inflections

Mature

Time

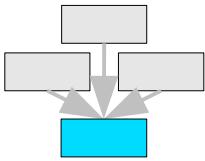
Space

Imperfection

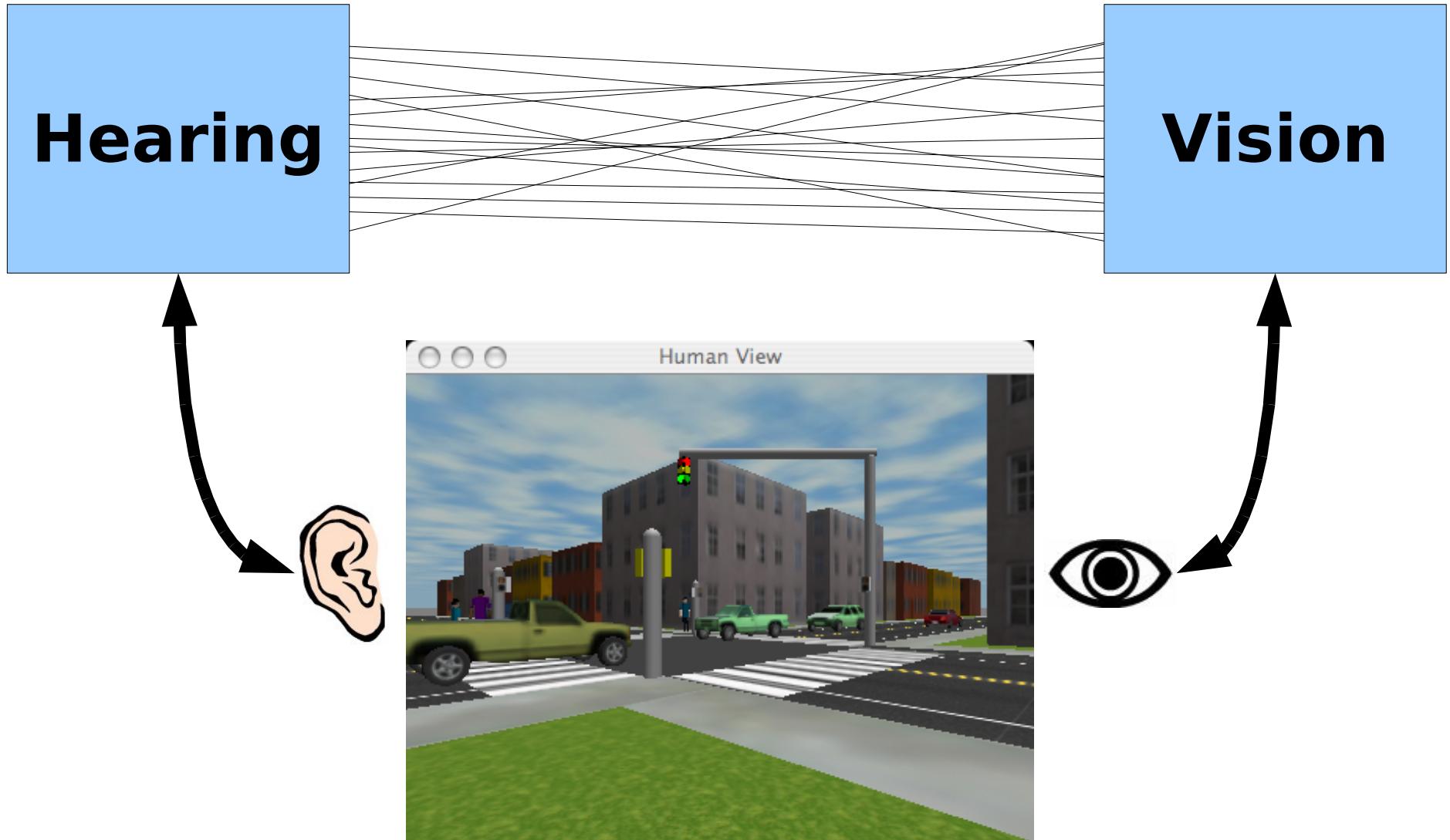
$O(b)$

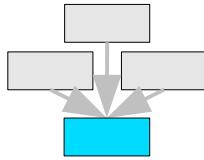
$O(s^2)$

lost/extr
message
elements



Proof of Concept

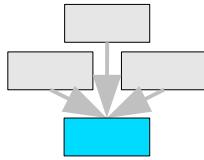




Results: interpretations of symbols capture dynamics

- 156 relations from 83 min, including:
 - **DONTWALK** sometimes leads to **CUCKOO**, then disappears.
 - **CUCKOO** and **WALKLITE** are the same thing.
 - A moderately loud sound is always followed by the appearance of a **CAR**.
 - **WALKLITE** only happens when engines **IDLE**, which in turn happens only when there is a **CAR**.





Results: interpretations of symbols capture dynamics

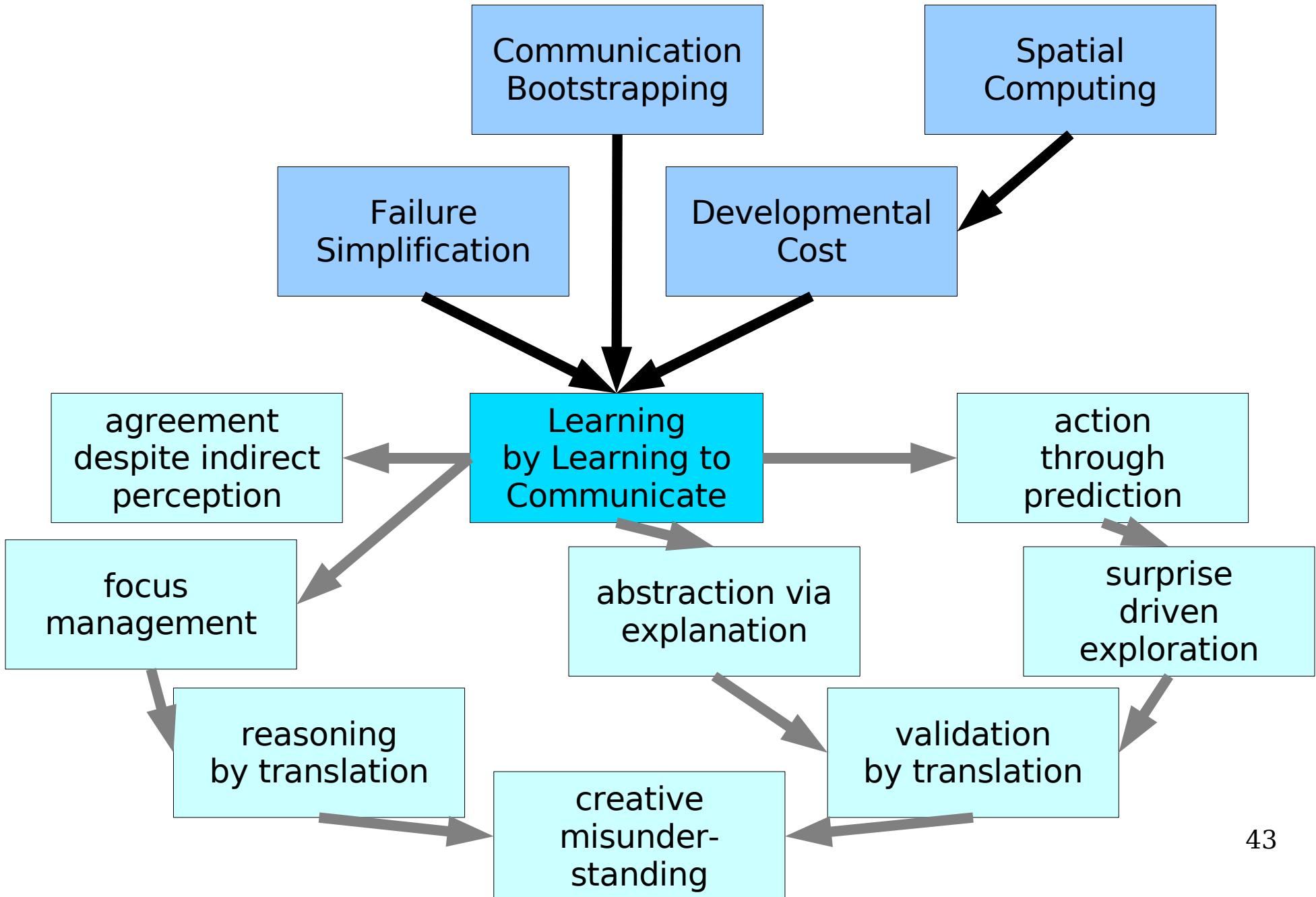
- Robust to sampling rate, activity level



