A Computational Explanation for Using Episodic Memories for Associative Learning and Memory Consolidation in a Robot

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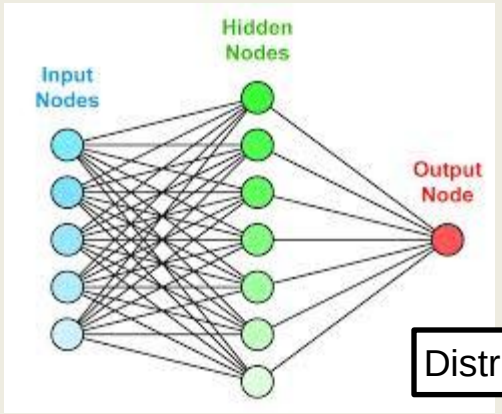
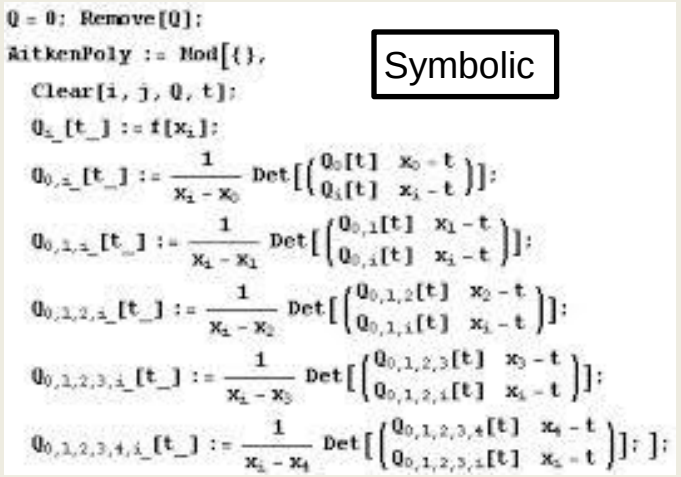
SS-RICS

ARL

- U.S Army Human Research and Engineering Directorate (HRED)
- Symbolic and Sub-symbolic Robotics Intelligence Control System (SS-RICS)
  - Combines abstract symbolic representation with distributed sub-symbolic representations in a hybrid format

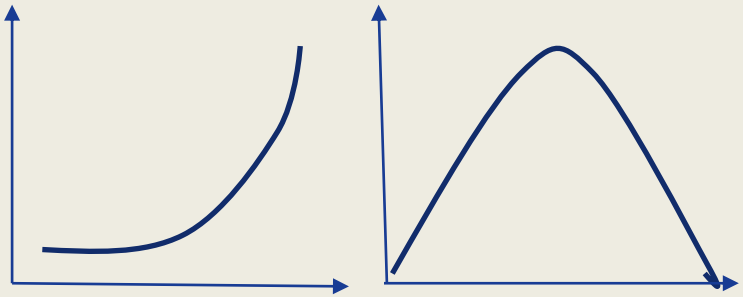




Exciting Events

Let α = vector of observations
Let β = number of observations in α
Let μ = matrix of observation correlations
Let T = threshold value for a correlation
Let B = % of T, give set of observations
Let γ = number of correlations that exceed the threshold T

Kelley, T. D., & McGhee, S. (2013, May). Combining metric episodes with semantic event concepts within the Symbolic and Sub-Symbolic Robotics Intelligence Control System (SS-RICS). In *SPIE Defense, Security, and Sensing* (pp. 87560L-87560L).



Boring Novel

```
γ ⟵ 0
for i = 0 ⟶ β – 1
        for j = 0 ⟶ β – 1
                if i == j continue
                μ i,j ⟵ correlation(α i , α j)
                if μ i,j > T then γ ⟵ γ + 1
        end
end
```

or, where x = correlation(α_i, α_j):

$$\gamma = \sum_{\substack{i,j=0 \\ i \neq j}}^{\beta-1} f(x) > T$$

Let **τ** = % of correlations that exceed the threshold

$\tau = \gamma / ((\beta^2 - \beta)/2)$

```
if τ > B then
        RobotStatus ⟵ Nothing has changed
else
        RobotStatus ⟵ Novel event occurred
end
```

Episodic Indexing (Sleep)

Sleep is unproductive?

- Appears to be a dangerous activity
- Why would an organism deliberately put itself in an unconscious state?

