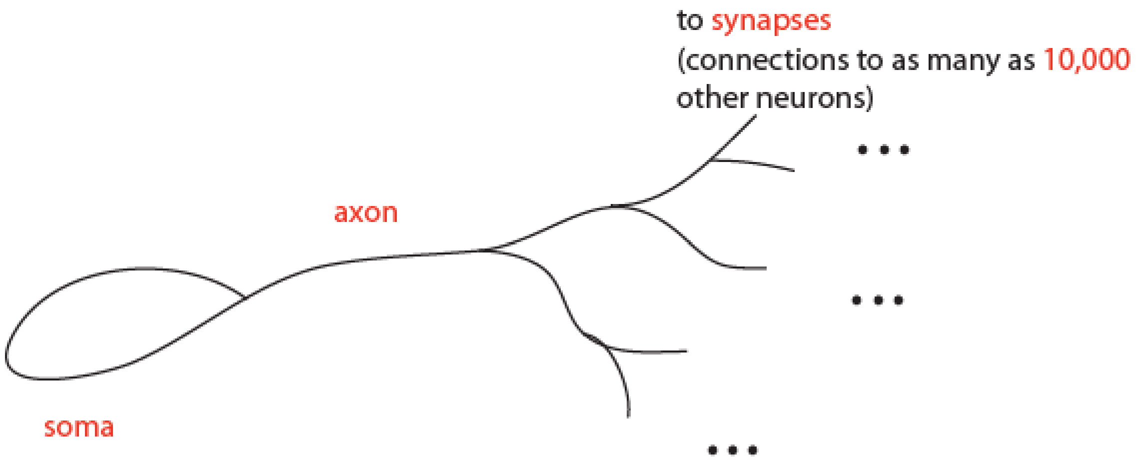
Central Nervous System Organization

Sketch of a Neuron



Loops in the Central Nervous System

Prevalence and Importance

Organization of the Neocortex

Neurons in the human neocortex are organized in

500,000 columns (0.5mm diameter/2mm depth)
~ 70,000 neurons in each column.

The columns are divided into six layers, I through VI:

Layers I-III provide cross and intra-column connections.

Layer IV primarily receives incoming sensory information.
Layers V-VI primarily project out of cortex.

Recent details: *Science* 342 (22 Nov. 2013) (Jeff Lichtman - Harvard)

"(A) salt grain-sized .. cylinder of (mouse tissue contains) 680 nerve fibers … and 774 synapses ..."

The Prevalence of Loops in Neocortex (2)

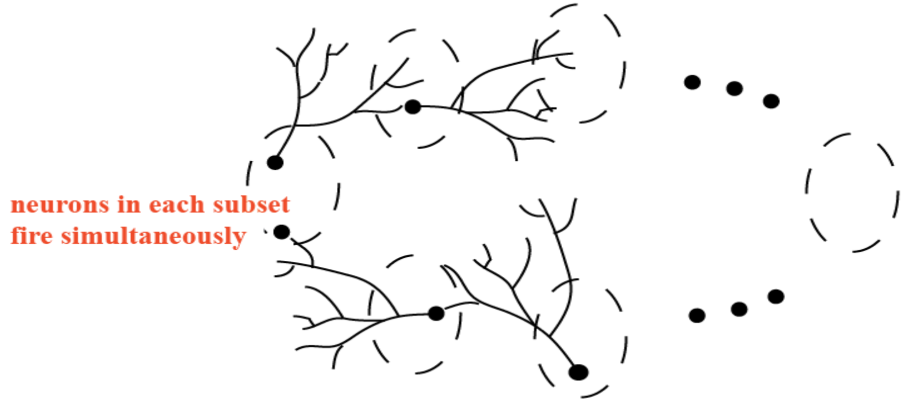
Because there are 1,000 or more synapses per neuron,
all possible loops, defined by selecting neurons 2-at-a-time, 3-at-a-time, up to length 25 or so, will be present in a grain-of salt-sized region.

