A Cognitive Architecture based on Dual Process Theory

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Goal

- A fully automatic computational model integrating
  - Concept formation
  - Reasoning
    - Deductive and inductive
    - Symbolic and subsymbolic

Dual process theory

- Kahneman contrasts fast and slow cognitive processes and Ron Sun explicit and implicit.

- We distinguish between
  - Perception: for sensing the environment and
  - Imagination: for speculating about the environment

- Failure to distinguish between perception and imagination can lead to delusions…

Network model

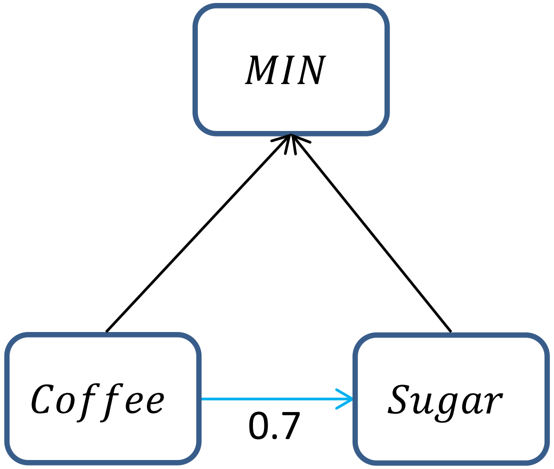
- A *network* is a labeled structure (V, P, I), where $P, I \subseteq V \times V$.

- Labels on the nodes $\mathrm{a} \in V$:
  - SENSOR
  - MOTOR
  - MIN
  - MAX
  - DELAY
  - SPACE(μ, σ)

- Each node $\mathrm{a} \in V$ has an associated number in [0,1] approximating $P(a)$.

- Each edge $(a, b) \in I$ has an associated number in [0,1] approximating $P(b|a)$.

Network example



P-edges are black and I-edges are blue.

Stimuli

Time →

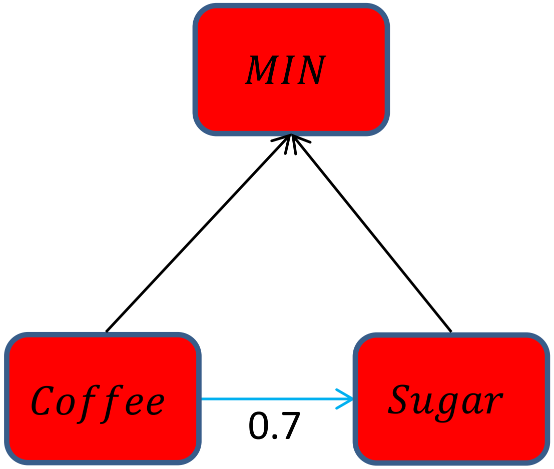
	0	1	2	3	4	5	…
$sensor_1$	0.4	0.4	0.4	0.5	0.5	0.5	
$sensor_2$	0.3	0.3	0.6	0.6	0.6	0.6	
$sensor_3$	0.2	0.3	0.4	0.5	0.6	0.7	
$sensor_4$	0	0	0	0	1	1	
$sensor_5$	1	0.9	1	0.9	0	0	
…							

Real values in [0,1] are assigned to the sensors at all times.

Two activities

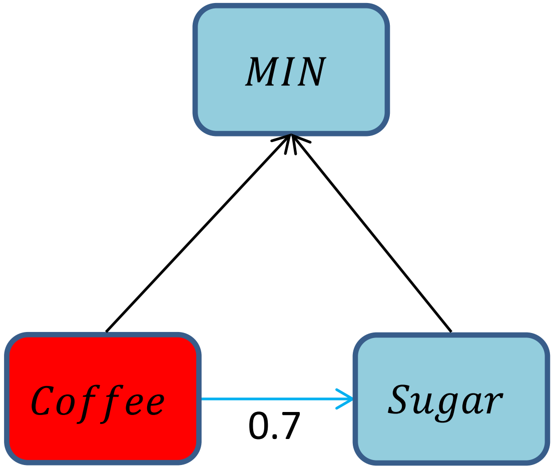
- Stimuli generate two types of activity:
  - Perception $p: V \times T \to [0,1]$
  - Imagination $i: V \times T \to [0,1]$

