

# Convolution-Based Model for Serial Order Memory

Presented By:  
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# Disclaimer

This presentation requires audience interaction.  
Be prepared to participate!

**Remember this!**

**7 6 8 8 1 3 6**

# Outline

- Introduction to Serial Recall
- Current State of Field
- The CADAM Model
- Struggles and Revelations!
- Simulation Results
- Future Work
- Questions

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# Intro to Serial Recall

## What is serial recall?

- Recall of information in which order matters
  - Telephone numbers
  - Credit card numbers
  - The Alphabet
  - Etc
- Why is it important?
  - Learning language
  - Motor actions
  - Learning music?

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What is serial recall?

It is the recall of information where order matters.

For example, telephone numbers, credit cards, your student number, the alphabet, songs, your schedule ...

Why is it so important?

Researchers think it is used in learning of languages

- Letter order in words, word order in sentences, etc

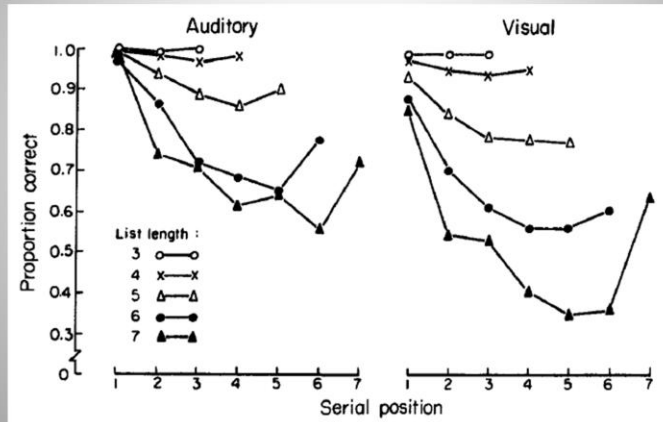
Motor actions

- Learning predefined motor actions (writing?)

Learning music?

# Human Performance

- Primacy and Recency effects



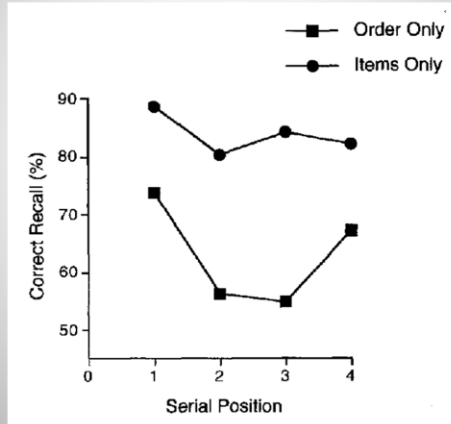
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Primacy effect: Recall accuracy increases as items get closer to start of sequence  
 Recency effect: Recall accuracy also increase (but not as much) towards end of list

# Human Performance

- Free recall



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Free recall

- Recall without constraint to order
- No primacy or recency effects here!

## **Remember those numbers?**

- Write them down on the piece of paper you have in front of you. (white squares)
- Then turn the paper over.



OutlineSerial Recall**Current Research**CADAM ModelRevelations!Simulation ResultsFuture WorkQuestions

## Current State of Field

- Convolution-Based Models
  - CADAM (1977)
  - TODAM (1982)
  - TODAM 2 (1992)
- Other Models
  - Oscillator Based Model (2000)
  - Recurrent Network Model (2006)
  - Gain Field Model (2007)

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Here are some of the more well known models of serial recall

- Will elaborate on the convolution based models to give a general idea of how they work

Outline
Serial Recall
**Current Research**
CADAM Model
Revelations!
Simulation Results
Future Work
Questions

# CADAM

- Notation:
  - Convolution: \*
  - Correlation: #
  - Memory Trace: **M**
  - Presented Item: **I**
- Storage:
$$\mathbf{M}_i = \alpha \mathbf{M}_{i-1} + \sum_{n=1}^i \mathbf{I}_n$$

where  $\sum_{n=1}^i \mathbf{I}_n = \mathbf{I}_1 * \mathbf{I}_2 * \dots * \mathbf{I}_i$

  - E.g. A three item list: **ABC**
$$\mathbf{M} = \mathbf{A} + (\mathbf{A} * \mathbf{B}) + (\mathbf{A} * \mathbf{B} * \mathbf{C})$$

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Alpha is a forgetting parameter!

Note: This is in regular convolution, circular convolution operations are the same

## CADAM – Cont.

- Retrieval:

$$\sum_{n=1}^{j-1} I_n \# M = I'_j \rightarrow I_j$$

- Example retrieval from sequence **ABC**:

$$M = A + (A * B) + (A * B * C)$$

$$\delta \# M = A' \rightarrow A$$

$$(\delta * A) \# M = B' \rightarrow B$$

$$(\delta * A * B) \# M = C' \rightarrow C$$

- Note:  $\delta = [0 \dots 0 \ 1 \ 0 \dots 0]$

## TODAM aka Chaining

- Storage:  $M_i = \alpha M_{i-1} + I_i + I_i * I_{i-1}$

– E.g. A three item list: **xABC**

$$M = x + A + (A * x) + B + (B * A) + C + (C * B)$$

- Retrieval:

$$I_j \# M = I'_{j-1} + I'_{j+1} \rightarrow I_{j+1}$$

$$x \# M = A' \rightarrow A$$

$$A \# M = x' + B' \rightarrow B$$

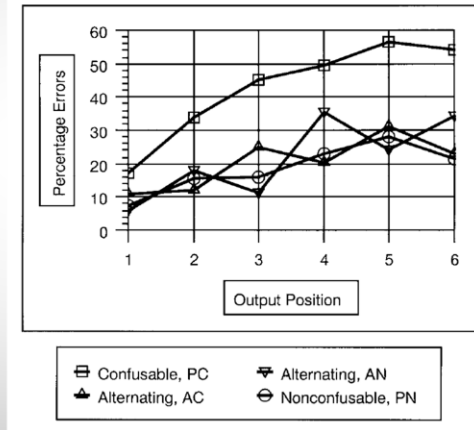
$$B \# M = A' + C' \rightarrow C$$

Because of chaining -> requires a “initiation” signal

## TODAM – Problems

Chaining has major problems

- Accuracy of items recall depends on recall accuracy of preceding items
- Possibility for loops



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Chaining model problems

-The recall accuracy of items depends on the recall accuracy of preceding items. This contradicts human data where confusable items do not affect recall of subsequent items

-Also, possible for loops to occur within recall

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## TODAM 2

- Encoding:
  - It's super complicated!  
(So here is an example instead)
  - E.g. A three item list: ABC

$$M_1 = A$$

$$M_2 = A + (A + B)^2 = A + (A + B) * (A + B)$$

$$= A + A*A + 2A*B + B*B$$

$$M_3 = A + (A + B)^2 + (A + B + C)^3$$

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Involved chunking and addition of chunks.