A calculation using the binomial theorem shows that there are over 10 billion distinct directed loops in this salt-sized a region.

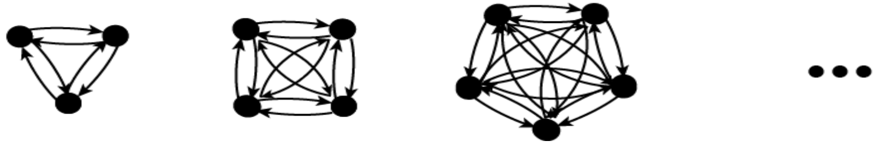
The Origin of Loops

A connected set of 3 neurons in a small section of neocortex will make over 1 trillion synaptic contacts. Many of these contacts will be with the originating 3 neurons, producing loops.

Loops allow neural pulses to *recirculate*, so that a given neuron can *restimulate* itself via the intervening neurons in the path.

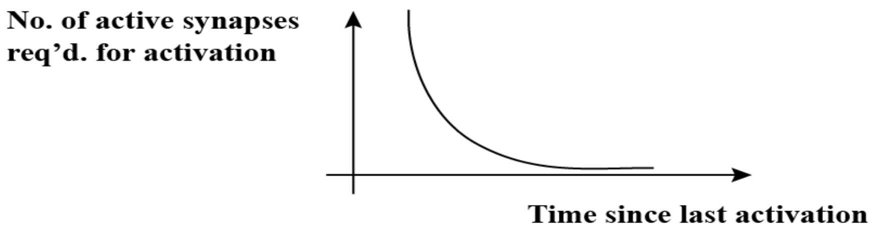


By looking at connected neurons in a small neo-cortical section 2-at-a-time, 3-at-a-time, and so on, it is clear that the section contains a vast number of loops. A calculation using the binomial theorem shows that there are more than 10^9 distinct loops in a grain-of-salt sized section.

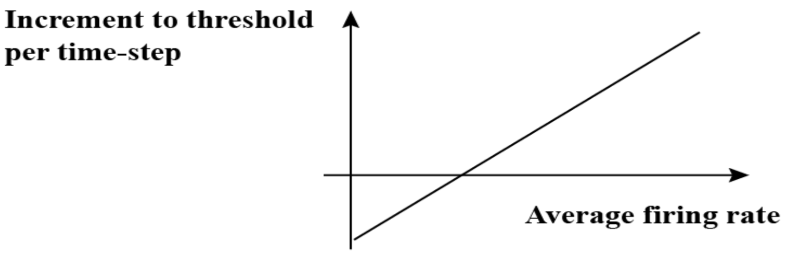


Properties of Neurons Relevant to Recirculation
of Spikes in Loops

Time-varying threshold



Fatigue **(increasing threshold based on firing rate)**



Hebb's learning rule

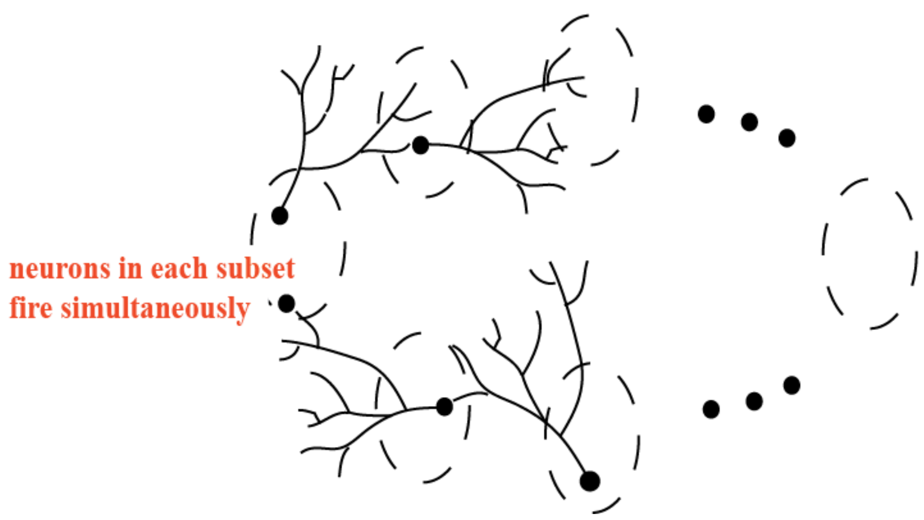
When neuron A is directly connected to neuron B