Contributions

- Developed a method for engineering robust, composable devices: dossiers characterize a device's behavior over a wide range of conditions and **failure simplification** can manage its misbehavior.
- Established a six-part measure of **Developmental Cost** that allows us to estimate the plausibility of individual devices contributing to a larger model of intelligence.
- Developed a mechanism that creates the four sendipity conditions for **Communication Bootstrapping** in a set of specialist parts.
- Used a simulated world observed by two senses, vision and hearing, to demonstrate that differing symbol **interpretations can capture world dynamics**,

Our Quest for Intelligence

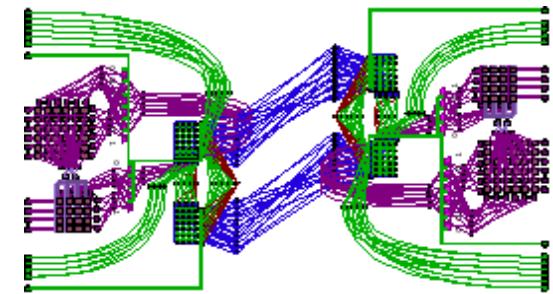


**END OF MAIN
TALK**

Observable Signature

(tests for the C.B. mechanism's presence)

Observable Signature?



- Structure: high graph expansion
- Activity: three distinct phases
 - Unidirectional organization
 - Bidirectional organization
 - Normal use

Predicting a Pendulum

(proof of concept for future work)

$x = -3$

$x = -2$

$x = -1$

$x = 0$

$x = 1$

$x = 2$

$x = 3$

$v = -3$

$v = -2$

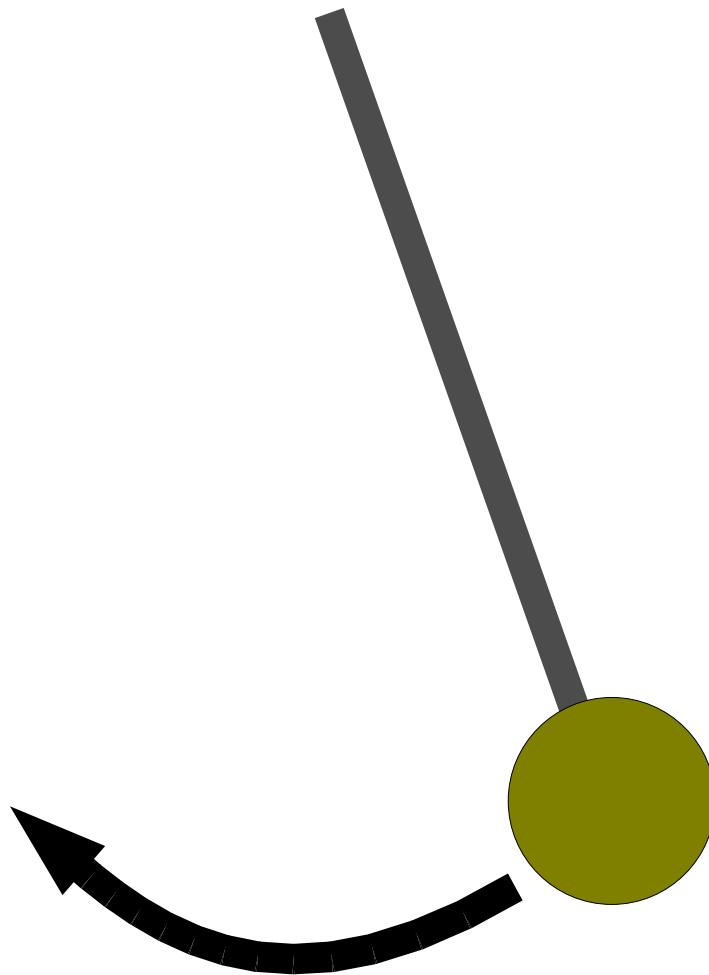
$v = -1$

$v = 0$

$v = 1$

$v = 2$

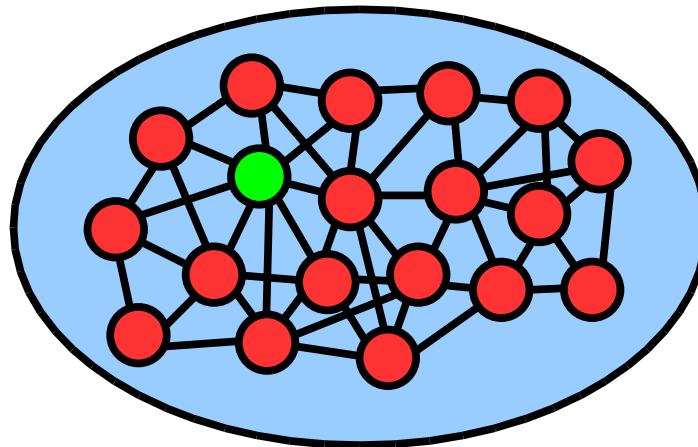
$v = 3$



Device Details

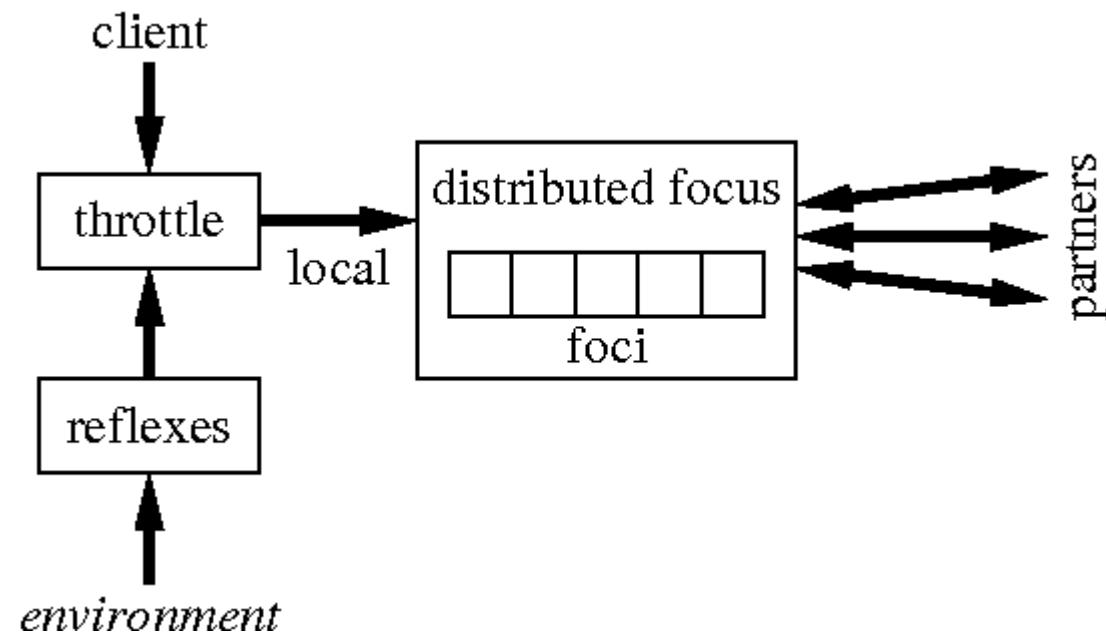
(competition, shared focus, relation maps)