Sleep is a powerful learning mechanism

- Sleep must be extremely beneficial
- Associative learning mechanism

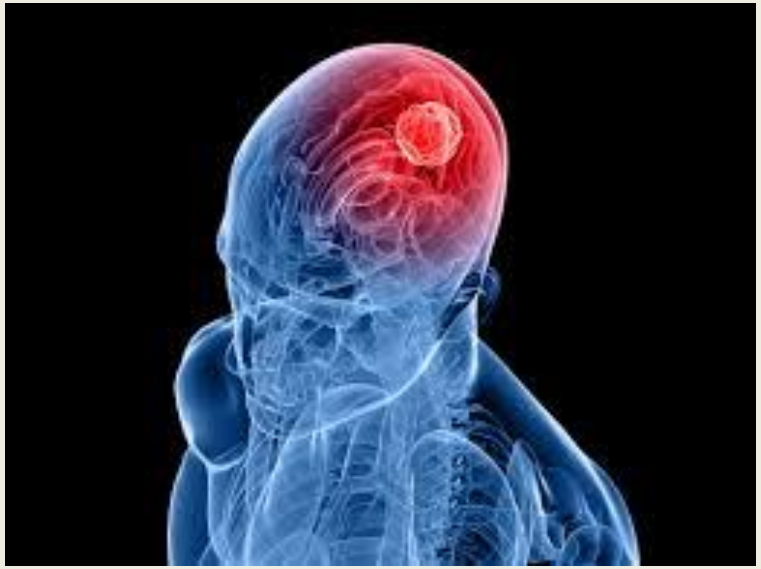
Theories

- Early theories were that sleep is an “unlearning process” where “random events” are activated
- (Activation Synthesis Model of Sleep)

Computational Benefits?

What are the computational benefits of sleep?

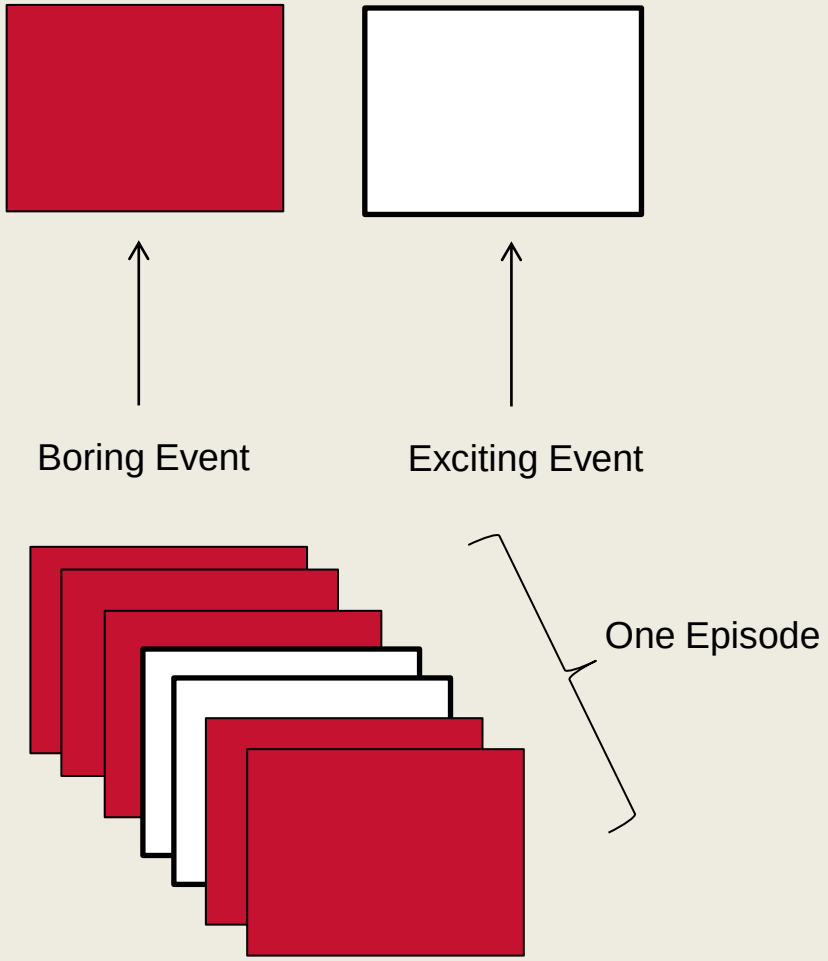
What is the benefit of "replaying the days events"



Replaying episodic events and defining cues for memory retrieval was more beneficial than other strategies for memory retrieval

What To Remember?