- **If A fires and B fires immediately afterward (~1msec):**
  - **then the connection between A and B is strengthened.**
- **If A fires and B does not fire immediately afterward**
  - **then the connection between A and B is weakened.**

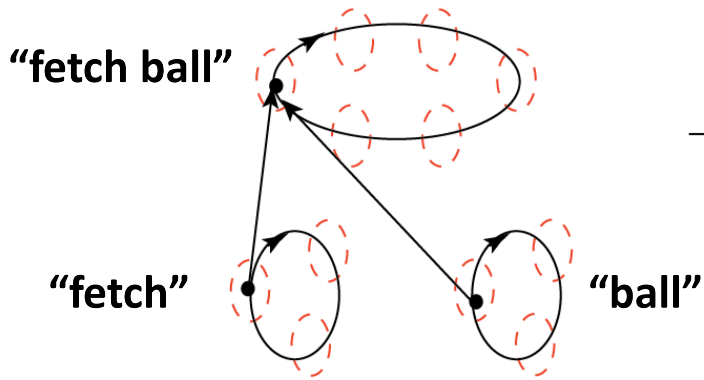
Activity in CNS Loops

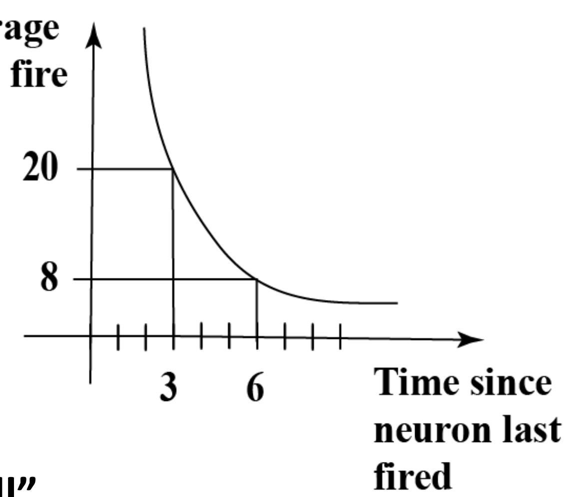
The neurons in self-stimulating loop continue firing until fatigue raises their thresholds to the point that the returning spikes cannot fire them.

A longer loop accumulates fatigue more slowly because the member neurons are firing at a lower frequency; thus a longer loop once started remains firing for a longer time than a shorter loop.



A very simple saccade hierarchy (1).





For this example assume all synpases have close to the same strength.

