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http://summerschool2014.ciirc.cvut.cz/

Cognitive Robotics

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Center for Machine Perception
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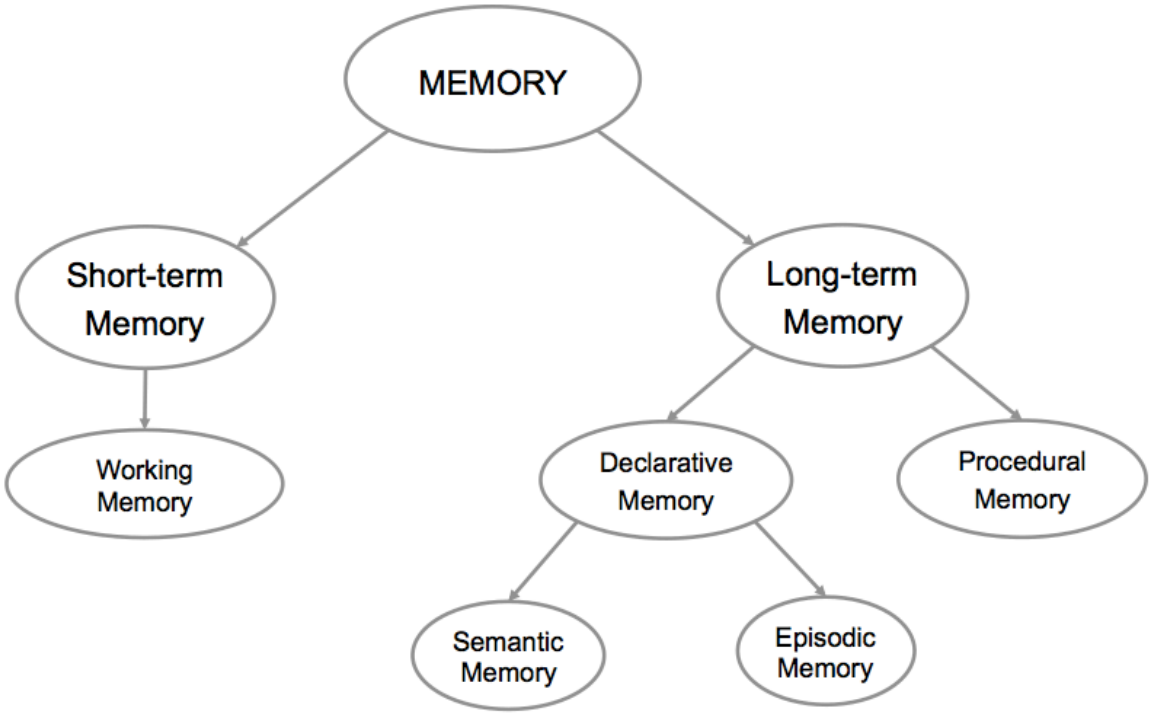
Cognitive Robotics

Talk 3

- Aspects of a cognitive architecture
  - Memory & Prospection
  - Knowledge & Representation

Types of Memory

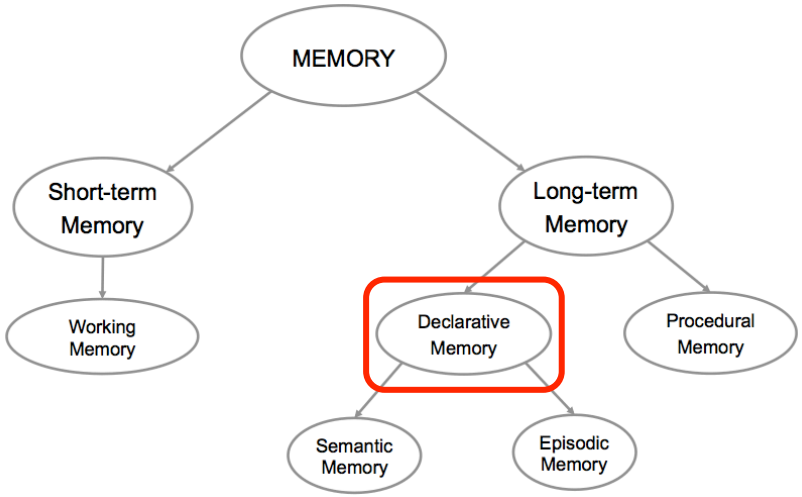
- Declarative
- Procedural
- Semantic
- Episodic
- Long-term
- Short-term
- Working
- Modal
- Amodal
- Symbolic
- Sub-symbolic
- Hetero-associative
- Auto-associative