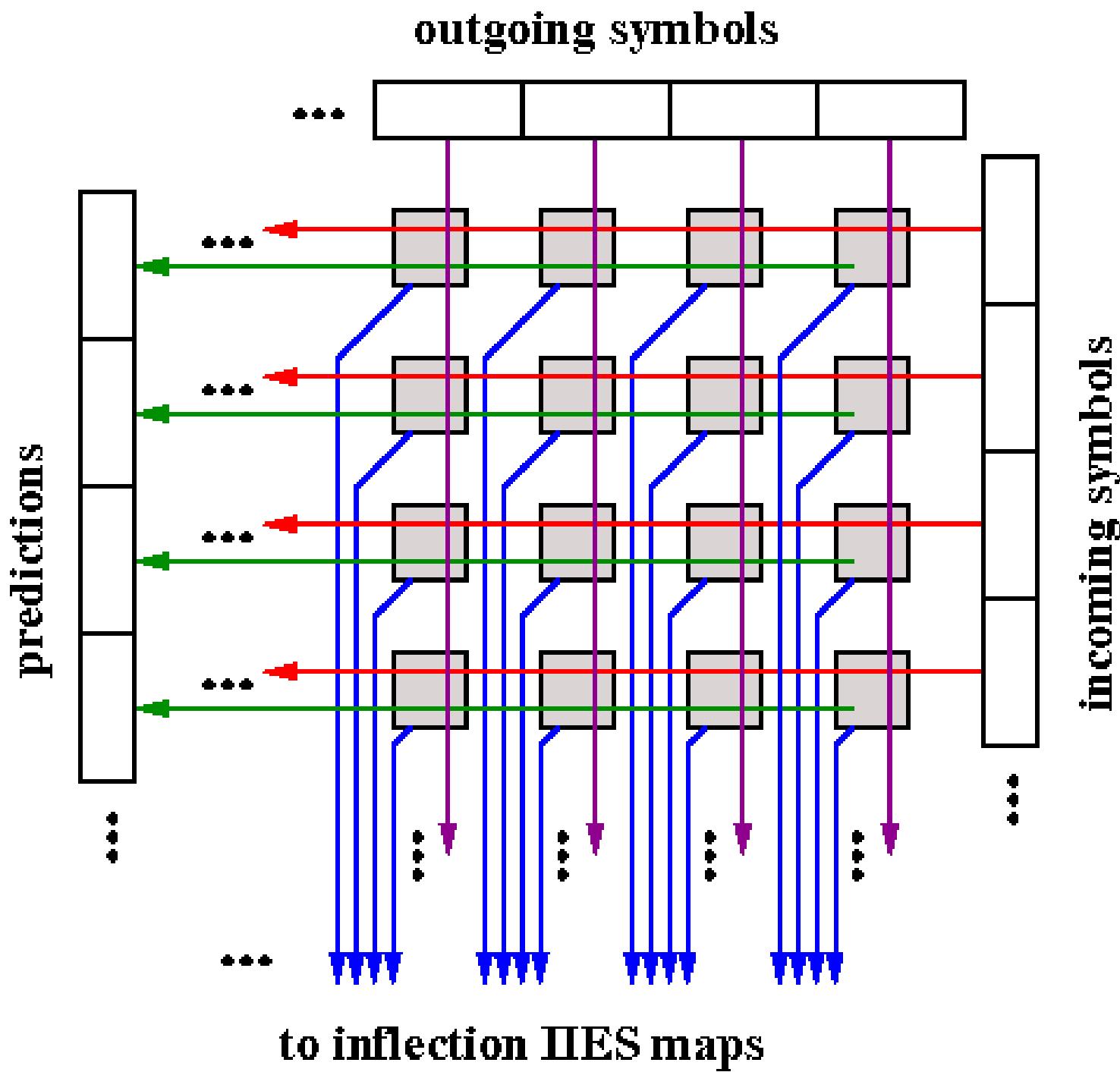
Competition

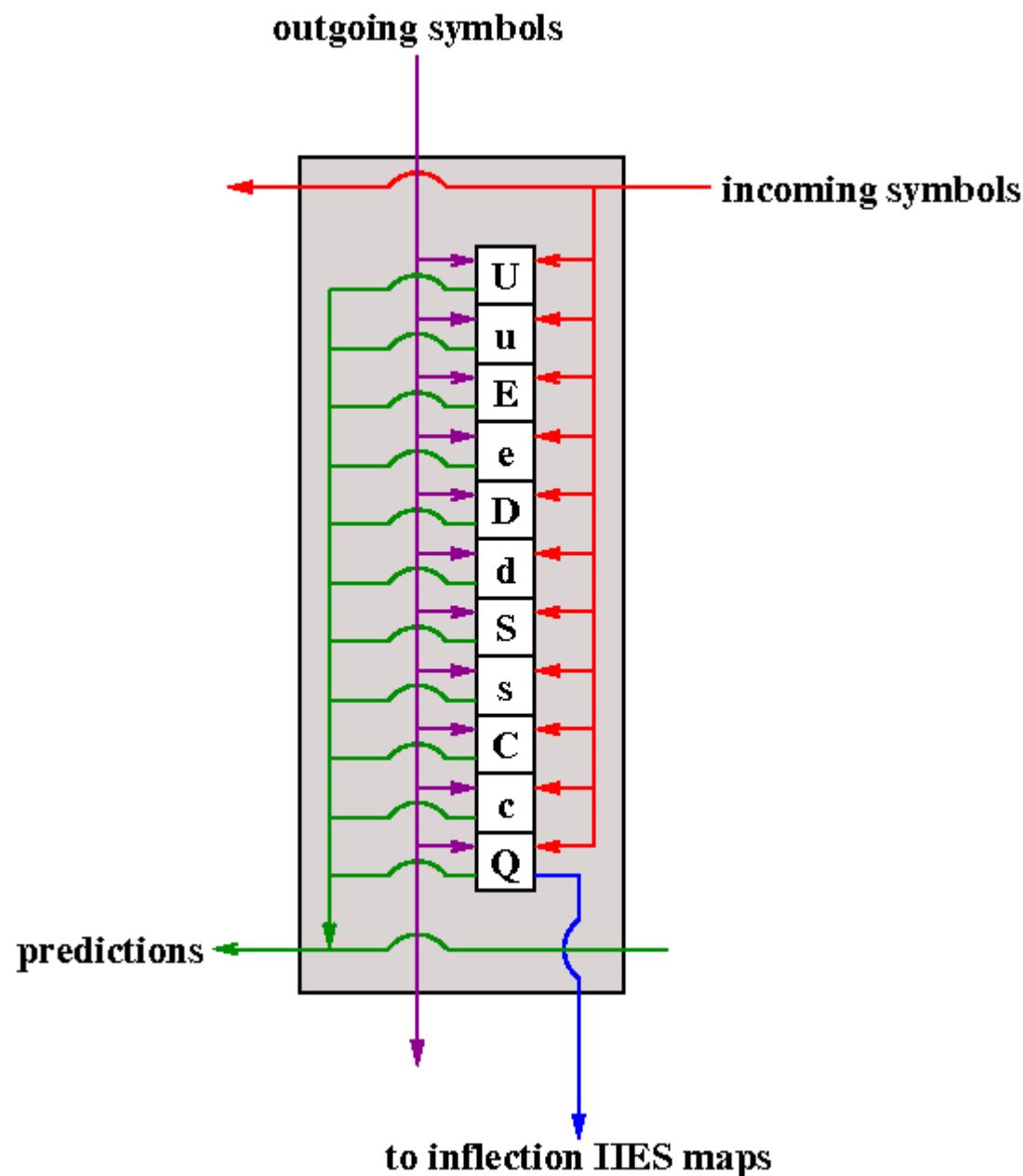


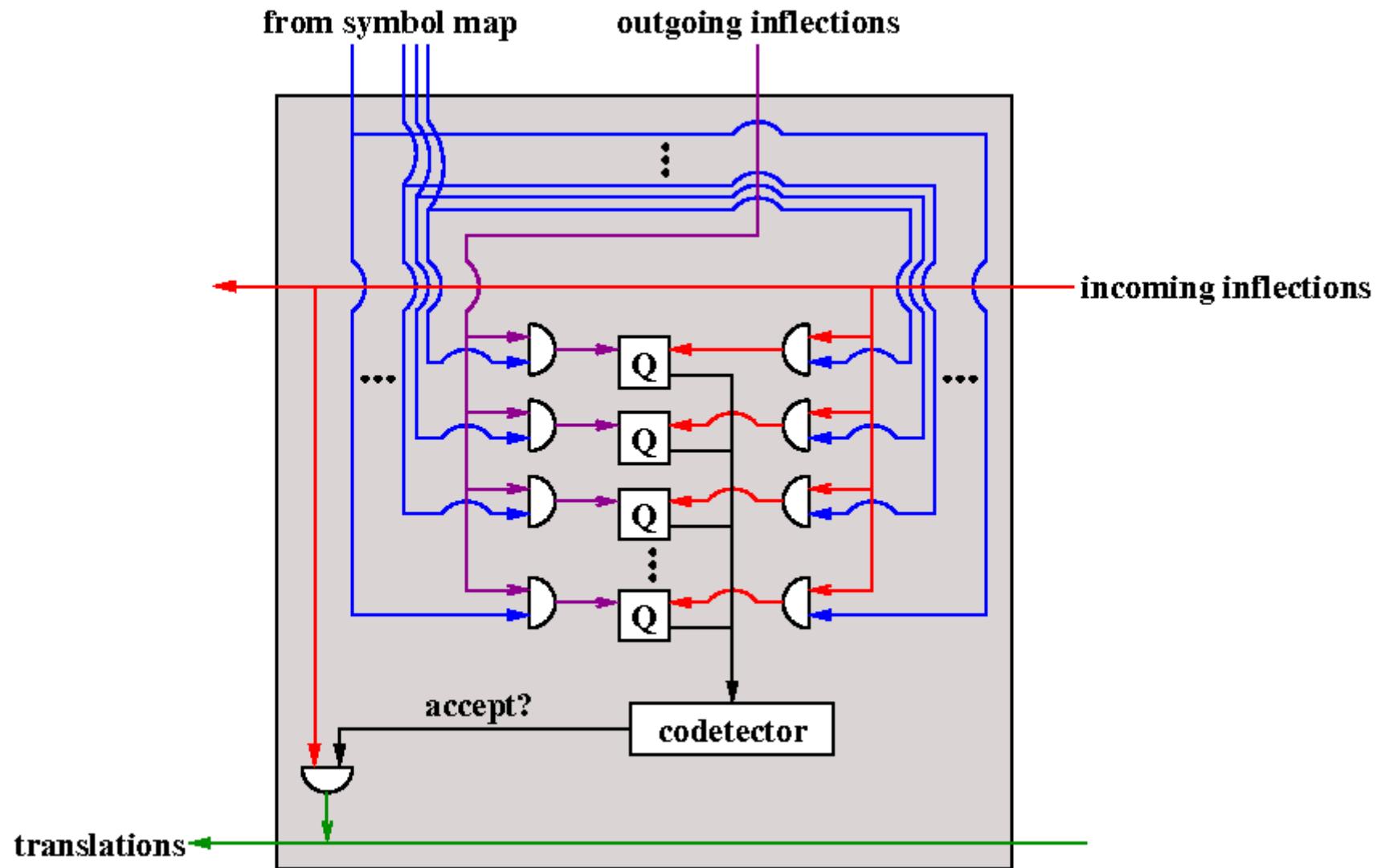
Mat. Time	Mat. Space	Dev. Time	Dev. Space
O(1) am.	O(n)	O(1)	O(1)

Shared Focus



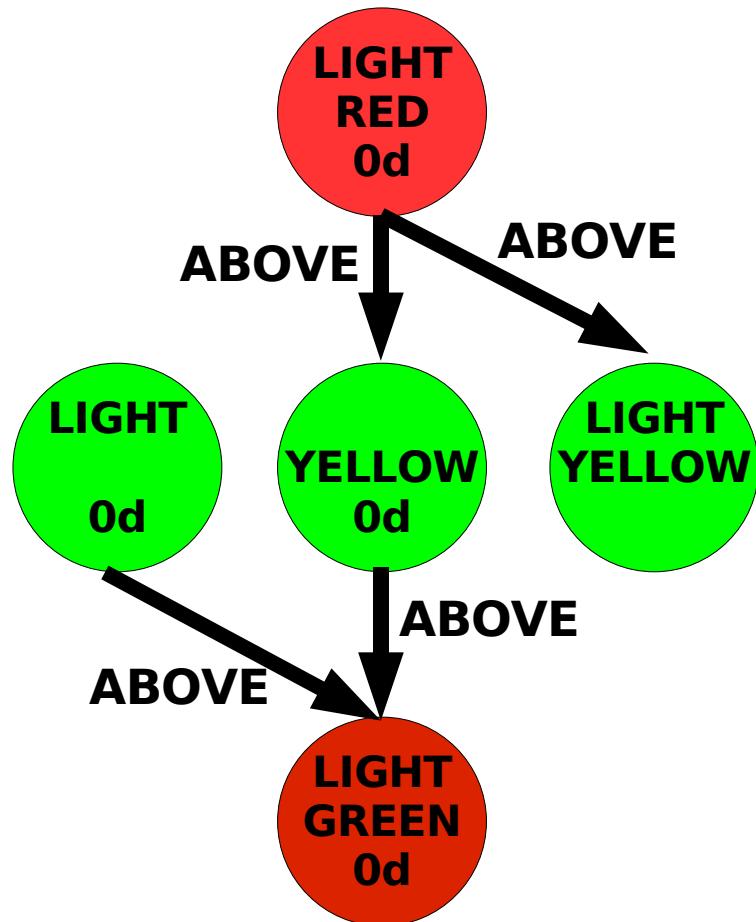






Message Ambiguity

(ambiguity in related objects)



**LIGHT=FOCUS1, FOCUS2,
BELOW1, ABOVE2**

RED=FOCUS1

GREEN=FOCUS2

**0d=FOCUS1, FOCUS2,
BELOW1, ABOVE2**