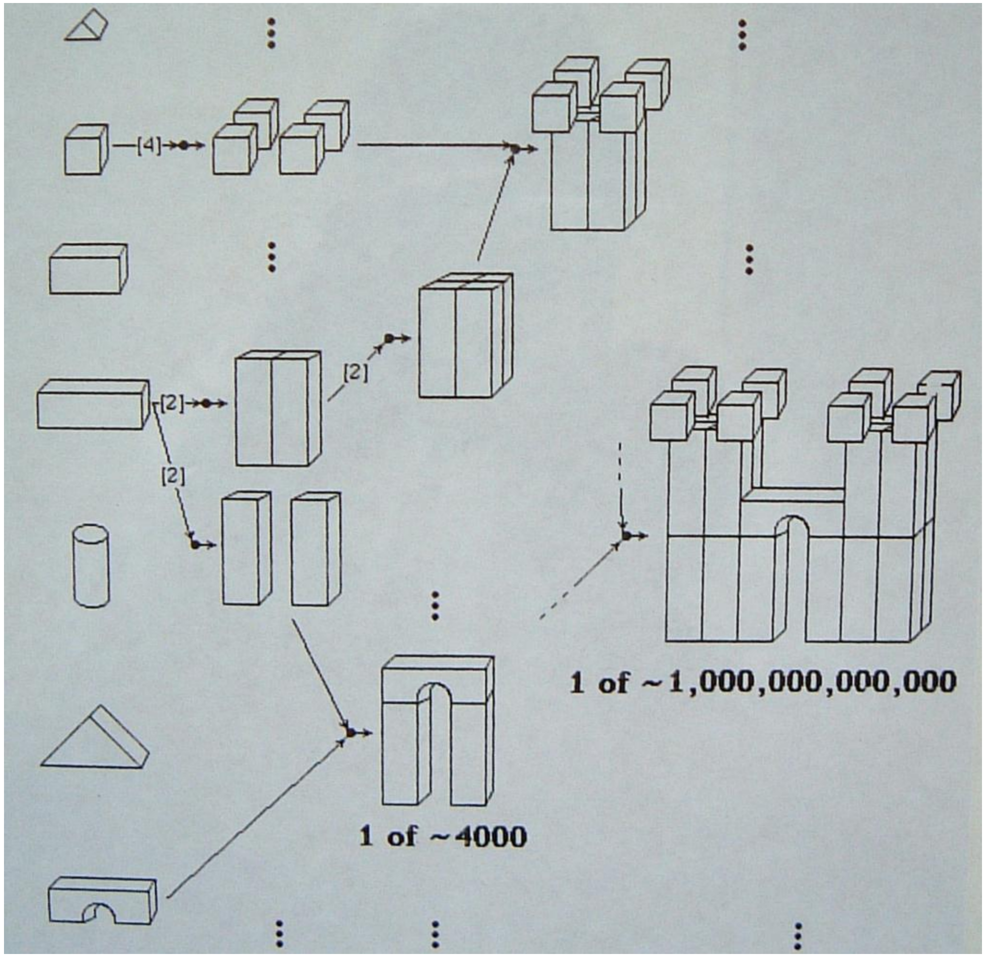
Assume also that:
(i) it takes 20 simulataneous spikes to fire a neuron on time-step 3 (the first time-step after the absolute refractory period).

(ii) it takes 8 simulataneous spikes to fire a neuron on time-step 6 (4 time-steps after the absolute refractory period).

Building Blocks

Loop interaction allows various activities (such as utterances) to act as building blocks for higher order activities (such as utterance sequences).

The Combinatorics of Building Blocks



A very simple saccade hierarchy (2)

Because there are so many loops in even a small section of cortex, loops with the desired hierarchical properties will almost always be present.

Comparison to Current Research

BRAIN, EU (Max Plank), Hidden Layer, IBM (Alamaden)

- **Supervised**
- **Google version**

3 Kinds of Models

Data-driven Models

(e.g. weather prediction)