- We *know* that people tend to remember emotional or exciting events
- Don't remember boring information
- If you get attacked by a tiger at the watering hole try to remember the event so that it can be avoided in the future



Three Strategies

***Strategy* 1**

- Complete Memory Search
- Remember everything
  - Not very practical but serves as a benchmark

***Strategy* 2**

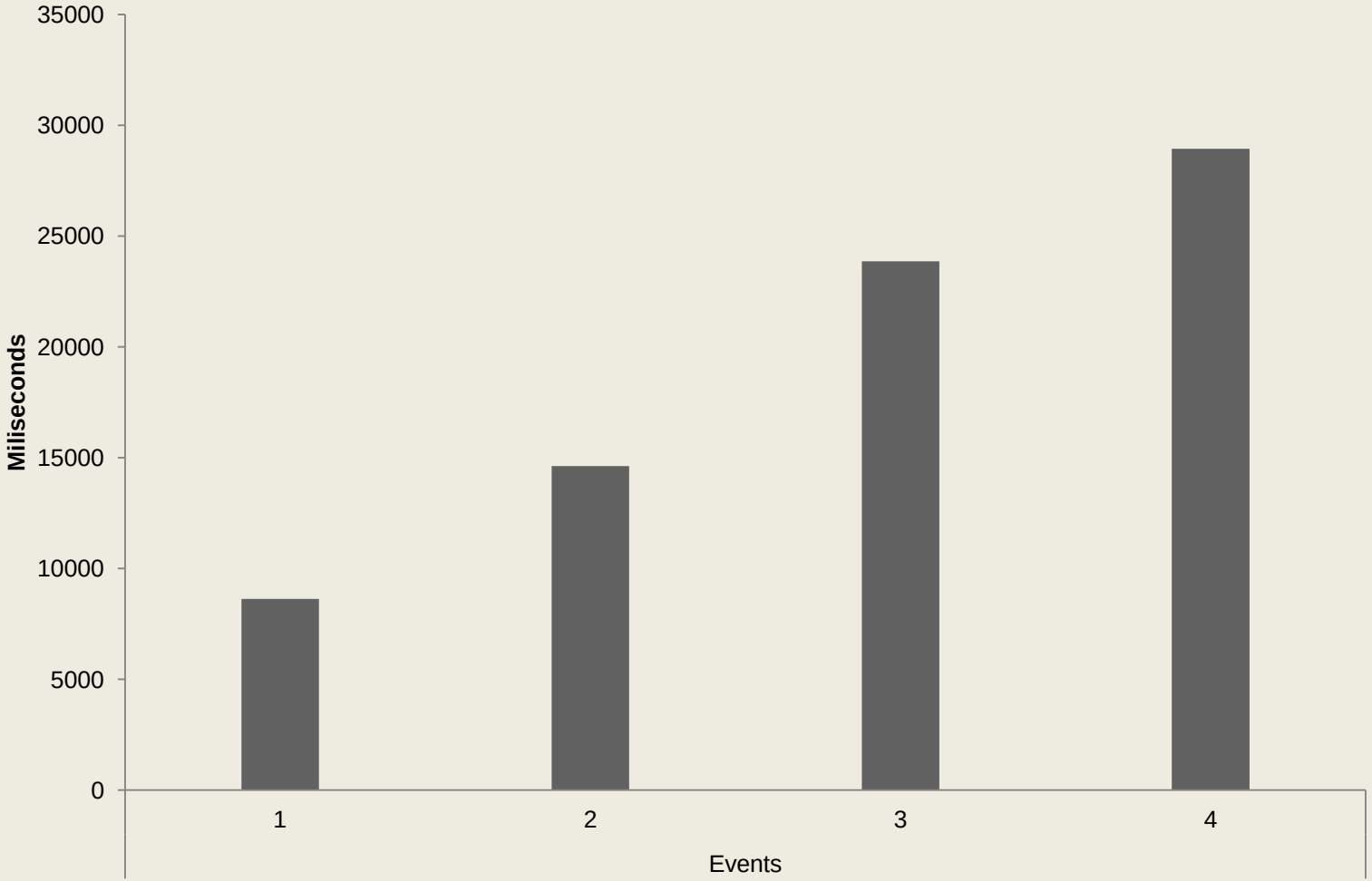
- Recent Memory Search
- Remember only exciting events
  - Seemed to be very practical

***Strategy* 3**

- Episodic Indexing
- Remember everything and process post hoc
- Add cues to exciting events
  - Prune out the boring events

Kelley, T. D. (2014). Robotic Dreams: A Computational Justification for the Post-Hoc Processing of Episodic Memories. *International Journal of Machine Consciousness*, *6*(02), 109-123.