Propagation of perception



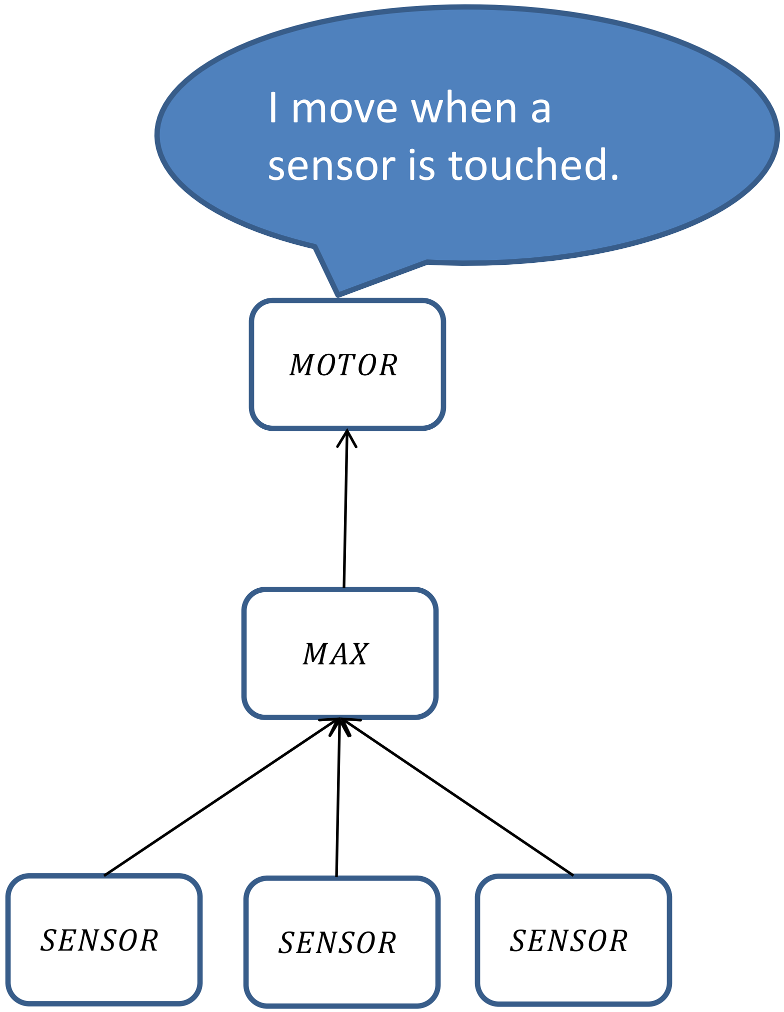
Propagation of perception (red).

Propagation of imagination



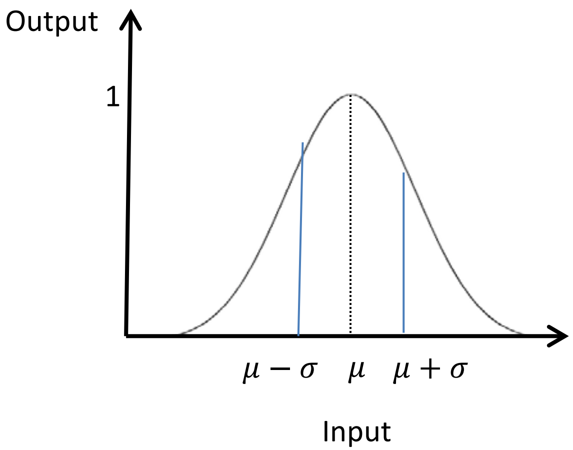
Propagation of perception (red) and imagination (blue).