Each chunk is a the autocorrelation of the addition of all previous items

## Chunking Model (Simplified)

- Information Retrieval:

$$\delta \# M = A' \rightarrow A$$

$$A \# M = A' + 2B' \rightarrow B$$

$$(A*B) \# M = 3A' + 3B' + 6C' \rightarrow C$$

## More Numbers!

- First, on the paper with grey squares, write down the numbers from the previous set.
- Are you ready for the next set?  
(It won't matter if you are color blind)





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## Back to the CADAM Model!

- Used for this project
  - First convolution-based model
  - Simple to implement
  - Does not rely on chaining
- So, how do we make this work in neurons?
  - Simple! We just need to convert these formulas into neurons!

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-The CADAM model was the first convolution based model proposed.  
It can also be used to form associative memory traces  
It is very simple to implement, and does not rely on chaining.

## CADAM to Neurons

- Let's start with the storage equations
  - Re-write the equations:

$$\mathbf{M}_i = \alpha \mathbf{M}_{i-1} + \prod_{n=1}^i \mathbf{I}_n$$

where  $\prod_{n=1}^i \mathbf{I}_n = \mathbf{I}_1 * \mathbf{I}_2 * \dots * \mathbf{I}_i$

$$\mathbf{M}_i = \alpha \mathbf{M}_{i-1} + \mathbf{C}_i$$

where  $\mathbf{C}_i = \mathbf{C}_{i-1} * \mathbf{I}_i$

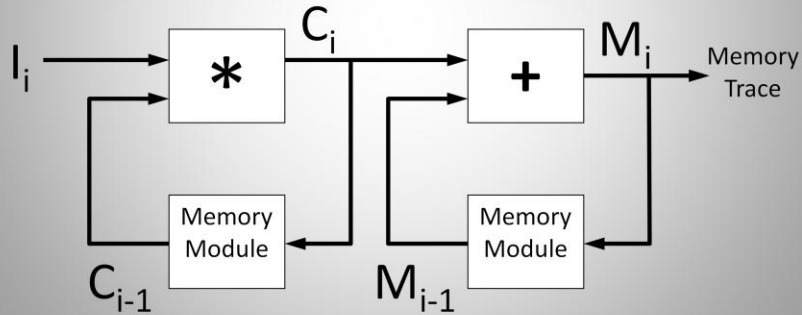
Equations are rewritten to exploit memory use in circuit

## CADAM to Neurons Cont.

$$M_i = \alpha M_{i-1} + C_i$$

$$\text{where } C_i = C_{i-1} * I_i$$

- From the equations, design a network:



## CADAM to Neurons

- Now for item retrieval:
  - Rework the formulas a bit

$$M_{ABC} = A + (A * B) + (A * B * C)$$

- Here is the first iteration:

$$M_{ABC} \rightarrow A$$

$$C = M_{ABC} - A = (A * B) + (A * B * C)$$

$$C \# A = (B + (B * C))' = M_{BC}$$

New method of decoding is derived.  
Basically a loop, first iteration is show

## CADAM to Neurons

- The example:

$$M_{ABC} \rightarrow A$$

$$C = M_{ABC} - A = (A * B) + (A * B * C)$$

$$C \# A = (B + (B * C))' = M_{BC}$$

- The formulas:

$$M_{i-1} \rightarrow I_i$$

$$C_i = M_{i-1} - I_i$$

$$M_i = C_i \# I_i$$

## CADAM to Neurons

- Why not the original formulas?

$$\delta \# M = A' \rightarrow A$$

$$(\delta * A) \# M = B' \rightarrow B$$

$$(\delta * A * B) \# M = C' \rightarrow C$$

- Easier to compute:
  - New method does not require convolution and correlation operation (just requires one correlation)
- Results are the same

## **Remember the colored numbers?**

- Write them down on the piece of paper you have in front of you. (white squares)
- Then turn the paper over.

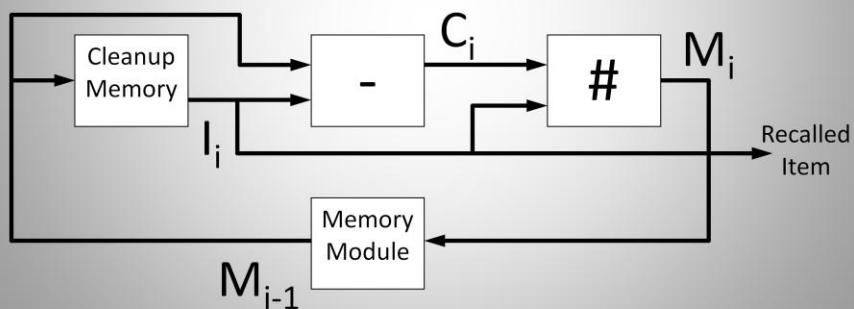
## CADAM to Neurons

- Item retrieval network:

$$M_{i-1} \rightarrow I_i$$

$$C_i = M_{i-1} - I_i$$

$$M_i = C_i \# I_i$$





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## CADAM to Neurons

Issues to solve:

- Memory Module
- Cleanup Memory

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Note that the convolution and addition circuitry is feedforward, so the memory module needs to be able to store values from the current cycle, while outputting the value from the previous cycle.