Strategy 1 Results: Remember Everything



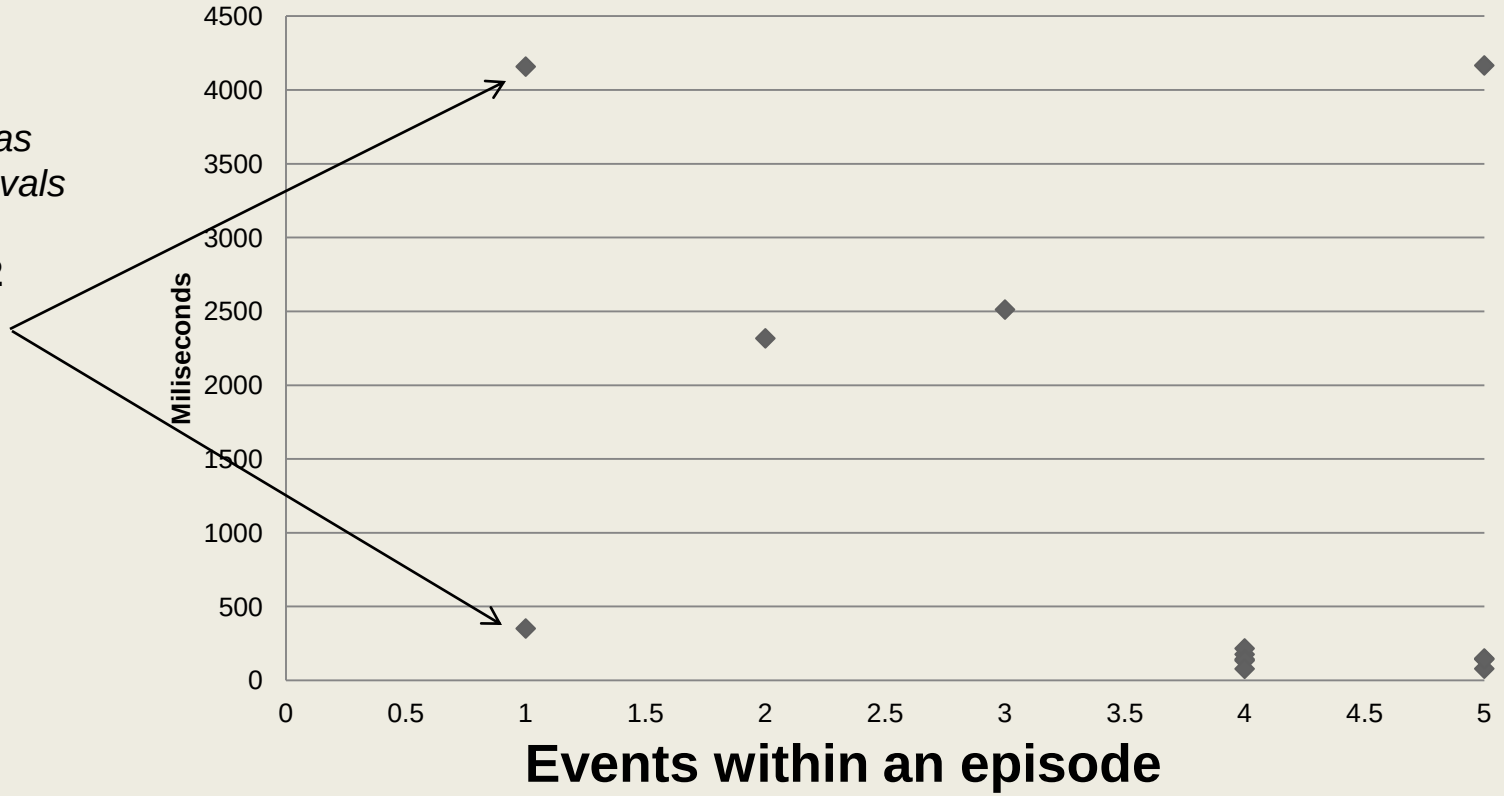
Problem: Obviously a linear increase in retrieval times with an increase in memories