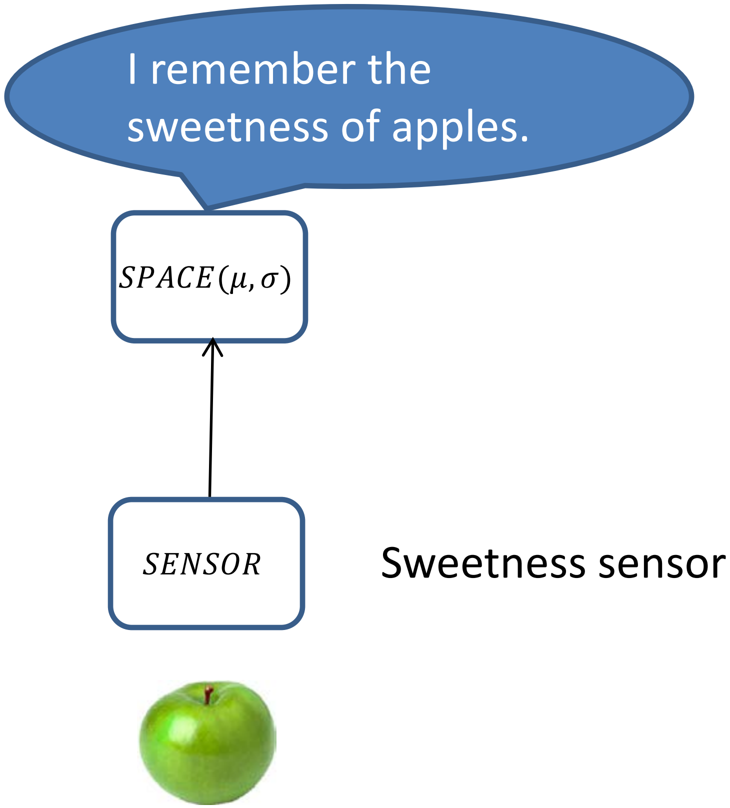
Network examples



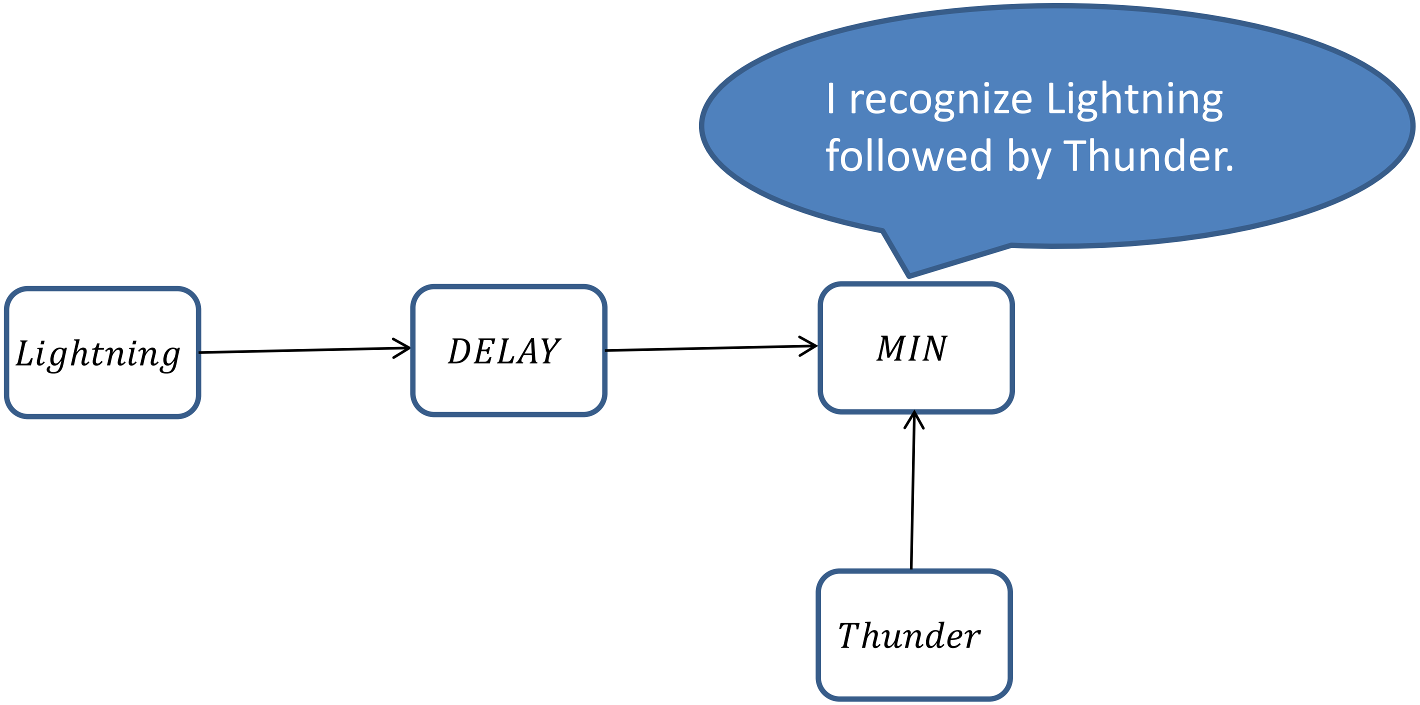
Touch sensors

Network examples

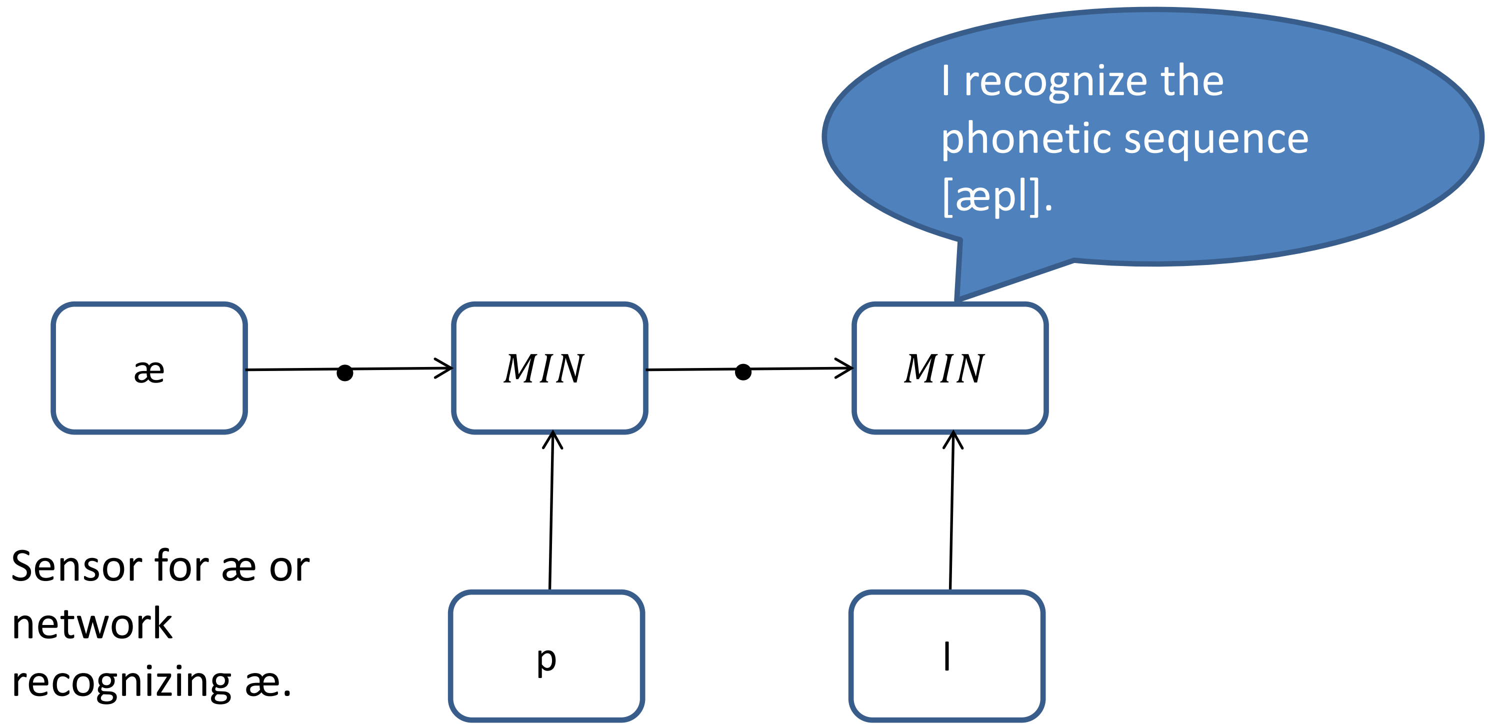