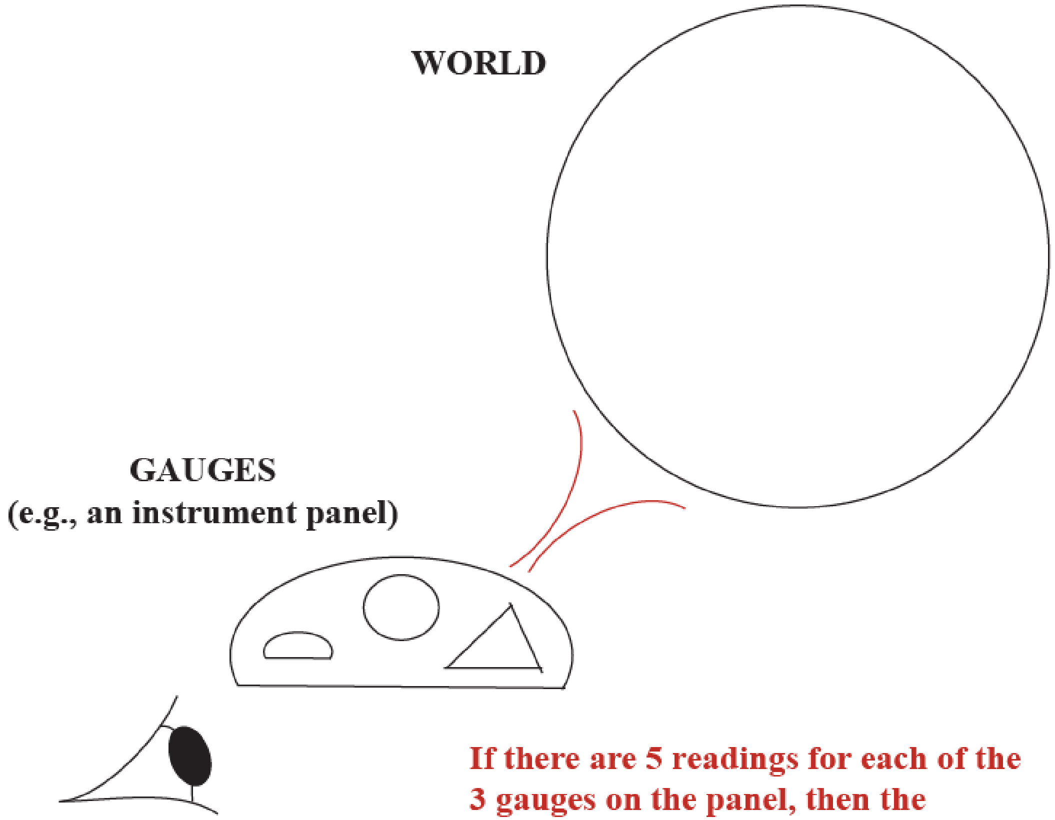
Existence-proof Models

(e.g. von Neumann's self-reproducing machine)

Exploratory Models

(e.g. combinations of well-known mechanisms to form the internal combustion engine)

Observing the World



If there are 5 readings for each of the 3 gauges on the panel, then the model would use $5^3 = 125$ states.

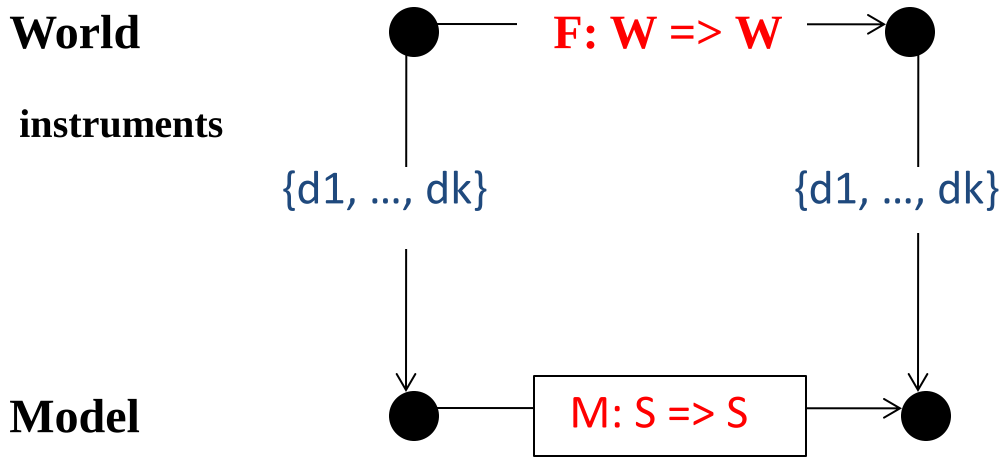
Of course, some readings may not occur in the actual obsevations.

In the model a time between successive observations must also be specified (e.g., if the instrument panel is for an airplane the time interval would be say 1/10 second, while for a telescope it might be months or even years).

Models: Reduction and Emergence

The contemplation in natural science of a wider domain than the actual leads to a far better understanding of the actual.