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# Struggles

- Memory Module
  - How to store a value while outputting old value as well?
  - Put two memory cells in parallel, and gate them!

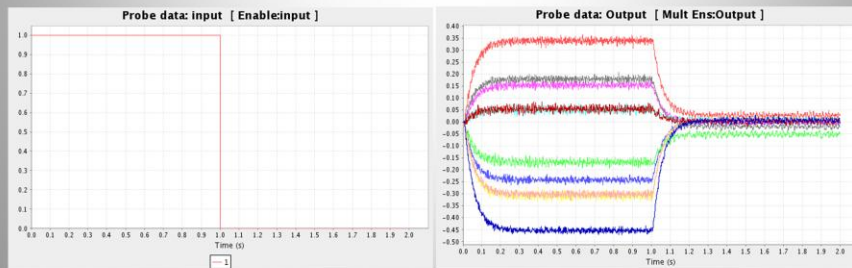
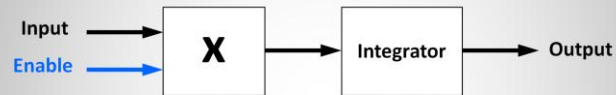
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Other circuits were also tried:

- Playing around with time constants
- Chaining memory cells

# More Struggles!

- How to create a gated memory cell?!
  - Try using a multiplier

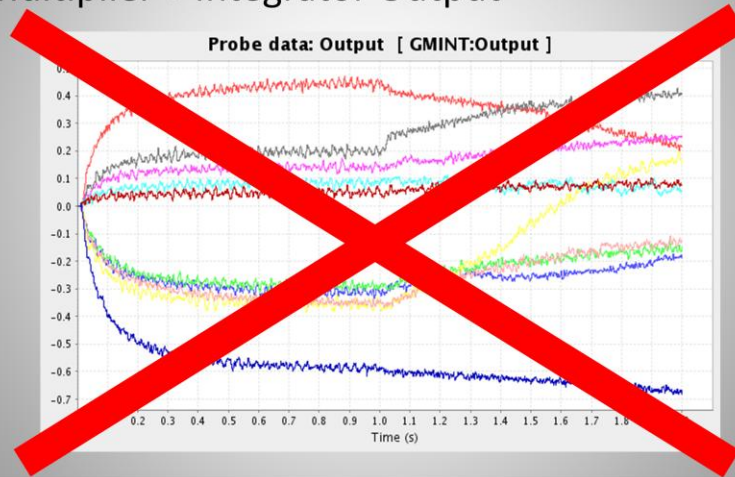


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## Struggles Cont.

- Multiplier + Integrator Output




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## The Month+ of Frustration

- How about a controlled integrator?



- ~~• Integrator with modified response curves~~
- ~~• Integrator with modified response curves + the multiplier~~
- ~~• Integrator with modified response curves + multiplier with modified response curves~~

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Controlled integrator, from NEF book

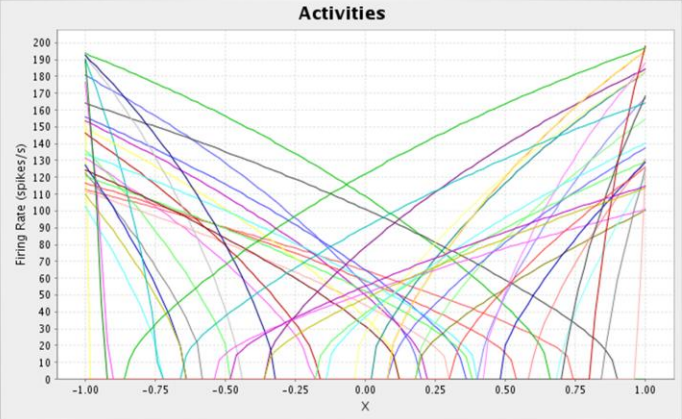
Modified response curves, with zero activity at  $x = 0$  for both on and off neurons

Also tried cross-connecting two memory cells, like in a flip flop

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## Back to the Basics

- How does an ensemble represent values?

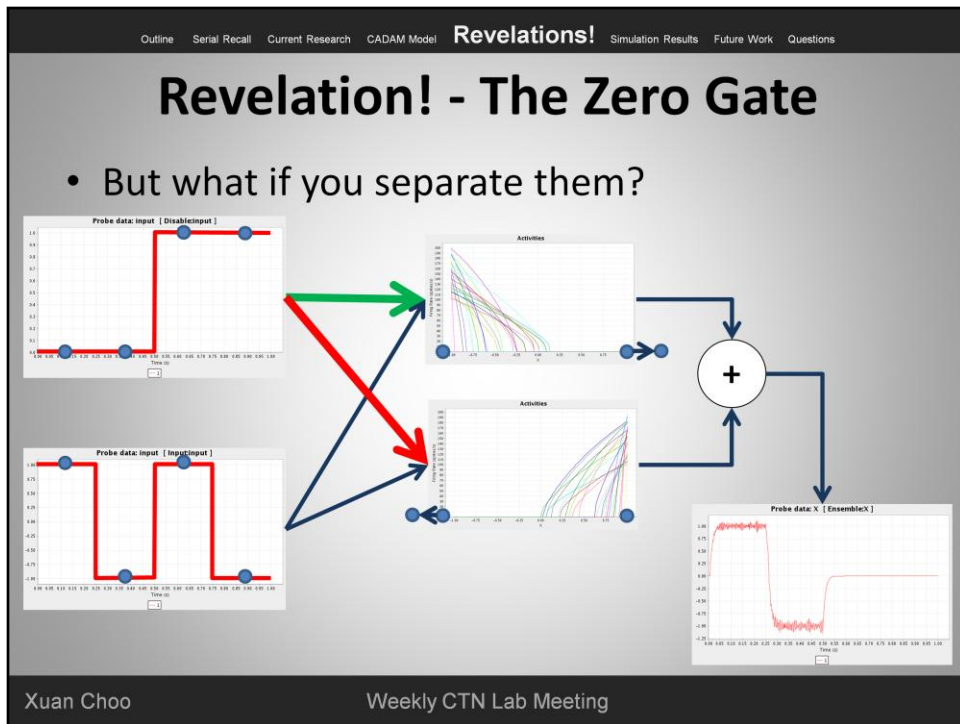


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Ensembles have two sets of tuning curves, on & off.