Network examples

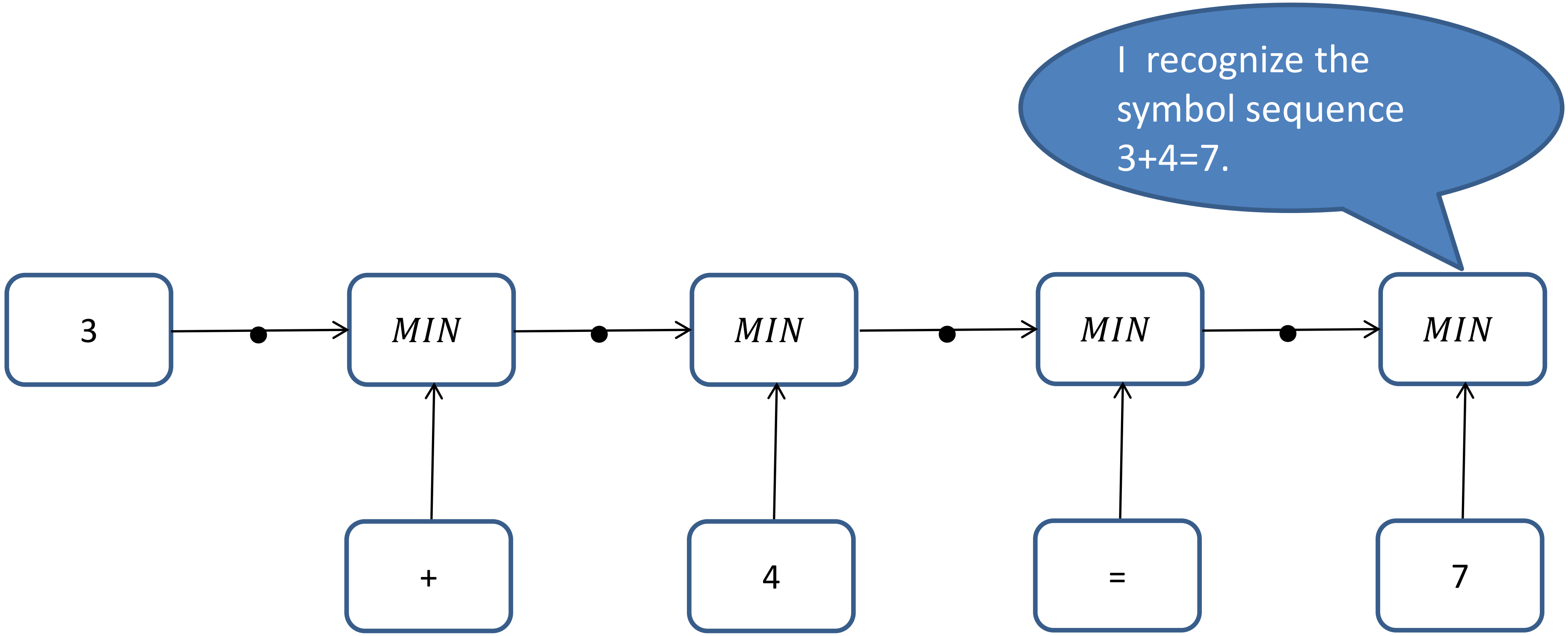


Network examples

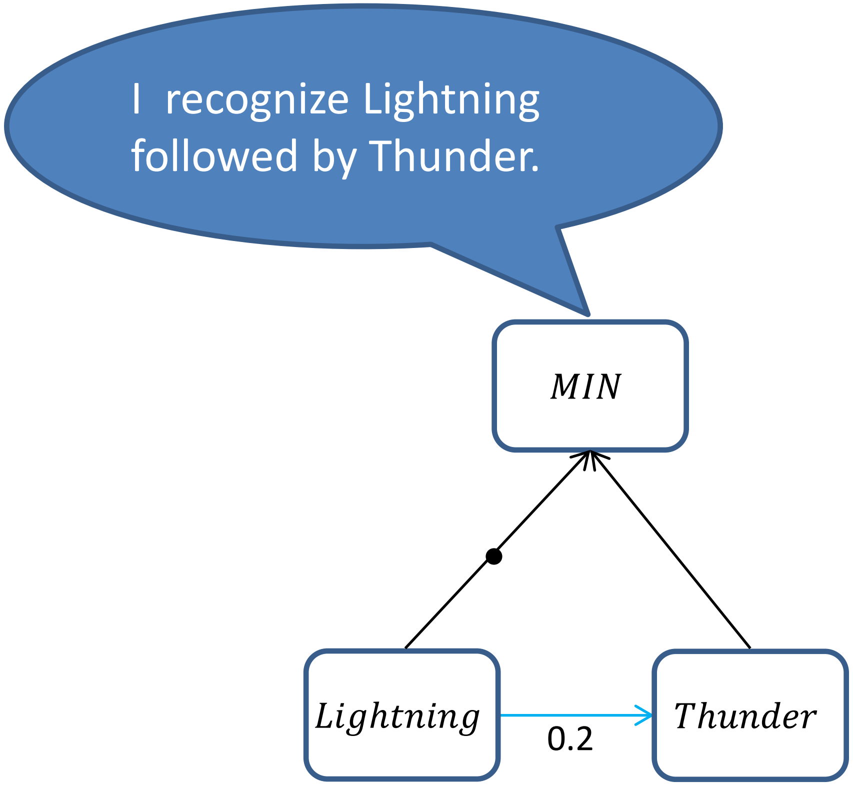


• = DELAY node