YELLOW=BELOW1, ABOVE2



Incremental Interval Example Segmentation

(learning from streams of messages)

**70db=FOCUS1
DRIVE=FOCUS1
LF=FOCUS1**

**70db=FOCUS1
DRIVE=FOCUS1
LF=FOCUS1**

**70db=FOCUS1
DRIVE=FOCUS1
LF=FOCUS1
F=FOCUS1**

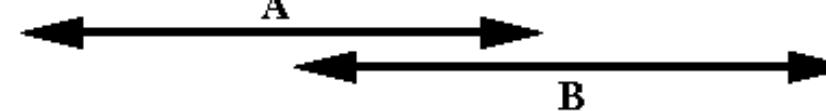
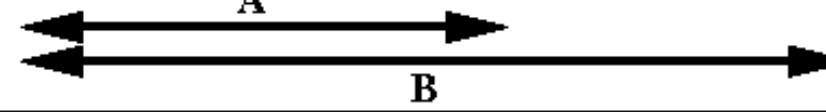
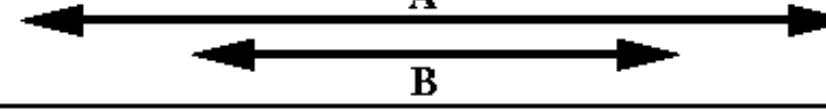
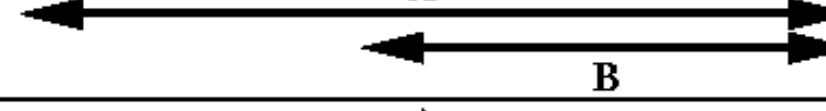
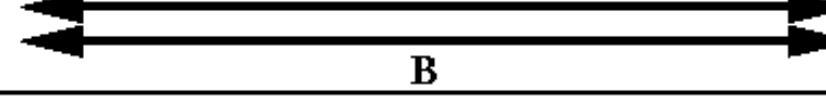