-- A. S. Eddington



Gell-Mann points out that 3 orders of magnitude in the scale of observations (e.g. from molecules to fluid flow) requires new laws. New laws are *constrained* by, but *not determined* by, the laws at lower levels.

Objective: An agent-based model of language acquisition and evolution

Each agent's survival depends upon its ability to collect resources that are distributed spatially in its environment.

Language has value to the agent only if it increases the agent's ability to collect these resources.

> **There's no explicit a priori value assigned to language.**

Control experiments are possible: The model can be run with and without language acquisition.

Levels of Consciousness

The following discussion of *levels of consciousness* is based on ideas presented to me by Professor Helena Hong Gao, now at NTU Singapore.

Levels of Consciousness – Level 0

'Wired-in' (inherited) cognitive abilities.

Ability to imitate utterances and gestures.

Ability to distinguish between objects and actions.

Awareness of a mutually apprehended salient object or action.

Basic learning procedures (akin to Hebb's learning rule).

IF (any signal) THEN (random effector activity)

Levels of Consciousness – Level 1

Control of motion (as precursor to gesture).

Task: Bring hand in controlled motion across visual field.

Mode: Innate reinforcement for predictable outcomes.

Anticipation: Movement according to command.

IF (hand in vision cone) THEN (<move hand right>)

Levels of Consciousness – Level 2

Utterance for immediate, "wired-in" reward, e.g. 'Teacher's' smile.

Task: Social interaction.

Mode: Imitation of situated utterance.

Anticipation: Positive interaction.

IF (milk bottle present) THEN (<utterance "milk">)

This rule will be strengthened, over other random utterances, because [T-smile] increments sociality reservoir.

Levels of Consciousness – Level 3

Utterance to “move” visible object.

Task: Food acquisition (when food visible).
Mode: Conditioning.
Anticipation: Food.

IF (milk bottle visible) THEN < “milk”>
‘Teacher’ moves milk bottle to mouth.
IF (<milk bottle at mouth>) THEN (<consume milk>)

Levels of Consciousness – Level 4

Utterance to cause appearance of object.

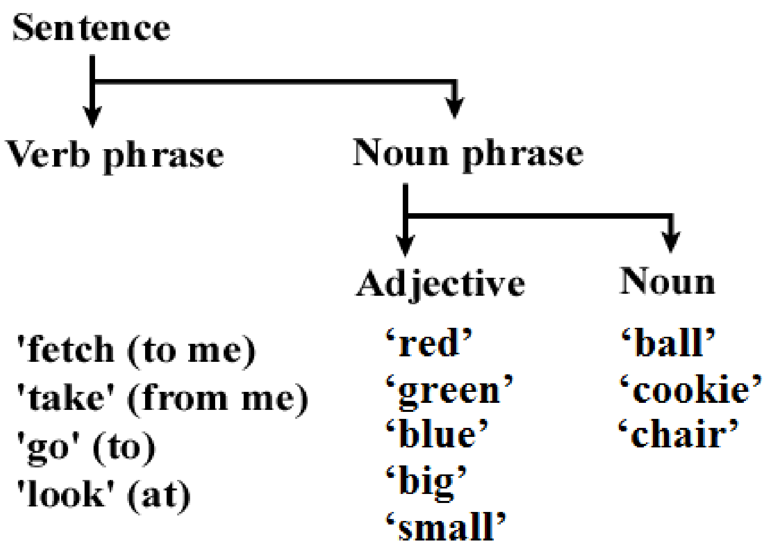
Task: Food acquisition (when food not visible).
Mode: Internal model (lookahead) – autonomy required.
Anticipation: Appearance of food (later generalized to arbitrary objects)

IF ([hungry] & no food visible) THEN <“milk”>
‘Teacher’ acts to fetch milk bottle.
IF (<T acts>) THEN <milk bottle visible>

Acquired from previous levels:
IF (milk bottle visible) THEN < “milk”>
‘Teacher’ moves milk bottle to mouth.
IF (<milk bottle at mouth>) THEN (<consume milk>)

Grammars

A grammar makes possible the combinatoric use of vocabulary.