Network examples



Network examples

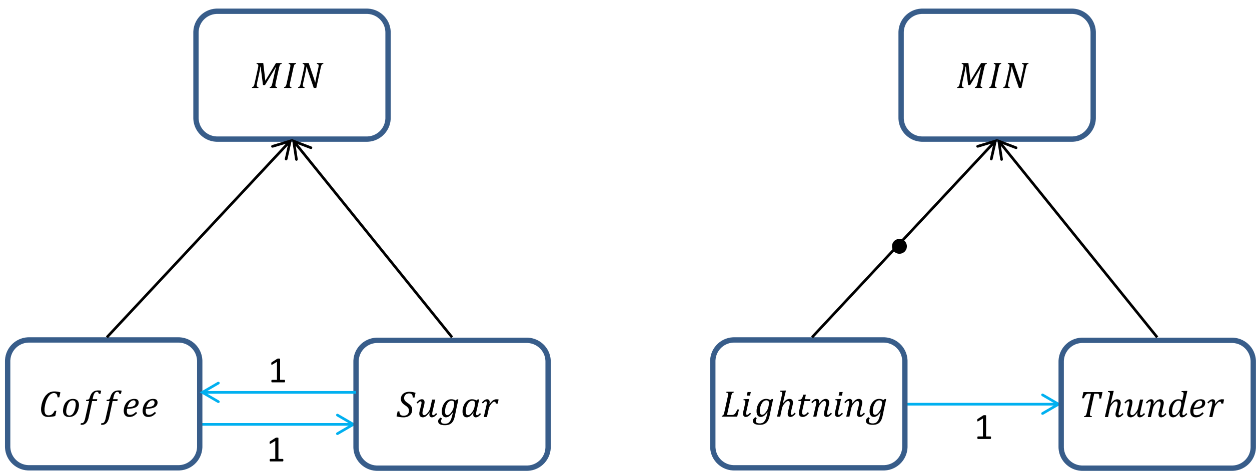


P(Thunder|Lightning) = 0.2

Network development

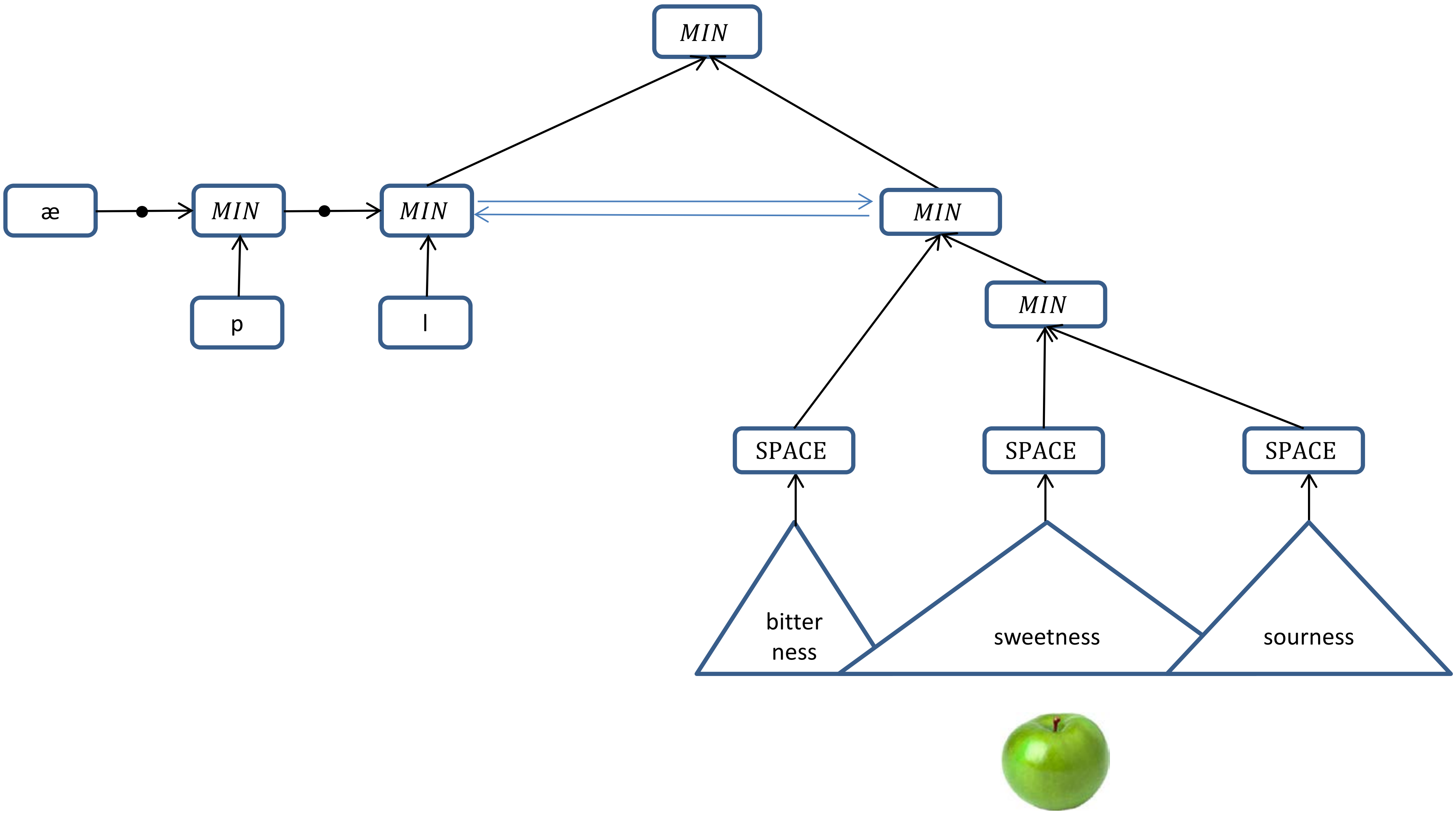
- Start with any genotype network.
- Develop a sequence of phenotype networks by means of rules for adding, deleting, merging, and updating memory structures.

Coupling



Two kinds of memory structures formed on top of the nodes at the bottom.
“If they fire together (with a delay) they wire together (with a delay).”