**CAR=FOCUS1
PICKUP=FOCUS1
R=FOCUS1
16d=FOCUS1
24d=FOCUS1
YELLOW=FOCUS1**

**CAR=FOCUS1
PICKUP=FOCUS1
R=FOCUS1
24d=FOCUS1
YELLOW=FOCUS1**

**CAR=FOCUS1
PICKUP=FOCUS1
R=FOCUS1
24d=FOCUS1
YELLOW=FOCUS1
BRIGHT=FOCUS1**

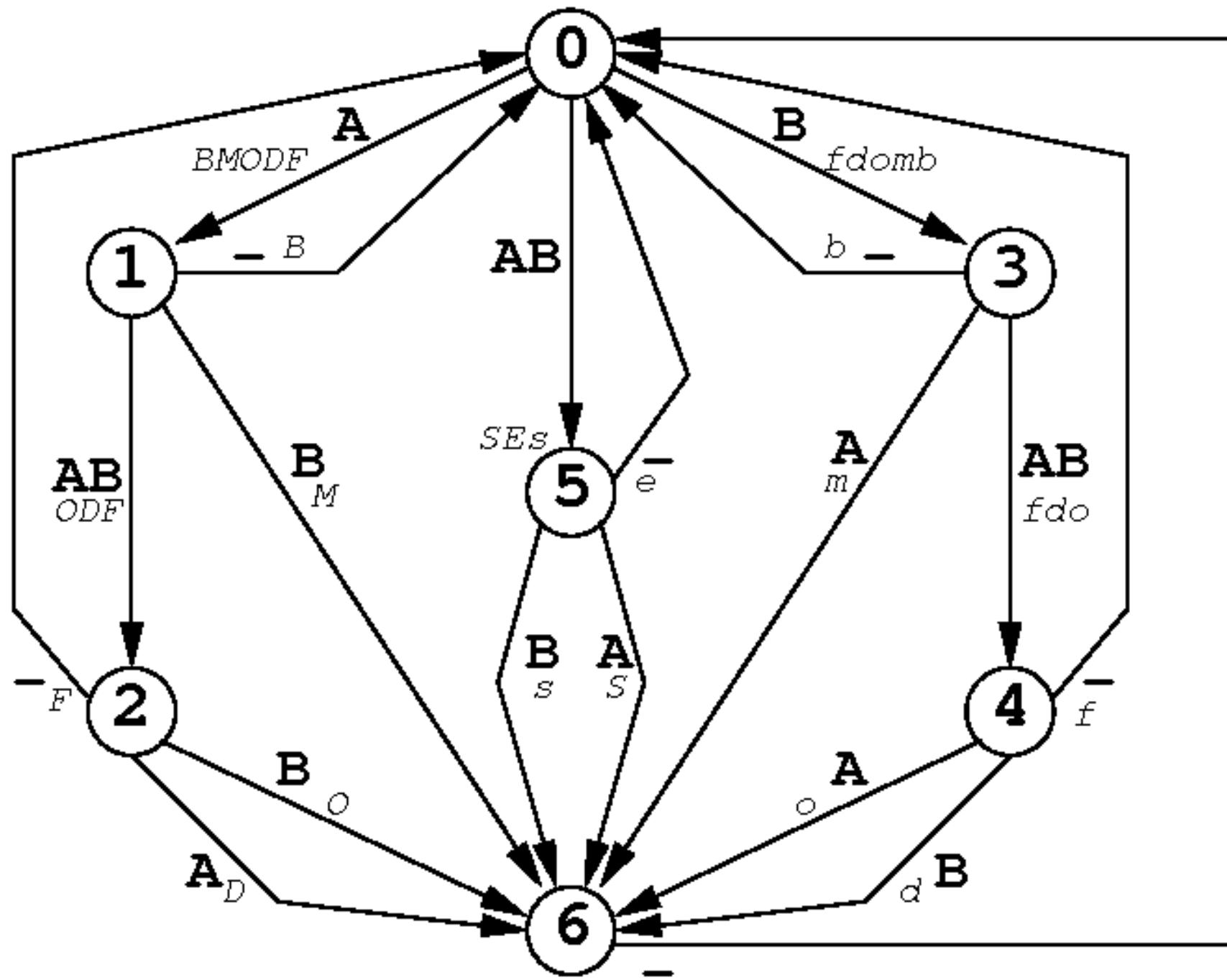
Allen's Time Interval Relations

Time		
(Before A B)		(Before ⁻¹ B A)
(Meets A B)		(Meets ⁻¹ B A)
(Overlaps A B)		(Overlaps ⁻¹ B A)
(Starts A B)		(Starts ⁻¹ B A)
(During A B)		(During ⁻¹ B A)
(Finishes A B)		(Finishes ⁻¹ B A)
(Equal A B)		

Predictive Relations

Name	Predictions	Allen Relations BMOSDFEfdsomb
EQUAL	A,A	0-1111111111-0
SUBCLASS	A,a	-----111--1--0
SEQUENCE	A,D	011-----000
CAUSE	A,-	011--1-0--00-
ENABLE	a,-	-11111100100-
DISABLE	-,D	-000-----0-11-

BMOSDFEfdsomb



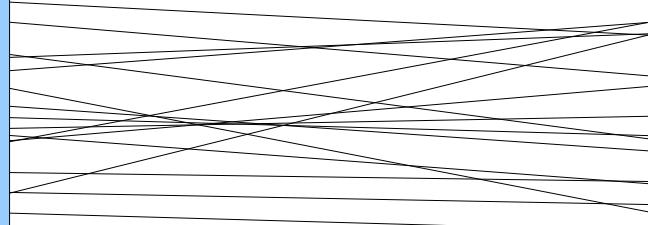
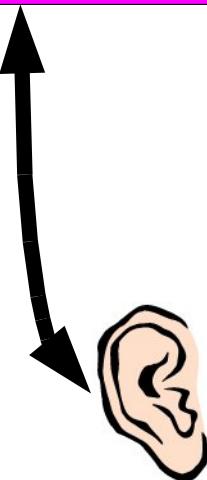
Focus of Attention

(bootstrapping precondition)

Hearing

70db
DRIVE
LF

Low-Level



Vision

LIGHT
GREEN
0d

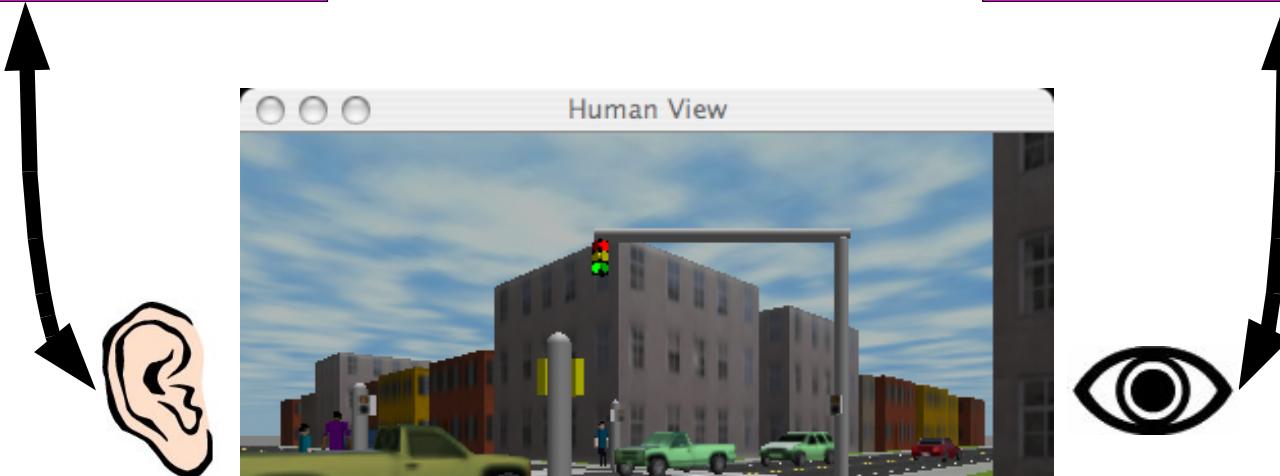
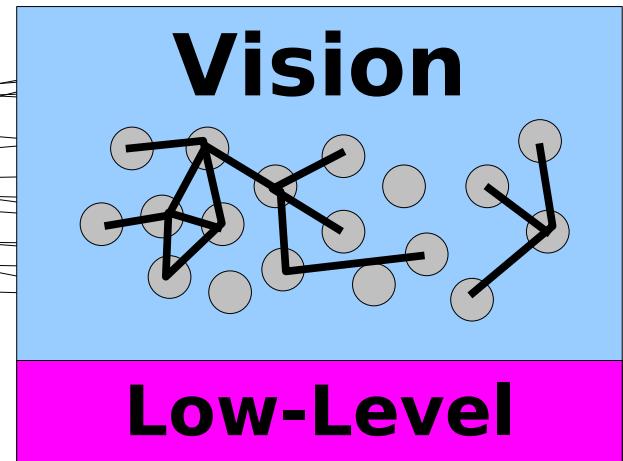
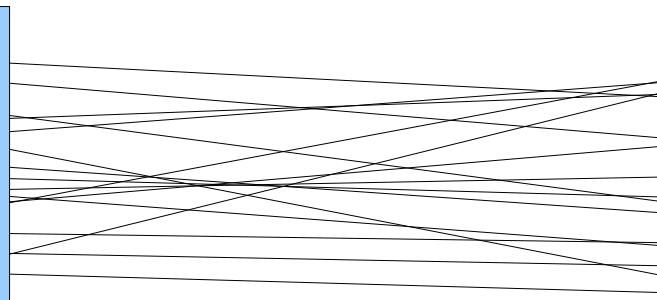
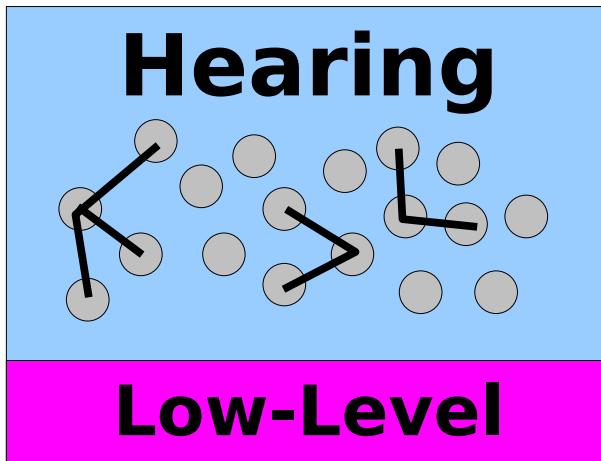
ABOVE