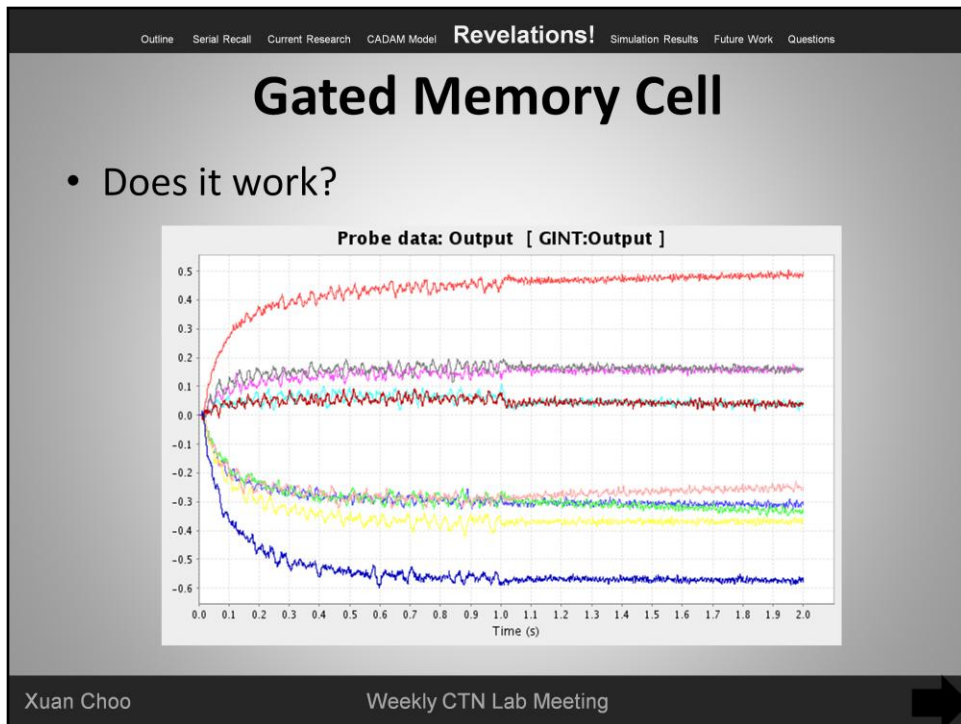
- On neurons are good at representing positive values
- Off neurons are good at negative values
- But with their powers combined, they can represent anything! (The strength of the NEF, and the issue that is causing the problem here)



So we separate the on / off populations, and provide a gating signal to each.

\*\* Point on slide how the input signal changes activity response

- When disable signal is high,



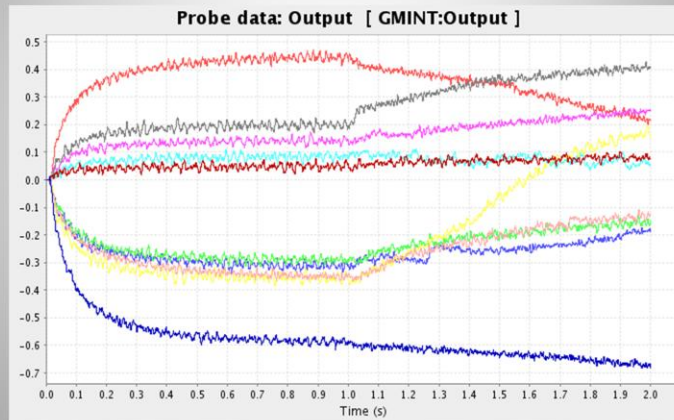
Click black arrow to compare differences

And from C. Anderson's talk, seems like it is also found within the brain!



# Lets Compare!

- Multiplier + Integrator Output



## Last set, I promise!

- On the paper with grey squares, write down the numbers from the previous set (colored numbers).
- Are you ready for the next set?



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## Cleanup Memory

$$\mathbf{M}_{i-1} \rightarrow \mathbf{I}_i \qquad \mathbf{C}_i = \mathbf{M}_{i-1} - \mathbf{I}_i \qquad \mathbf{M}_i = \mathbf{C}_{i-1} \# \mathbf{I}_i$$

- Take the dot product with all the items in cleanup memory
- Find the maximum dot product
- Match to item

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Needs to find the maximum dot product because need to always have result.  
If no result (ie  $l_i = 0$ ), formulas will crap itself in the next cycle

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## A Slight Problem

- Finding the maximum dot product
  - Basic winner-take-all circuit

The diagram illustrates a basic winner-take-all circuit. An 'Input' line on the left branches into three horizontal paths, each entering a box labeled 'Dot Product with Item 1', 'Dot Product with Item 2', and 'Dot Product with Item 3' respectively. Each box has a feedback loop on its top that returns to its input. Additionally, there are vertical double-headed red arrows between each box, representing lateral inhibition. A curved red arrow on the right side points from the output of the 'Dot Product with Item 1' box back to its input, indicating a recurrent connection that maintains the current state.

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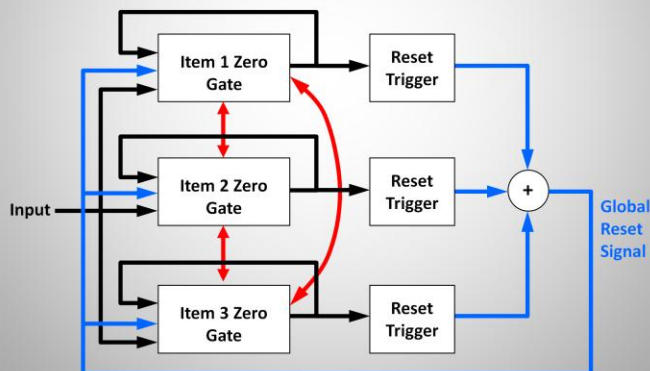
Red lines indicate lateral inhibition

Note the feedback

Problem: Once the maximum has been found, the recurrent connection will maintain it, even if input changes!