Types of Memory

– Declarative

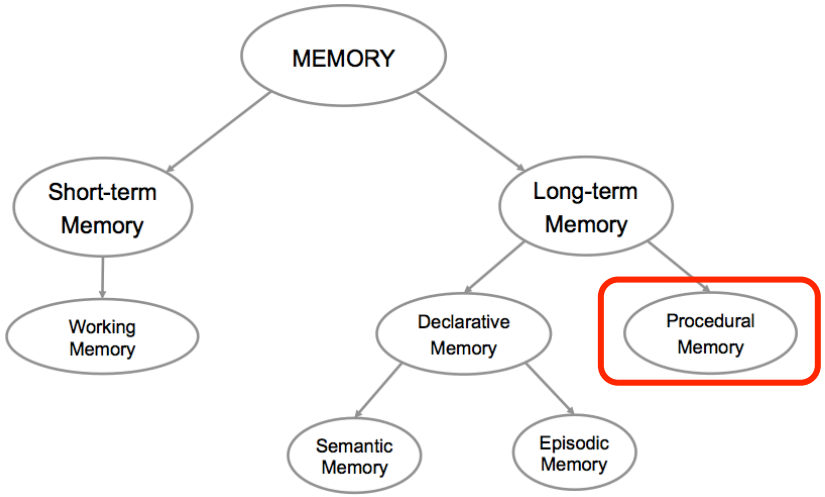
- **Knowledge of things / facts**
- “Knowing that”
- ***Propositional memory*** (true or false)
- Can be communicated from one agent to another through language
- Can be acquired in a single act of perception or cognition
- Accessible to conscious recall
- ***Explicit memory***



Types of Memory

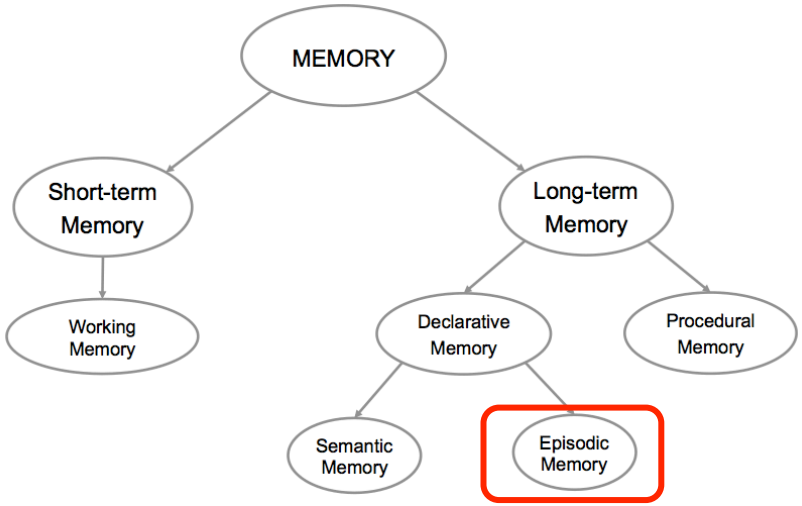
– Procedural

- **Skill-oriented memory of actions**
- “Knowing how”
- Can only be demonstrated
- Acquired progressively and may require an element of practice
- Not accessible to conscious recall
- ***Implicit memory***
- ***Non-declarative memory***