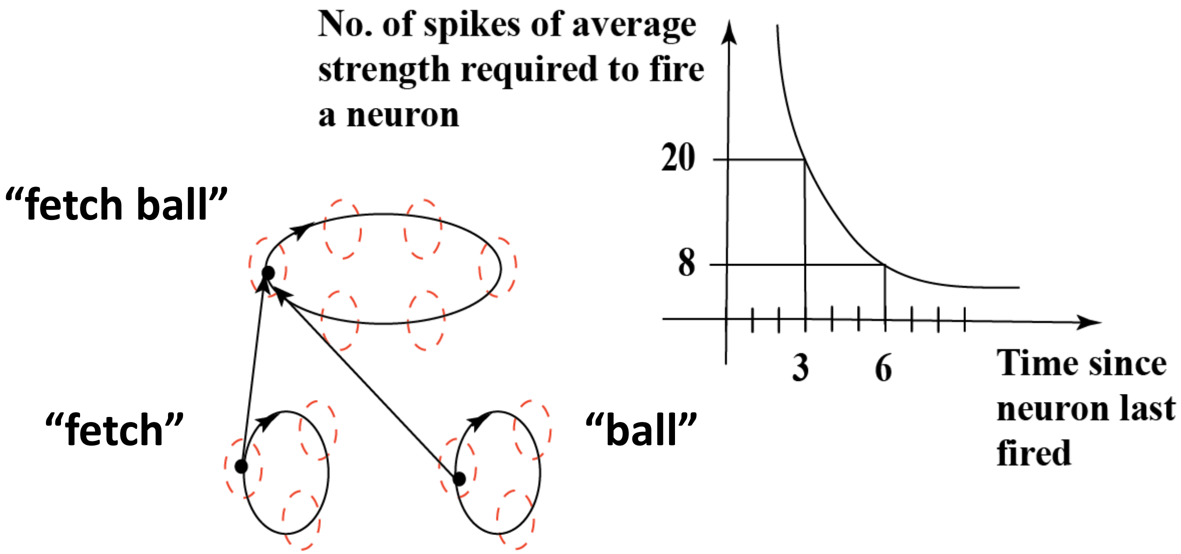


60 meaningful triples can be constructed from the 12 utterances shown.

If there are 10 utterances in each category, 1000 meaningful triples can be constructed, and so on.

Recall CNS Loop Interactions
(toward formation of sentences)

A very simple saccade hierarchy (1).



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Steps in Learning a Proto-Grammar

1) **Acquisition of vocabulary.**

Babbling (random action) samples possibilities (diversity) for attaching utterance to situation.

Some inputs invoke imitation (e.g., 'shared salient object or action', 'Teacher' utterance)

'Meaning' emerges from generalization of conditions associated with the same utterance.

2) **Acquisition of specific utterance pairs.**

Sequences reduce ambiguity.

3) **Generalization of sequences to 'grammatical' rules.**

Highlights of Language Model

- **The proposed exploratory model is a signal-processing, agent-based model situated in a environment.**

- **The survival of the agents, and hence of any structured proto-linguistic means of communication, depends upon the agents' ability to collect resources in the environment.**

- **The capacities of any agent are completely determined by a set of condition/signal rules.**

- **Each agent**
  - **uses general-purpose triggering mechanisms (akin to imprinting) to build default hierarchies**

  - **supports goals and sequential action through the formation of bridging rules**

  - **uses a genetic algorithm to explore the space of possible rules by recombining parts of extant rules**