Strategy 2 Results: Remember Exciting Events

5 Events

Each event has multiple retrievals

Event **1** has **2** retrievals

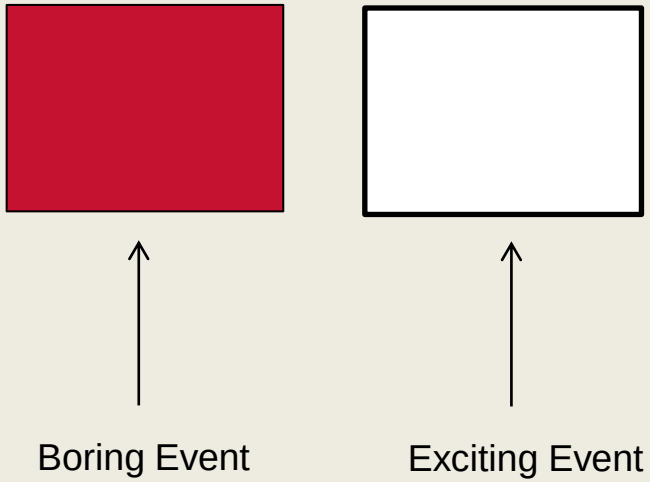


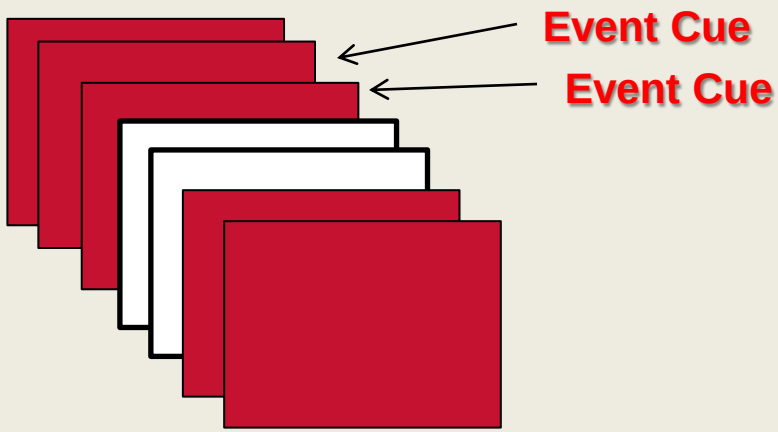
Problem: *Speed* **of events. Things can happen too fast for processing**
Problem: **After the first retrieval the stimulus has** *changed*
Problem: **Retrievals are** *costly* **in terms of resources and take away from attention to the event**
Problem: **Some retrievals are fast, but some can take too long if there is not a good match**

What's Wrong?

We know that people tend to remember emotional or exciting events

- But we can't *ONLY* remember exciting events – why?
  - Because exciting events are *dynamic* and memory retrievals during the event are computationally expensive and inefficient
  - If we get attacked by a tiger we can't only remember "getting attacked" a better strategy is to remember the events right before the attack in order to *avoid* future attacks
  - If we *only* remember exciting events then the information before the event is not available for associative learning
  - We must *save* everything an post process (dream) the days events

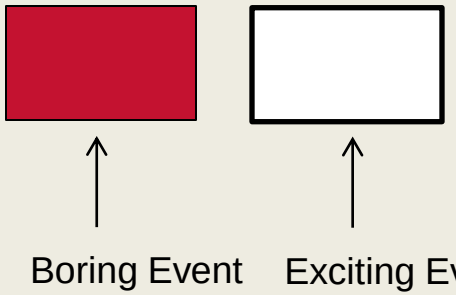


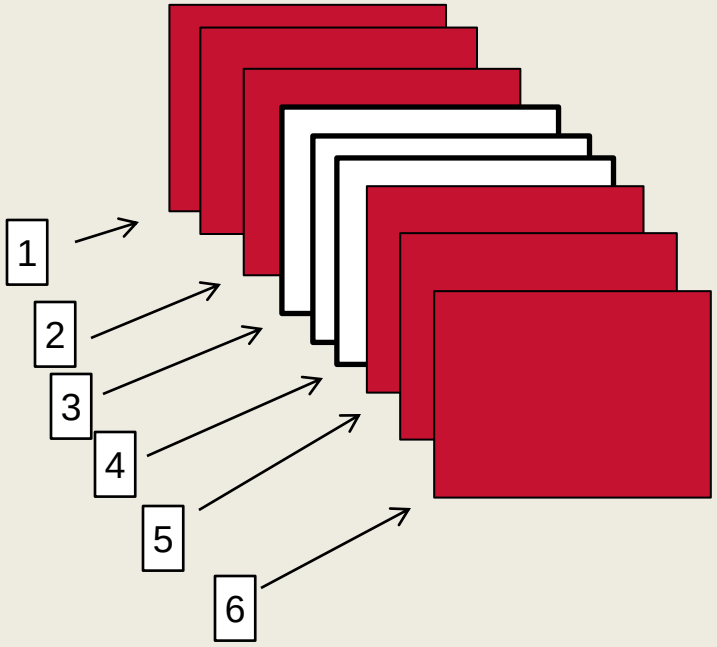


Strategy 3 : Remember everything and dream

Strategy 3

- *Remember* everything until some limit is reached (tired)
- *After* some limit is reached, post process the data (dream)
- *Some* boring events are removed
- *Cues* are inserted in order to member exciting events by saving the preceding boring information (Associative Learning)
- *Abstraction* is used to characterize the entire event at a symbolic level
  - *Symbolic* categorization increases recall speeds over metric retrievals