LIGHT
YELLOW
0d

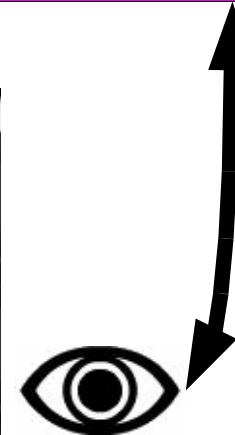
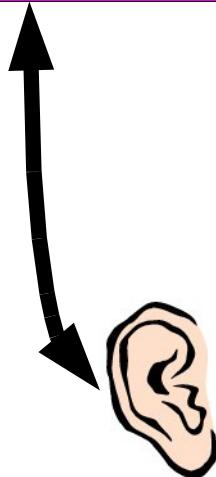
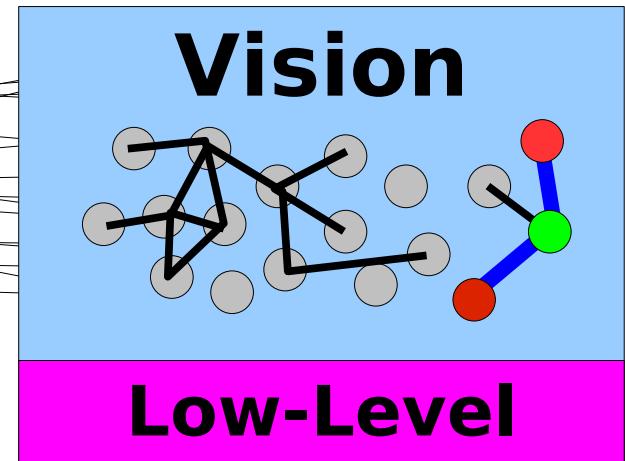
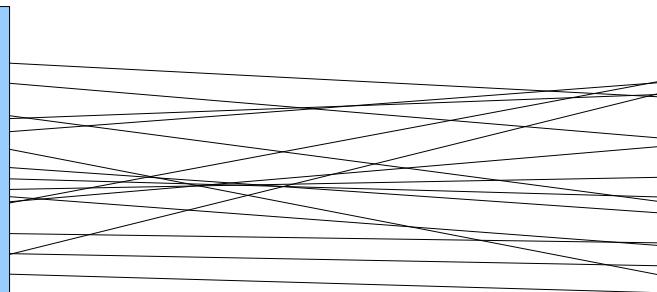
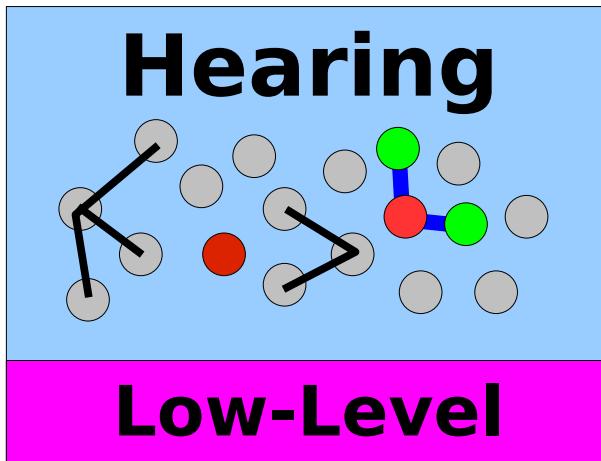
Low-Level



vroooooOooooom!



vroooooOoooooom!



vroooooOoooooom!