Three Lines of Research

Consciousness

loops in CNS

Symmetry-breaking and the origin of hierarchies

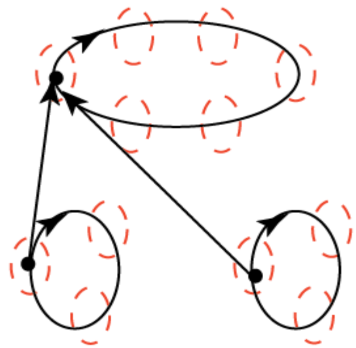
gated urn models

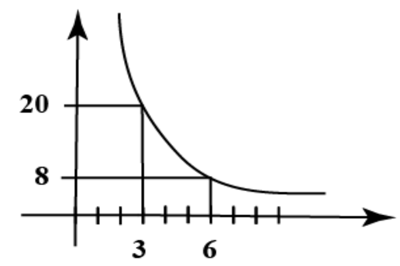
Control via saccades

mammalian vision

Additional Details

A very simple saccade hierarchy (2).





A self-stimulating 3-loop requires 20 simultaneous pulses/ neuron because the returning pulses arrive just after the absolute refractory period.

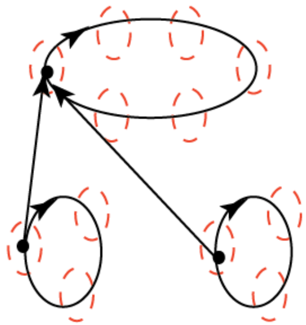
The 3-loop will continue firing until the neurons in the loop accumulate enough fatigue to raise the threshold above the required number of incoming pulses.

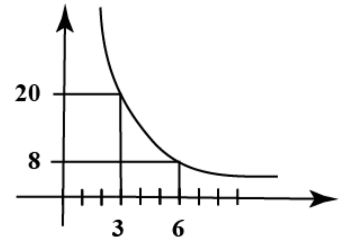
A self-stimulating 6-loop requires only 8 simultaneous pulses because of the longer delay in the return.

Fatigue accumulates more slowly in the 6-loop because of the lower firing rate.

In the hierarchical arrangement the 6-loop remains firing through both firing cysles of the lower level 3-loops.

A very simple saccade hierarchy (3).





Assume for each neuron in one subset in the 3-loop that 8 of the 20 required pulses come from a still lower level, say from detectors activated by a pattern in the environment.

For example, the pattern could be detected by 3 eye saccades.

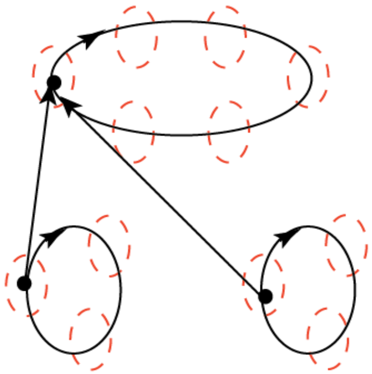
Then the 3-loop will only be activated when the 8 required pulses from the lower level are present. In effect, the 3-loop *represents* the lower level pattern.

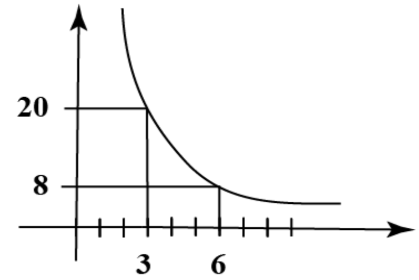
Assume further for each neuron in one subset of the 6-loop that 2 of the required pulses come via connections to the lower level 3-loops.

One or the other of the 3-loops must be active for the 6-loop to be active.

The 6-loop *represents the sequence* of two patterns presented to the 3-loops (caused, for example, by a saccade between the two patterns).

A very simple saccade hierarchy (summary).





The particular circuit connections between the neurons in this loops hierarchy represent the presence of a pair of patterns that are always linked by saccades.

Because there are so many loops in even a small section of cortex a circuit with the desired properties will almost always be available.

Note that, a connection between an active neuron in one 3-loop and a fatigued neuron in the other 3-loop will continually decrease in strength under Hebb's rule ("a fires and b does not fire").

In due time the two 3 loops will become cross-inhibitory (synapses of negative value) preventing the two 3-loops from being active at the same time.