# Cleanup Memory

- How to fix?
  - Replace ensembles with zero gates
  - Add a reset circuit!

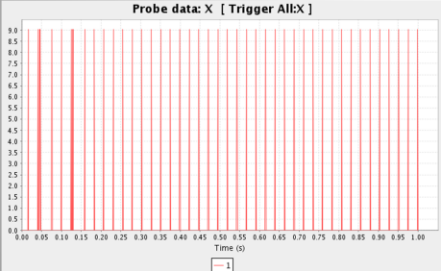


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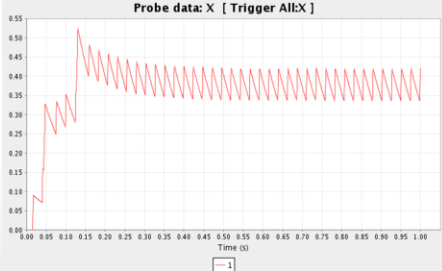
# Cleanup Memory

- Re-use the reset signal to determine which item “won”!

Probe data: X [ Trigger AllX ]



Probe data: X [ Trigger AllX ]

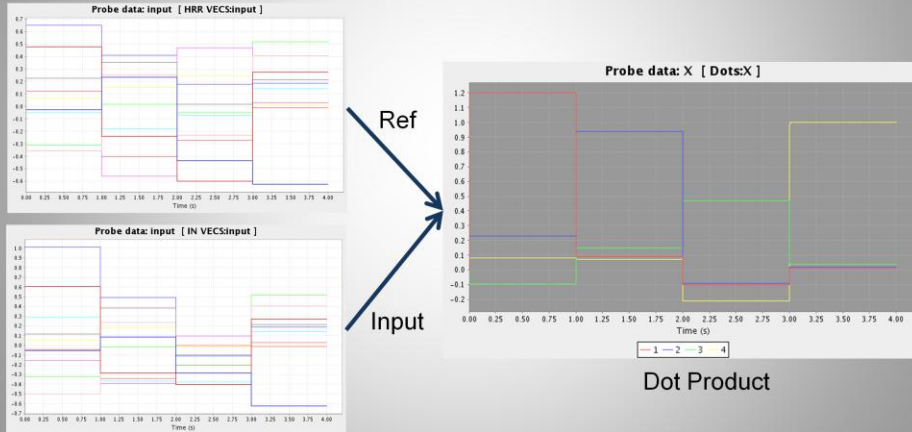


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Filter and feed the reset signal to a circuit that will select the correct item...

# Cleanup Memory

- Testing the network:

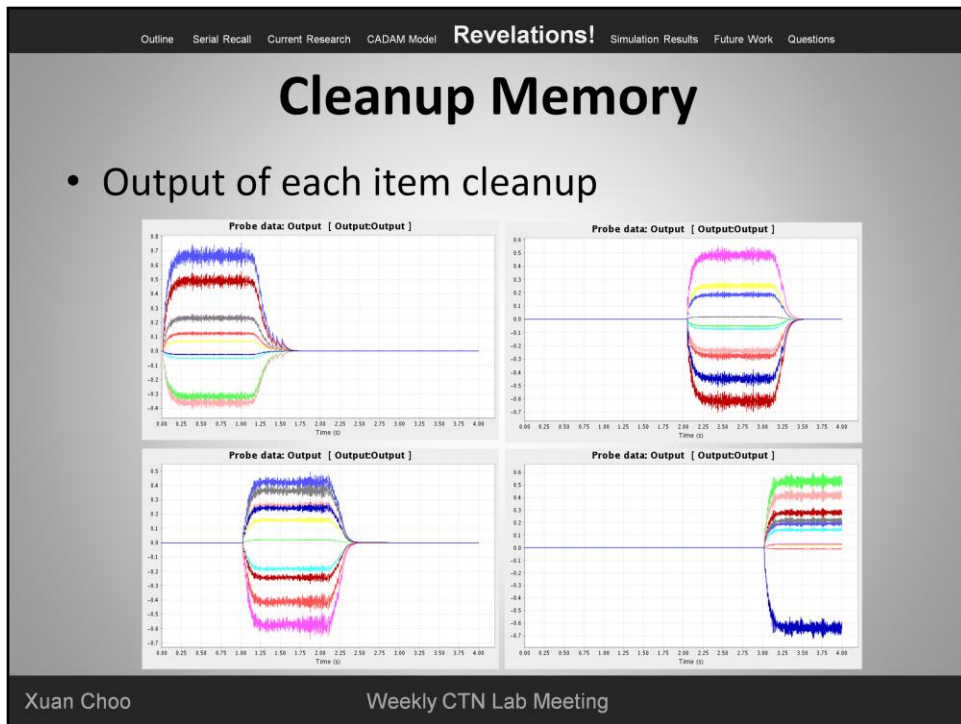


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The dot product indicates which item should be chosen.

- First 1 second, #1, after that, #2, etc, etc -> See diagram dot product.