**70db
DRIVE
LF**

**50db
STEPS
LF**

**70db=FOCUS1
50db=FOCUS2
DRIVE=FOCUS1
STEPS=FOCUS2
LF=FOCUS1, FOCUS2**

**LIGHT=FOCUS1, FOCUS2,
BELOW1, ABOVE2
RED=FOCUS1
GREEN=FOCUS2
0d=FOCUS1, FOCUS2,
BELOW1, ABOVE2
YELLOW=BELOW1, ABOVE2**

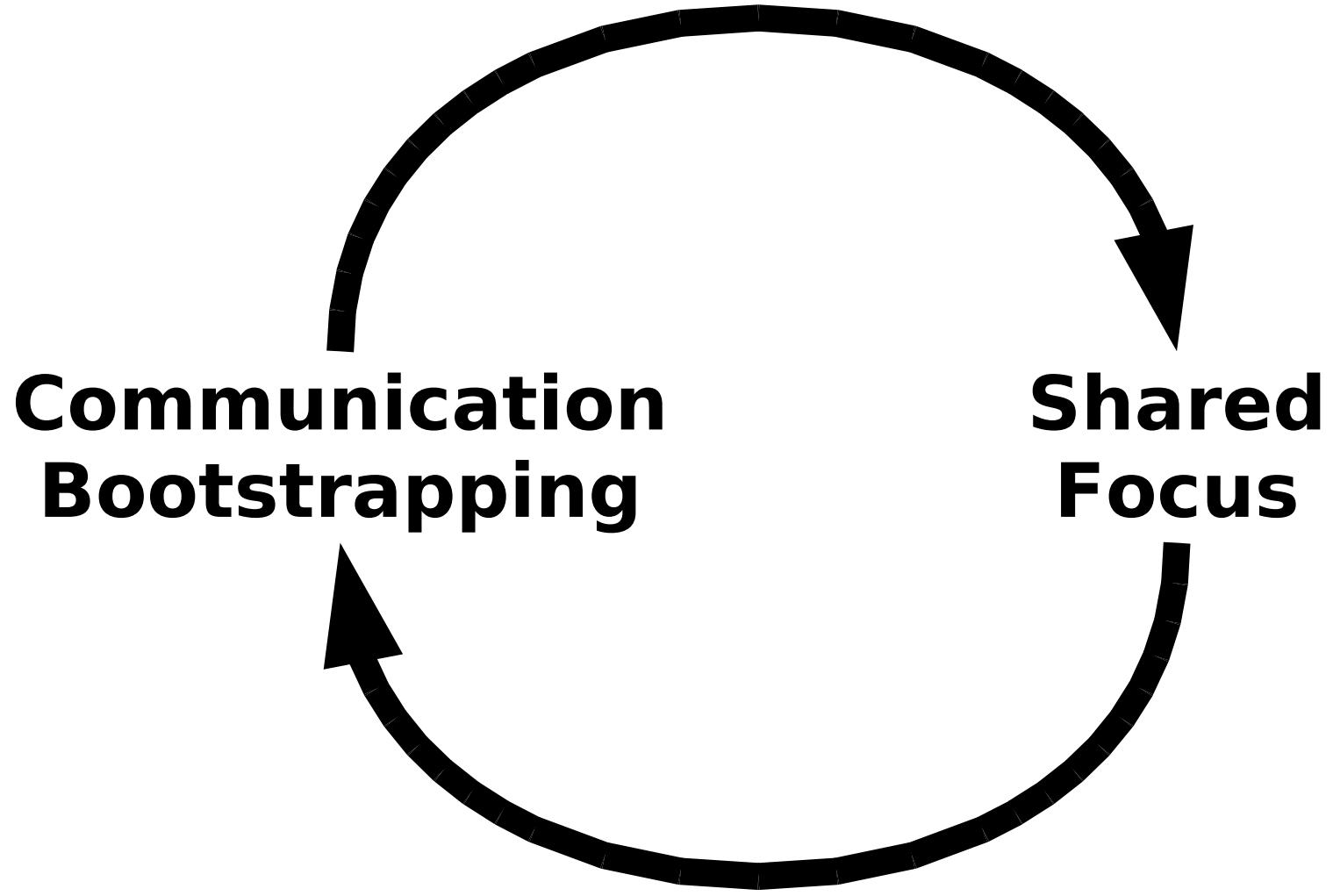
**LIGHT
RED
0d**

**LIGHT
YELLOW
0d**

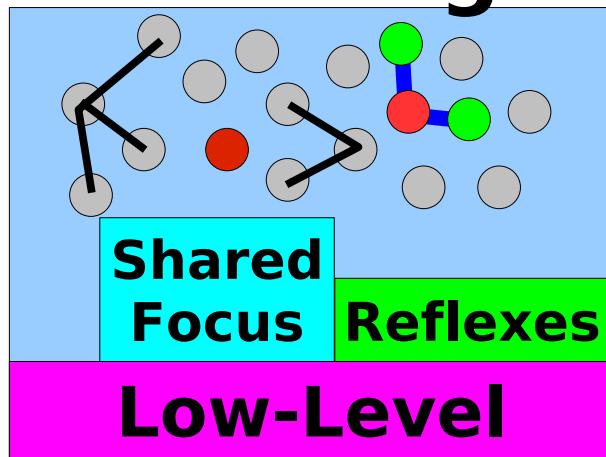
**LIGHT
GREEN
0d**

ABOVE

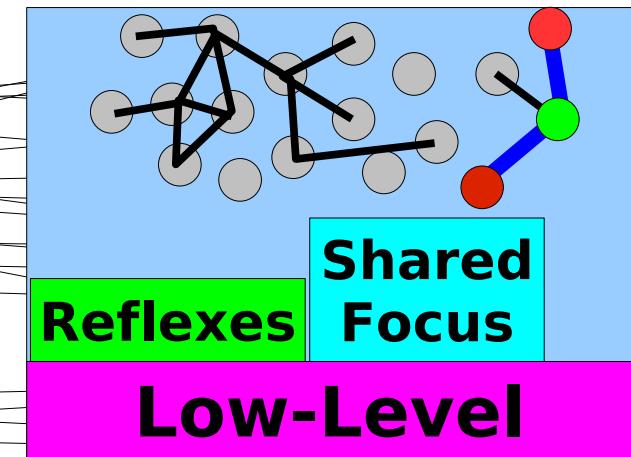
ABOVE



Hearing

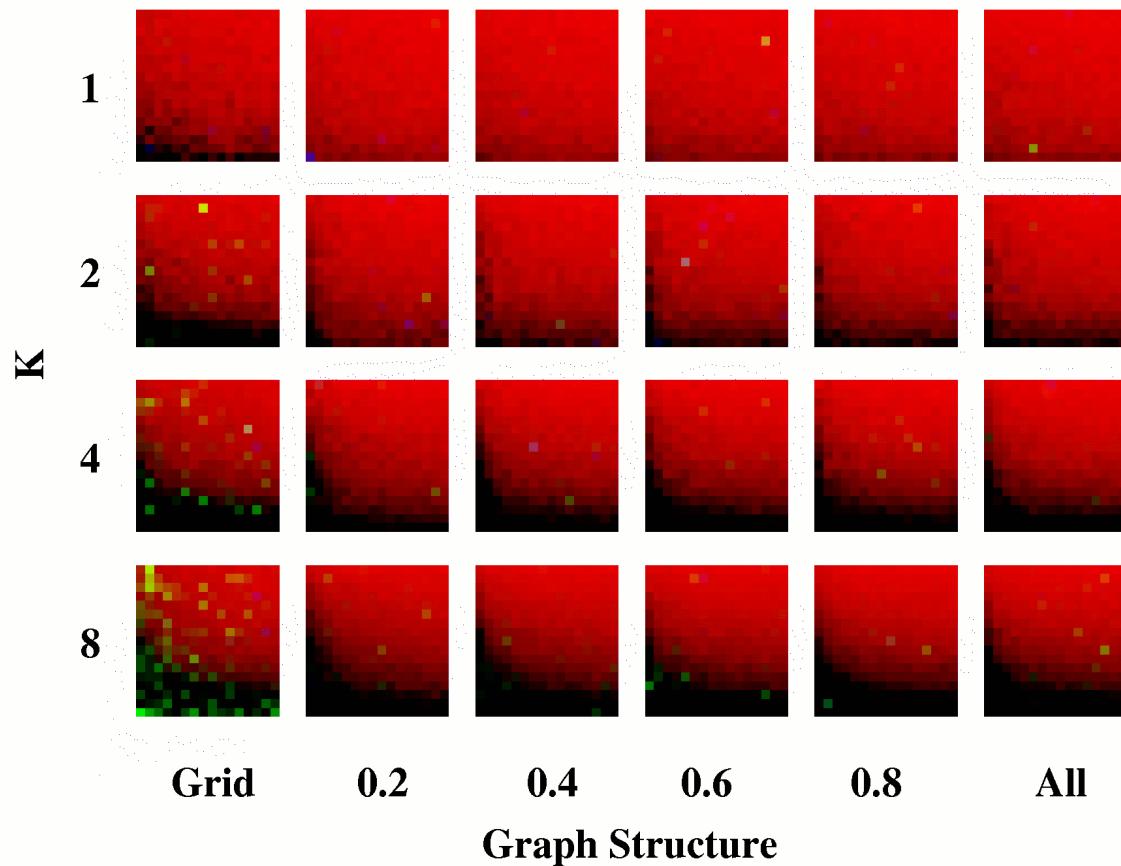


Vision

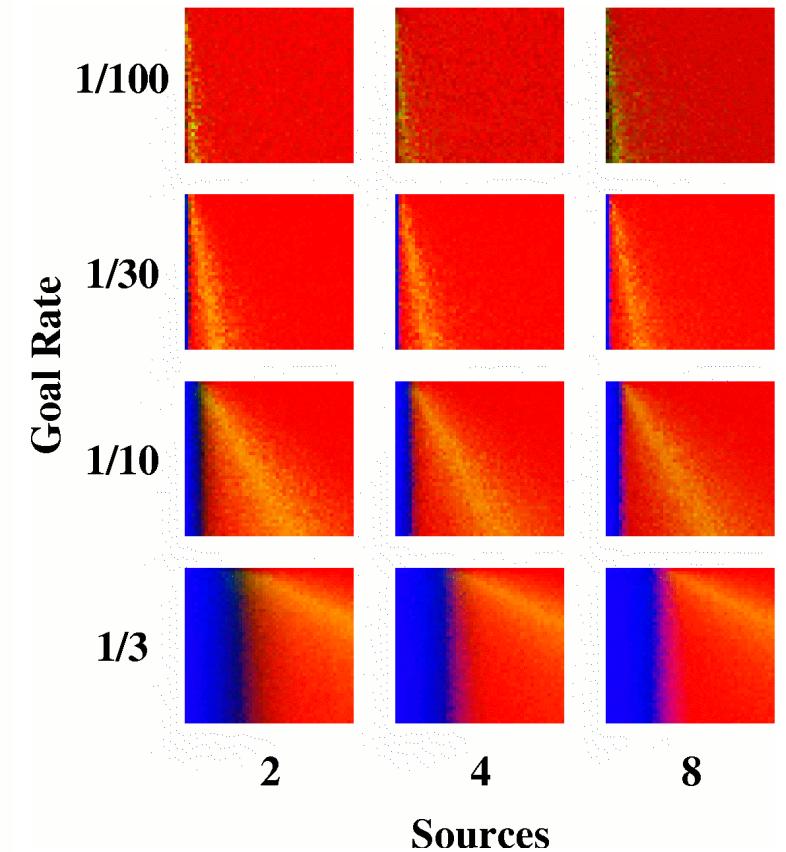


vroooooOoooooom!