Example

- Scenario: Getting attacked by a tiger at the watering hole
- If the mind only remembered being attacked, it would not be able to anticipate the attack, in order to avoid the attack in the future
- If the mind can post process the event by replaying the event as a dream, then the mind can use the events before the attack as cues, increasing reaction time, and possibly avoiding the event in the future
- The mind needs to remember the event AND the information before the event
  - Smells around the watering hole
  - The sounds of the birds before the attack
- Results can be “unlearned” through reinforcement learning
  - Go to the watering hole and we do not get attacked
  - This updates our reinforcement utilities

Dreaming: The Details

Remove **some boring information**

- **Events between 1 and 2 are removed, but not event 2, which serves as a cue**
- **Events between 5 and 6 are removed but not item 5, which serves as reinforcement**

Cueing **information is inserted**

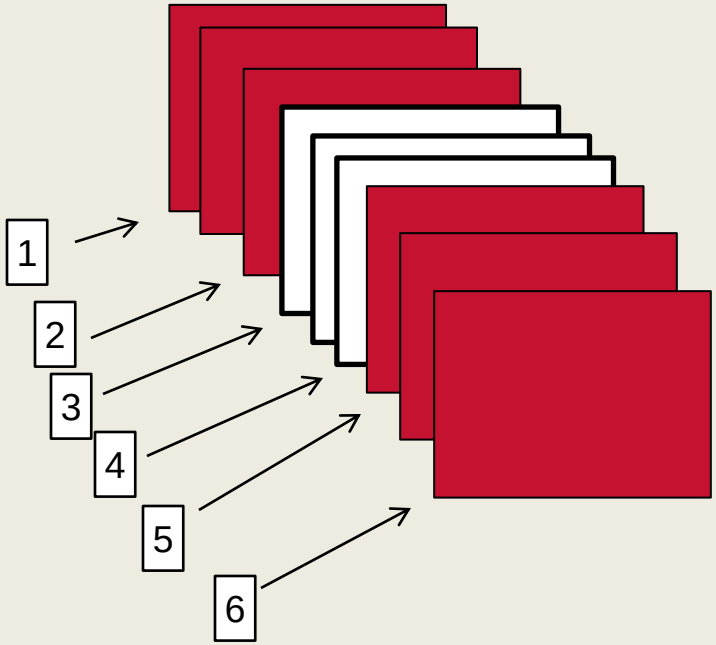
- **Event 2 becomes a cue to the exciting events between 3 and 4**

Reinforcement **can be tested**

- **Event 5 becomes a reinforcing state for later events**

Abstraction **is added for metric information**

- **The entire episode is characterized at the declarative level – speeding future retrieval times**
- **The declarative level representation can be simple**
  - **"At some location (cue), something big and orange (Tiger) moved from left to right resulting in pain (event)"**
- **Converting information from metric to symbolic greatly speeds retrieval times**