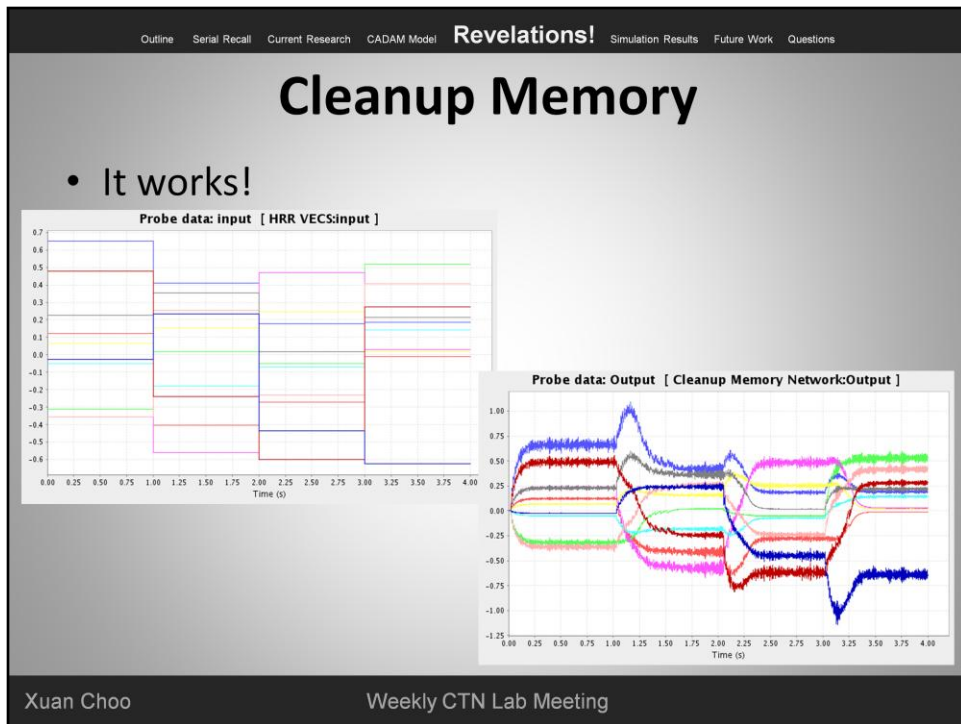
This is the output for each item ensemble in cleanup memory.

Top Left: Item 1, Top Right: Item 2

Bot Left: Item 3, Bot Right: Item 4

Note that all the item ensembles perform as expected.

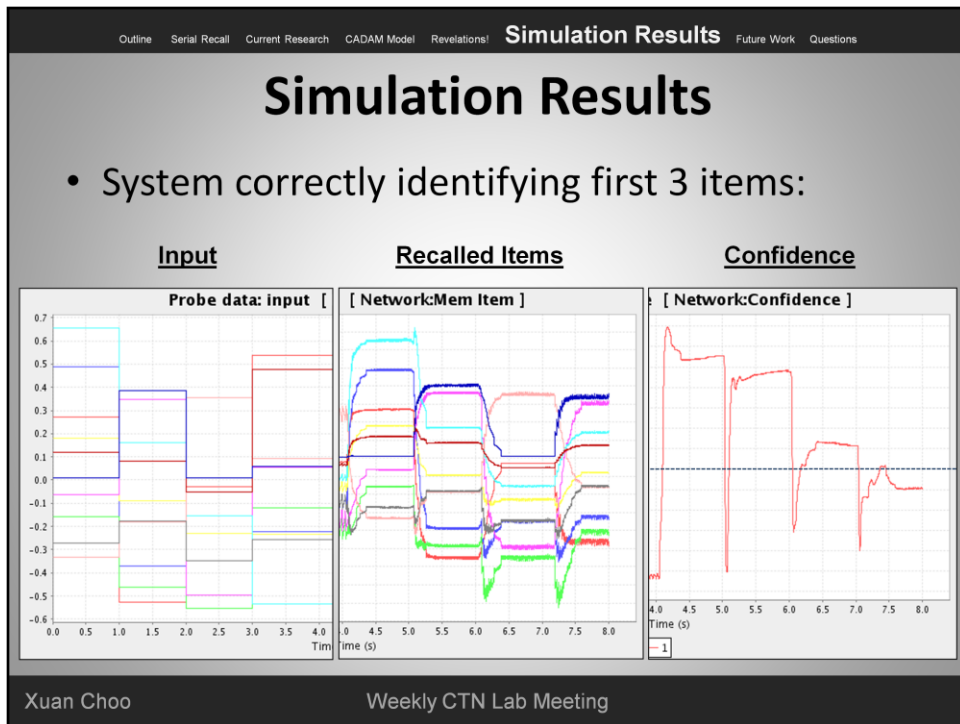




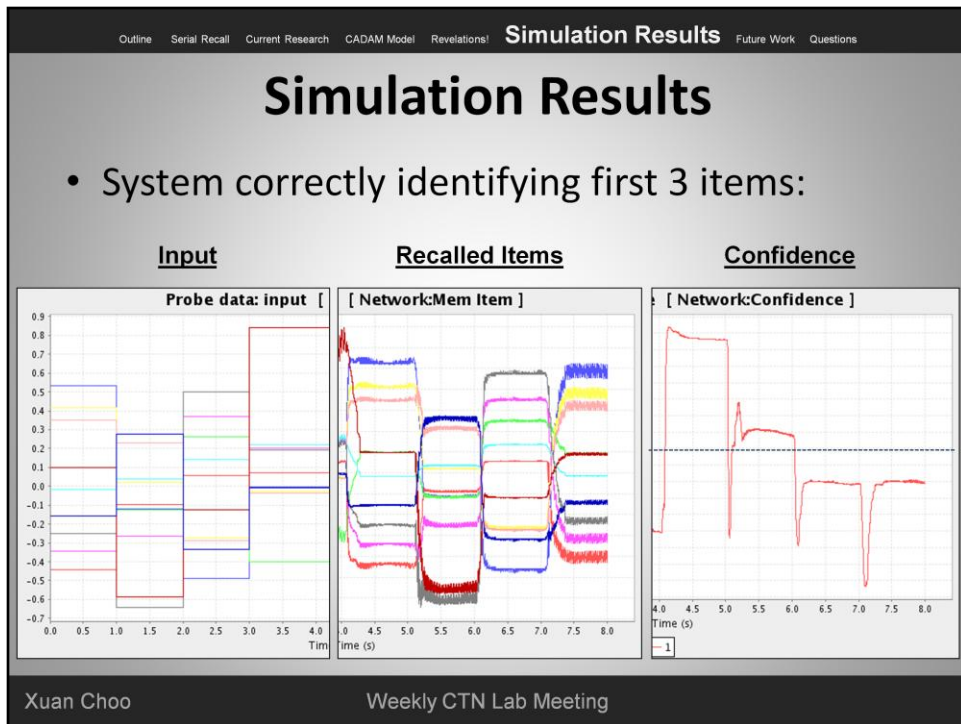
There is a comparison of the reference vectors (vectors placed in cleanup memory) with the output of the circuit selecting item 1, 2, 3 then 4 (from previous slide).