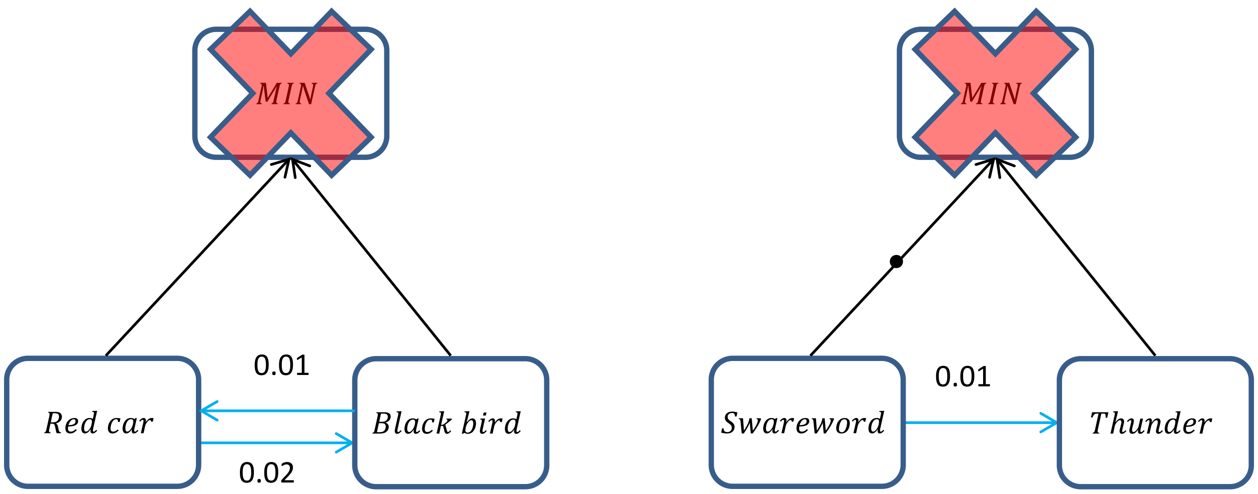
Iterated coupling



Network formation

- Thus the network is gradually populated with nodes representing, e.g.
  - Apple taste
  - Coffee smell
  - Coffee and Sugar at the same time
  - Lightning followed by Thunder
  - The symbol sequence “3+4=7”
  - The sound sequence [æpl].

De-coupling



Memory structures with small conditional probabilities are removed.
“Use them or lose them.”

Cognitive architecture

- Sensory-motor system*
  - The genotype
- Long-term memory (LTM)*
  - The phenotype
- Working memory (WM)*
  - A buffer that can contain (pointers to) a small number of nodes of the phenotype

*) implemented

Cognitive architecture

- Central control
  – Selects actions (external or internal)

- Slave systems
  – Rewriter*. Rewrites WM based on LTM
  – Speaker. Phonetic sequence player
  – Writer. Letter sequence player
  – Mover. Motor sequence player

Classify

Stimuli	**WM**	**LTM**	**Action**
Apple			Taste
	Apple	Apple → [æpl]	Associate
	[æpl]		Speak

Compute

Stimuli	**WM**	**LTM**	**Action**
$17 \cdot 3$			Look
	$17 \cdot 3$	$17 \rightarrow (10 + 7)$	Rewrite
	$(10 + 7) \cdot 3$	$(x + y) \cdot z \rightarrow x \cdot z + y \cdot z$	Rewrite
	$10 \cdot 3 + 7 \cdot 3$	$10 \cdot 3 \rightarrow 30$	Rewrite
	$30 + 7 \cdot 3$	$7 \cdot 3 \rightarrow 21$	Rewrite
	$30 + 21$	$30 + 21 \rightarrow 51$	Rewrite
	51		Write

Model supported by psychological experiments.

Prove

Stimuli	**WM**	**LTM**	**Action**
$p \vee (p \Rightarrow q)$			Look
	$p \vee (p \Rightarrow q)$	$(x \Rightarrow y) \rightarrow (\neg x \vee y)$	Rewrite
	$p \vee (\neg p \vee q)$	$((x \vee (y \vee z)) \rightarrow ((x \vee y) \vee z)$	Rewrite
	$(p \vee \neg p) \vee q$	$(x \vee \neg x) \rightarrow \text{True}$	Rewrite
	$\text{True} \vee q$	$(\text{True} \vee x) \rightarrow \text{True}$	Rewrite
	True		Speak

Model supported by psychological experiments.

Associate

Stimuli	WM	LTM	Action
	Beach	Beach → Ocean	Speculate
	Ocean	Ocean → Swim	Speculate
	Swim	Swim → Drown	Speculate
	Drown		

Status

- A partial implementation exists (in Haskell).
- It performs well on the classification problems of the UCI data sets Iris and Wine.
- It can do extrapolation based on its own experiences. For example, if it has seen the sequence ZEB, it will guess ZEBRA.
- It can do theorem proving in propositional logic
- It can do simple mathematics.

Conclusion

- This approach enables us to integrate concept formation and several types of reasoning.

- The network sometimes grows too fast. To tackle this we recently moved from novelty-based to reward-based concept formation.