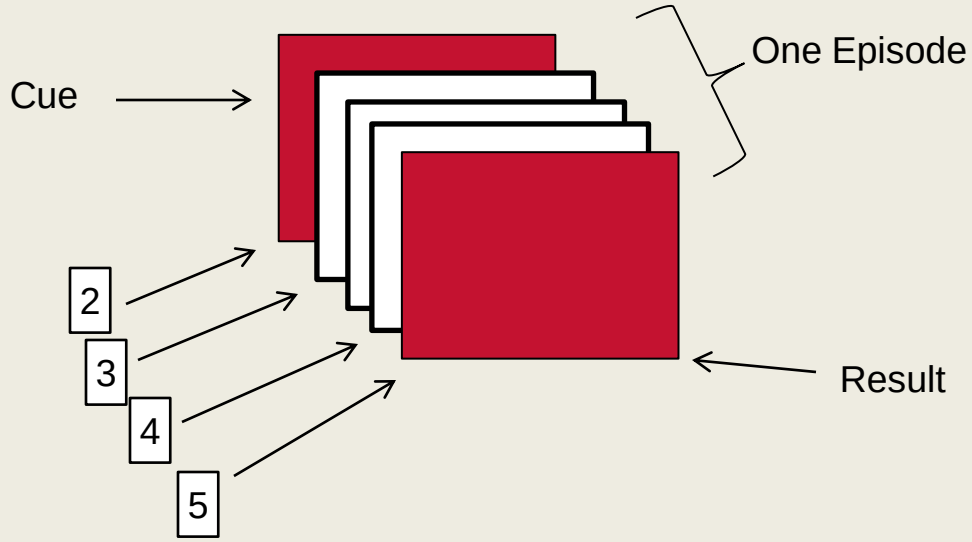
Implementation

A cue to the exciting event has been created

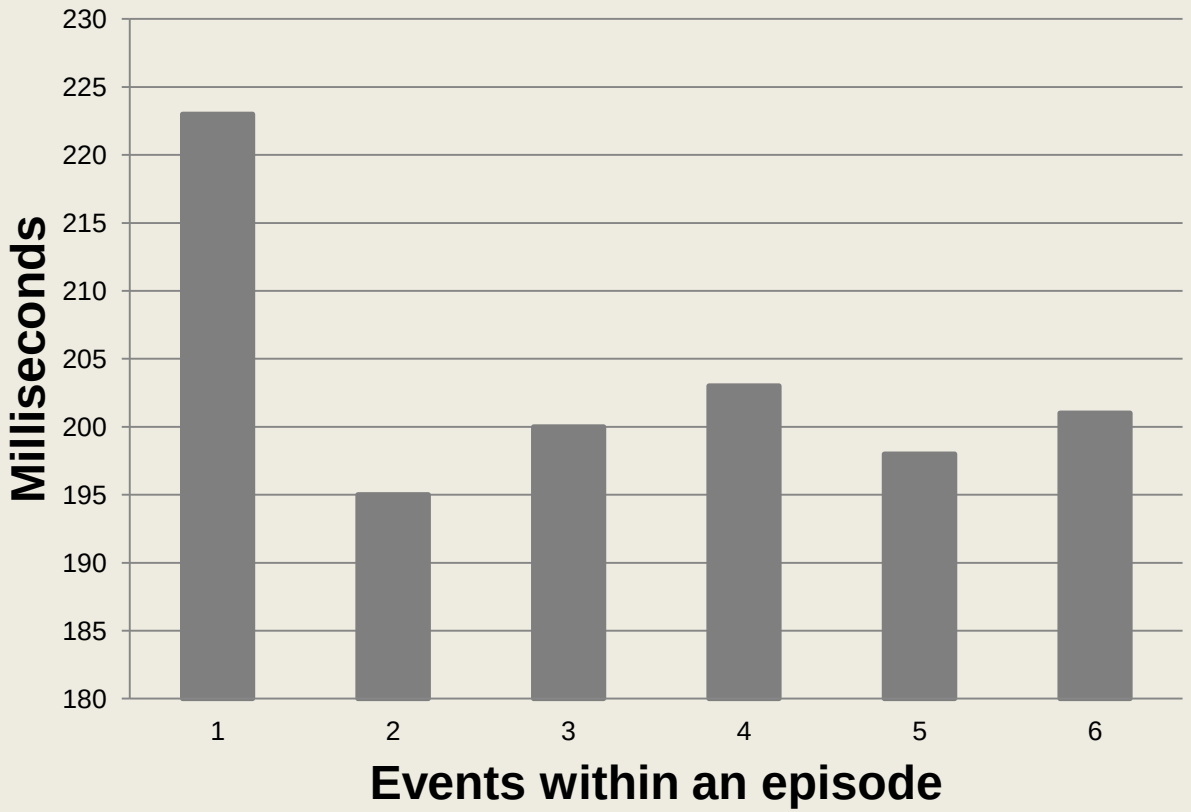
The metric information associated with the boring events has been removed if it was not used as a cue

Declarative information is used to characterize the event

- **The result of the event can be used for future *reinforcement* learning**
- **The entire event can be recalled as *one* important episode given a small cue**
- **The situation could be *generalized* given similar cues**