## **Almost there!**

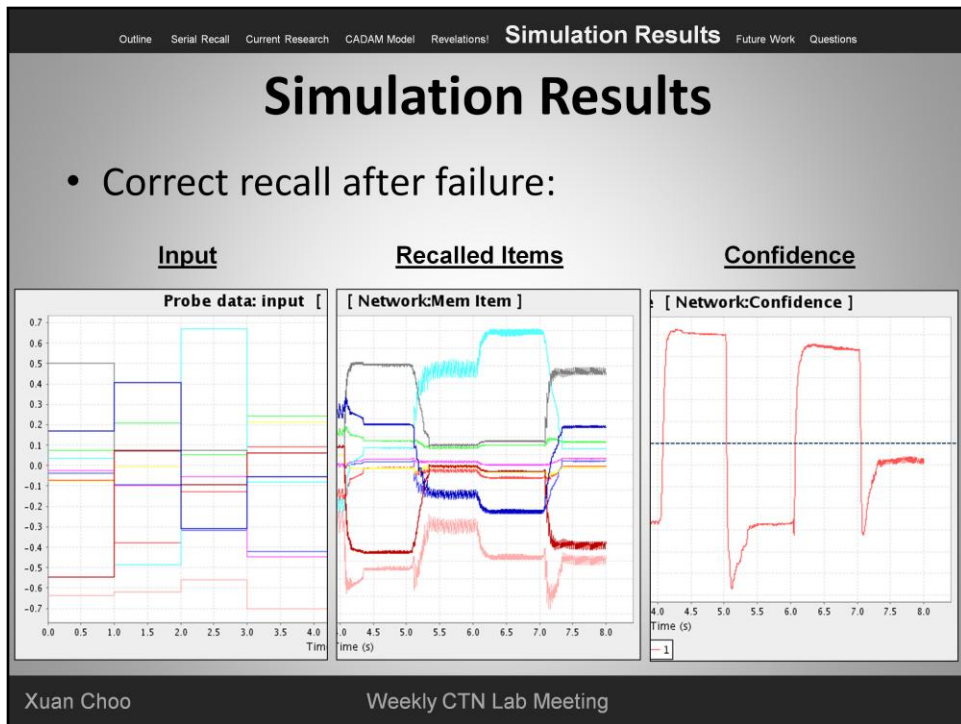
- Write down the numbers from the last set on the piece of paper you have in front of you. (white squares)
- Then turn the paper over.



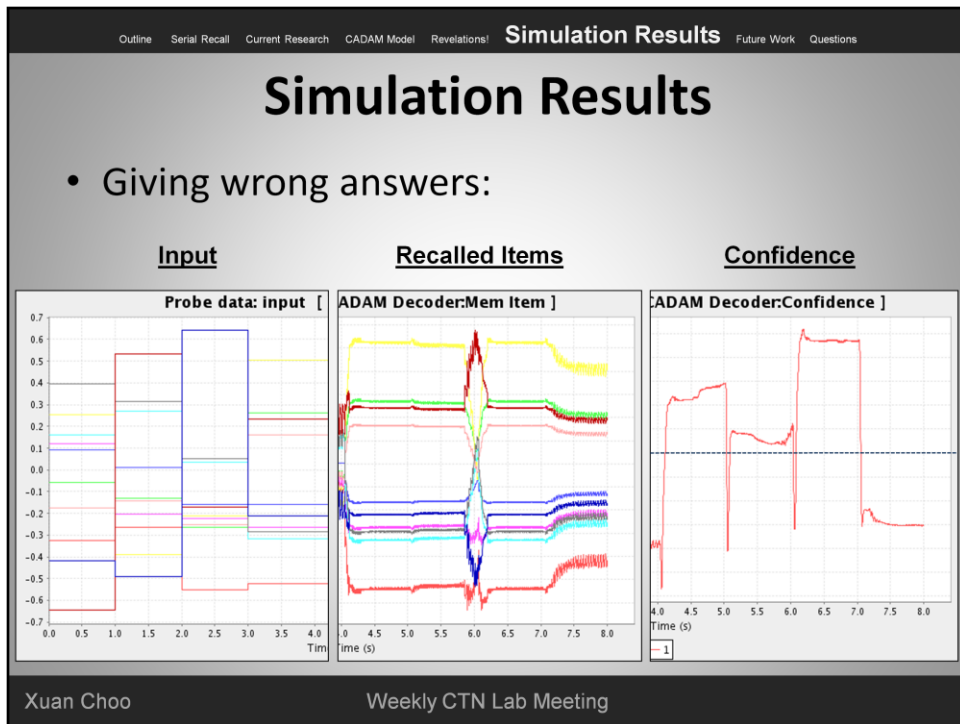
System correctly identifies items with above threshold confidence  
 Note the confidence threshold is arbitrary  
 Above confidence output can mean the subject indicated a response  
 Below threshold can mean the subject failed to recall, or skipped item



