How to build a brain

Cognitive Modelling

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So far...

- We have learned how to implement
  - high-dimensional vector representations
  - linear transformations
  - nonlinear transformations
  - recurrent, dynamic networks
The semantic pointer architecture uses these building blocks to construct cognitive models.

Three things to outline:

- Semantics
- Syntax
- Control
Semantic pointers are: Compressed, content-based ‘addresses’ to information in association cortices

‘Pointer’ because they are used to recall ‘deep’ semantic information (content-based pointer)

‘Semantic’ because they themselves define a ‘surface’ semantic space
SPA: Semantics

- E.g. The pointer would be the activity of the top level of a standard hierarchical visual model for object recognition.
- This pointer can then support 'symbol' manipulation.
- It can also be used to reactivate a full visual representation.

Serre et al., 2007 PNAS
SPA: Surface/deep semantics

- Applied to numbers: a) neuron tuning; b) generic SPs; c) input; d) reconstruction; e) surface semantics

a)

b)

0123456789

c)

6724521811
8370893790
1014195621

d)

6724521811
8370893790
1014195621

e)
Solomon & Barsalou (2004) showed that false pairings that were lexically associated take longer to process (e.g. dog-card 100ms quicker than banana-monkey).

Kan et al. (2003) fMRI observed activation in perceptual systems only in the difficult cases.

Deep processing is not needed when a simple lexically-based strategy is sufficient to complete the task.
SPA: Syntax

- Vector Symbolic Architectures (VSAs)
- Smolensky’s Tensor Products
- Kanerva’s Spatter Codes
- Gayler’s Multiply, Add, Permute (MAP) method
- Plate’s Holographic Reduced Representations (HRRs)
Structure representations

- All VSAs have some combination of 3 operations
  - Multiply (bind)
  - Add (compose)
  - Hide (protect from other vectors)

- Chosen VSA: HRRs
  - Constant vector length
  - Protect and bind happen in 1 step
  - Real valued
Structured representations

- HRRs (Plate, 1991; circular convolution)

- Circular convolution (binding)
  \[ C = A \otimes B \]
  \[ c_j = \sum_{k=0}^{n-1} a_k b_{j-k} \]

- Circular correlation (unbinding)
  \[ B \approx A \oplus C \]
  \[ b_j = \sum_{k=0}^{n-1} a_k c_{j+k} \]
  \[ A \oplus C \approx A' \otimes C \]
Circular convolution

- Circular convolution in the frequency space is piece-wise multiplication:

\[ \text{FFT}(A \otimes B) = \text{FFT}(A) \cdot \text{FFT}(B) \]

- Must use complex numbers, where

\[ a \ast b = (a_1 + a_2i) \ast (b_1 + b_2i) \]
Neural implementation

- Note first \( A \otimes B = W_{IFFT}(W_{FFT}A \cdot W_{FFT}B) \)

\[
\omega_{ik} = \alpha_k \tilde{\phi}_k W_{FFT} \phi_i \\
\omega_{jk} = \omega_{lk} = \alpha_l \tilde{\phi}_l W_{IFFT} \phi_k
\]
Circular convolution results

Circular Convolution for 6D Vectors
Circular convolution
To perform simple lexical processing, we need to ensure the result is a valid semantic pointer.

Because our chosen VSA is ‘reduced’, the output is typically not identical to a valid ‘answer’, so we need to ‘clean up’ the results.

Elsewhere we have presented a fast spiking network solution to this (Stewart et al., 2010).

Nengo includes an idealization of this to help build models.
Two main control issues in the brain:

- Choosing the next best thing to do (action selection)
- Applying the action to control the flow of information (routing)
The basal ganglia has been implicated in action selection.
• $M$ compares the cortical state with known SPs
• $M_t$ maps selected action to cortical control states
SPA: Action selection

- Timing predictions based on GABA neurotransmitter time constant (simple actions)
Simple action selection isn’t enough, we need to control the flow of information through the system.

A ‘gating’ operation is ubiquitous (e.g. attention, sequencing, prioritizing, etc.)

The controlled integrator is a simple 1D example (when A is zero and 1)

We can add content to the control signal with a convolution network
SPA: Question answering

- Sentence: “There is a red circle and blue triangle”
  \[ S = \text{sentence} + \text{red} \otimes \text{circle} + \text{blue} \otimes \text{triangle} \]

- What is red?
  \[ \text{Ans} \approx \text{red}' \otimes S \]

- Transformation: make the red thing a square
  \[
  \text{convert} = \text{square} \otimes (\text{red}' \otimes S)'
  \]
  \[ \text{Ans} \approx \text{convert} \otimes S \]
  \[ \approx \text{sentence} + \text{red} \otimes \text{square} + \text{blue} \otimes \text{triangle} \]
SPA: Control states*

- Timing predictions based on GABA neurotransmitter time constant (complex actions)
Conclusion

- The SPA/NEF addresses several neurally realistic cognitive modelling challenges
  - High-dimensional processing, control, syntax, semantics, statistical inference, relation to single cell models, network and cellular dynamics, etc.
  - Scales very well (Stewart & Eliasmith, 2010)
  - A nascent research approach that is flexible and unifying