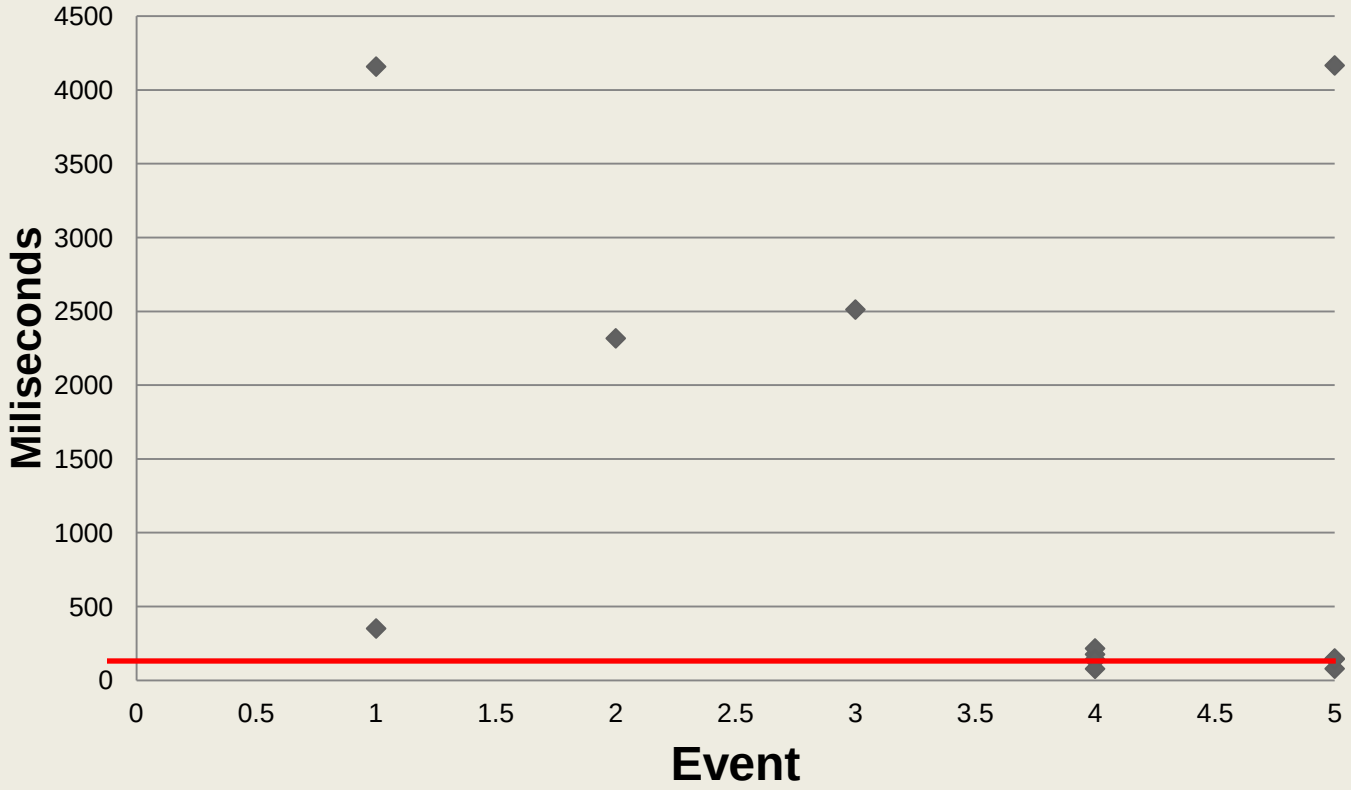


Strategy 3: Dream Retrieval Time Results



Number of milliseconds for a final *metric retrieval* following the post-hoc processing of events. Each bar is the time associated with the *last metric retrieval*, using the image correlation algorithm, at the end of the event (5) to confirm an expected result.

Compared to Strategy 2



In comparison with Strategy 2 all the retrievals for Strategy 3 were below the red line above.

Strategy 3 was an order of magnitude faster than Strategy 2

Why post hoc?

Big Question: Why is this done as a post hoc process(sleep)?

- **It *might* be computationally possible to accomplish this process immediately after an exciting event**
  - **Blocking incoming perceptual information is important**
- **There is *some* evidence that this type of associative learning can occur during restful periods that do not involve REM sleep**
- **If the mind is considered an analog system, then it would require re-winding the events of the day (much like a tape player) in order to find the right access points for the appropriate cues for associative learning**

Conclusions

- Dreams are important for *associative learning*
- The mind cannot *only* remember exciting events because the cues before the exciting events are important
- *Replaying* events as dreams and setting cues before exciting events allow the mind to anticipate events and possibly avoid them in the future
- The sleep/wake cycle can be seen as a *developmental* process for a cognitive system
  - The cognitive system has a *low* threshold for interesting or important events which changes with age
  - The cognitive system uses sleep to set associative cues to recall important events then *updates* the reinforcement parameters associated with each event
- As the cognitive system progresses through early life, events would become *less* interesting
  - This would lead to *less* learning, and the need for less post hoc processing (or sleep)
  - This is the process seen in humans