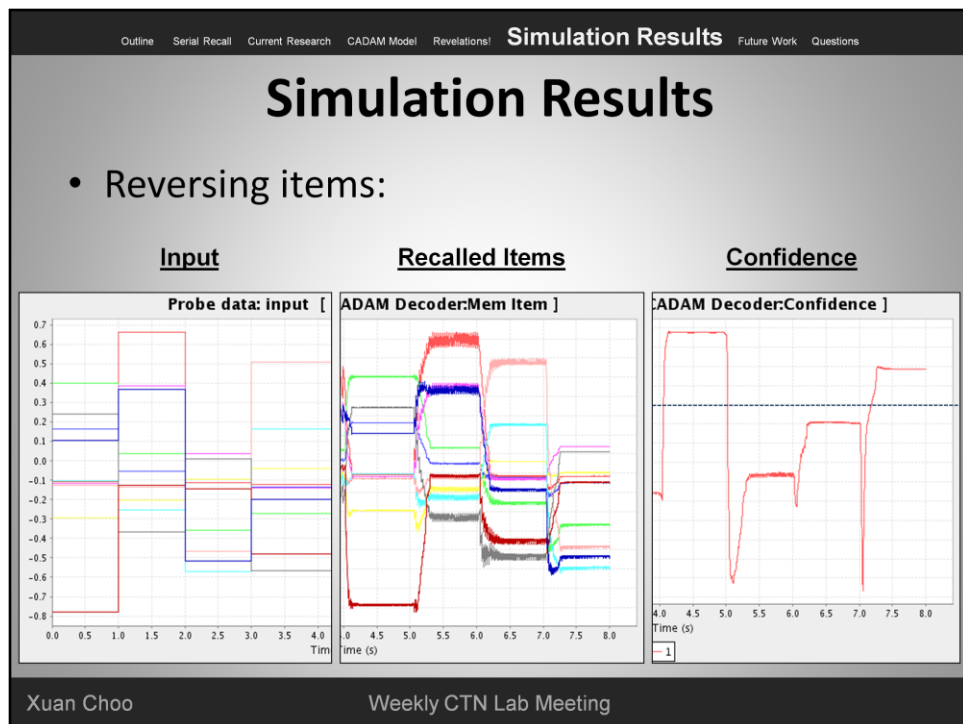
System correctly identifies items with 3<sup>rd</sup> item below confidence



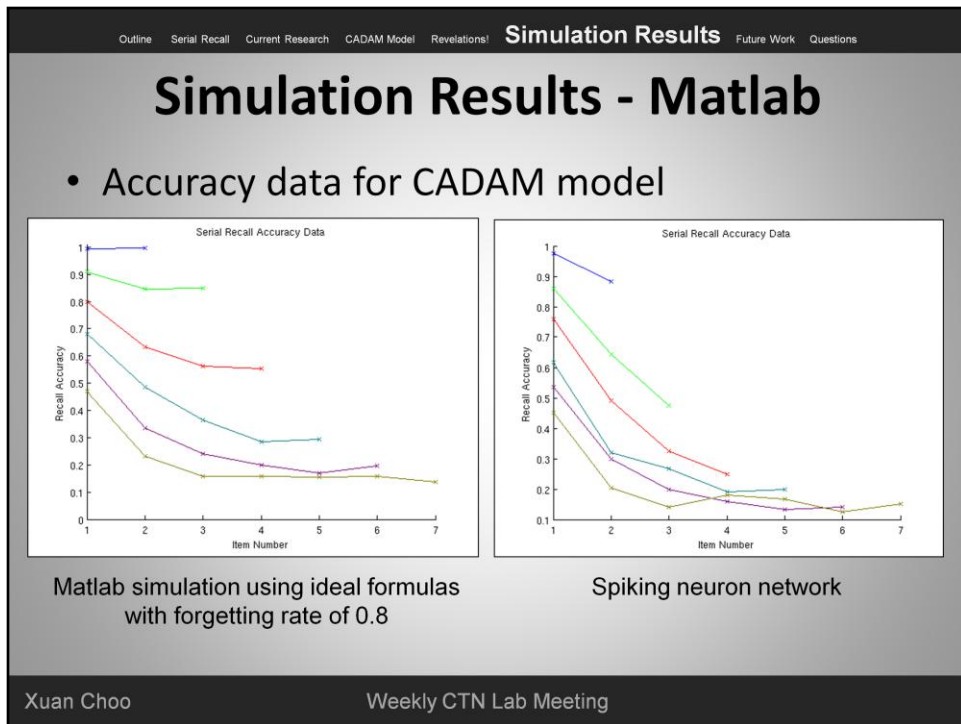
System is able to recall 3<sup>rd</sup> item after failure to recall 2<sup>nd</sup> item. Can be thought of as skipping the 2<sup>nd</sup> item.



System gets everything wrong! (And is confident about it)



Last two items are reversed.



Lack of recency effects. =(

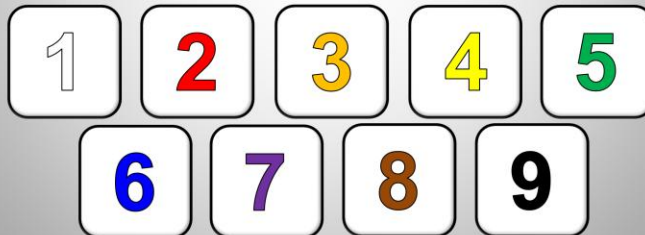


## Future Work

- Need to improve / redesign cleanup memory
  - Cleanup memory items are hard-coded
  - Needs one set of ensembles per item
  - “Over engineered”
- Lack of recency effects
- Unable to perform:
  - Free recall
  - Backwards recall
  - Recall from arbitrary position in list

## Phew!

- On the paper with grey squares, write down the numbers from the previous set (colored numbers).
- This time, I will provide the number – color association:



## Tally your scores

- Answers:
  - Seq 1: 7 6 8 8 1 3 6
  - Seq 2: 3 8 5 5 1 9 4
  - Seq 3: 8 6 4 2 2 1 7
- For each sequence, count the number of items you got in the right spot.
- Which sequence did you get most correct?

# Future Work

- Synesthesia and interaction of information from multi-modal sources
  - Visual
  - Auditory
  - Color
  - Smell
  - Touch
  - etc

# Questions?

## References

- Averbeck, B. B., Chafee, M. V., Crowe, D. A., & Georgopoulos, A. P. (2002, October 1). Parallel Processing of Serial Movements in Prefrontal Cortex. *PNAS*, pp. 13172-13177.
- Drewnowski, A., & Murdock, B. (1980). The Role of Auditory Features in Memory Span for Words. *Journal of Experimental Psychology*, 6 (3), 319-332.
- Eliasmith, C., & Anderson, C. H. (2003). *Neural Engineering: Computation, Representation, and Dynamics in Neurobiological Systems*. London: The MIT Press.
- Murdock, B. (1995). Developing TODAM: Three Models for Serial-Order Information. *Memory & Cognition*, 23 (5), 631-645.
- Plate, T. A. (2003). *Holographic Reduced Representation: Distributed Representation for Cognitive Structures*. Stanford: CSLI Publications.

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