$n = 50$, random



Convergence Rate



Request Throttle

Developmental Primitives

(details of developmental cost)

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!

Calculating Cost

- Three building blocks:
 - Simple program
 - Set of communication paths
 - Set of parts
- Building block costs are abstractions of neuroscience & synthetic biology

*Problems with building block assumptions
are likely to change cost constants only*

Primitive: Simple Program

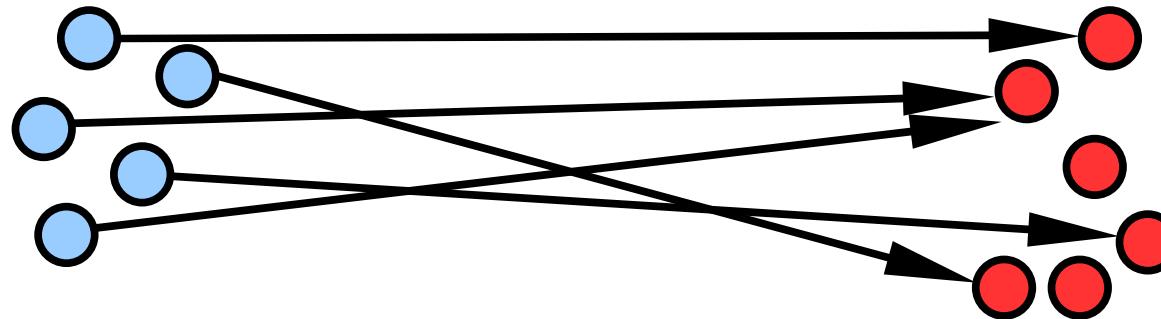
```
(defun add-example (state example)
  (if example
      (incf (strength state))
      (decf (strength state) miss)))
```

	Time	Space	Imperfection
Mature	$O(\text{ops} + \text{bits})$	$O(\text{ops} * \text{bits})$	abort
Development	$O(\text{ops} + \text{bits})$	$O(\text{ops} + \text{bits})$	DOA

Loops, function calls handled by expansion

Simple programs are cheap

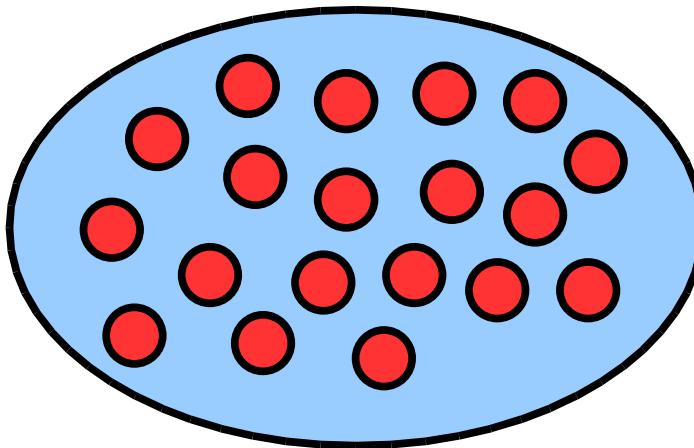
Primitive: Communication Paths



	Time	Space	Imperfection
Mature	$O(1)$ $O(\text{length})$	$O(\text{bits} * \text{paths})$	noise
Development	$O(\text{length})$	$O(\text{bits/reuse})$	extra or absent paths

Precision connections are expensive

Primitive: Set of Parts



	Time	Space	Imperfection
Mature	$O(\text{part})$	$O(\text{size} * \text{part})$	part
Development	$O(\text{part})$	$O(\text{part})$	set size & part

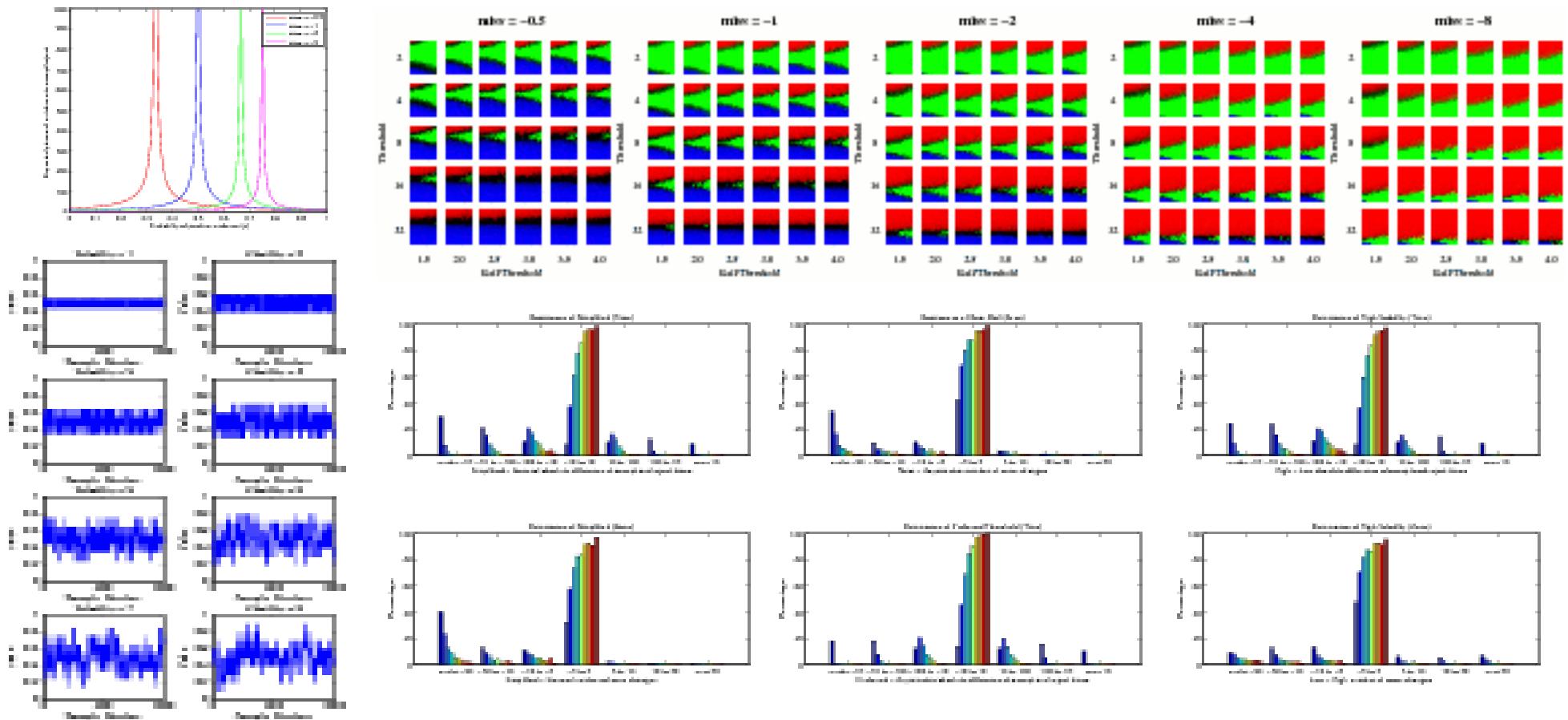
Can add mesh network for $O(1)$ added cost

Making copies is cheap

Other Random Slides

(example dossier, “Hilbert questions”)

Compiling a Dossier



“When in doubt, use brute force” -Ken Thompson

What makes human intelligence unique?
How are concepts grounded in experience?
How are perception and reasoning related?
What makes natural intelligence so robust?
How is an integrated mind formed from a collection of many different parts?

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