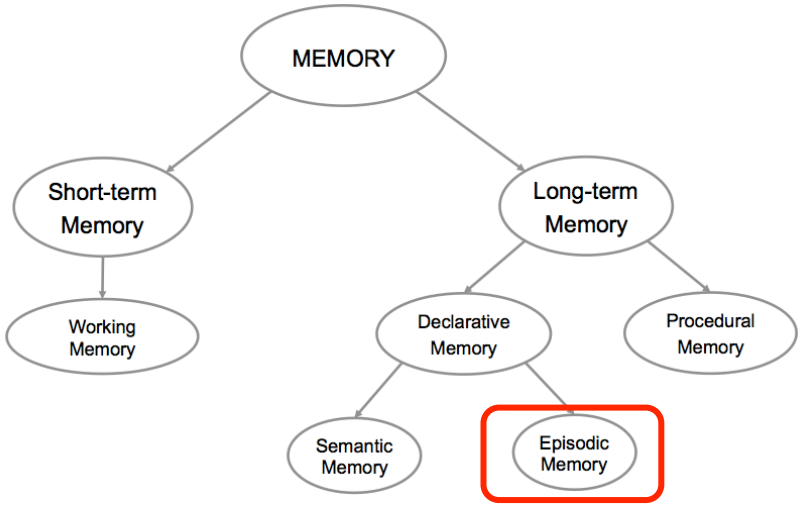
Types of Memory

- Episodic
  - Specific instances in the agent's experience: **autobiographical**
  - **Explicit spatial and temporal context**
    - what happened, where it happened, and when it happened
    - This temporal sequencing is the only element of structure in episodic memory
  - Highly structured: relationships between concepts, ideas, and facts
  - Sub-symbolic



Types of Memory

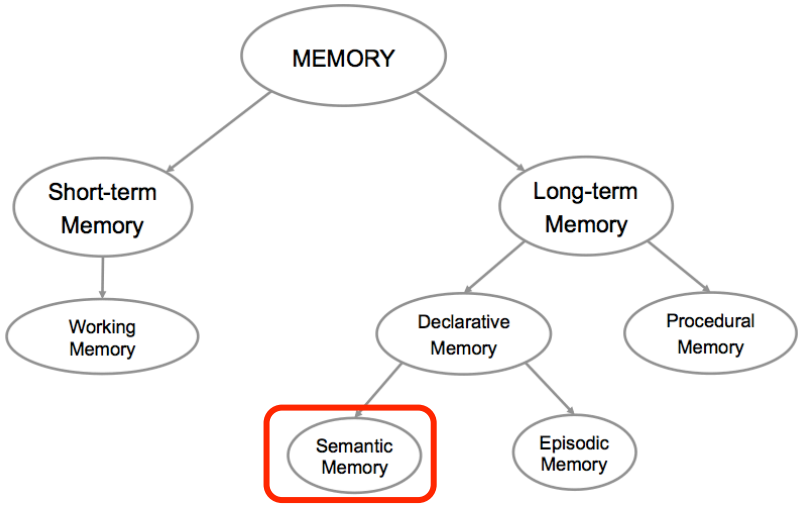
- Episodic
  - Episodic memory is a **constructive process**
    - Each time an event is assimilated into episodic memory, past episodes are re-constructed a little differently each time
    - Related to the role that episodic memory plays in the process of internal simulation that forms the basis of prospection, the key anticipatory function of cognition



Types of Memory

– Semantic

- General knowledge about the agent's world: facts, ideas, and concepts
- May be independent of the agent's specific experiences
- Memory necessary for the use of language
- Derived from episodic memory through a process of generalization and consolidation
- Symbolic



Types of Memory

- Modal memory
  - Tied directly to a particular sensory modality such as vision, audition, or touch
  - Episodic memory though is more likely to be modal since it is closely tied to an agents's specific experiences
- Amodal memory
  - Amodal memory has no necessary association with the sensorimotor experiences
  - Semantic declarative facts, represented symbolically, are typically amodal

Types of Memory

- Associative memory
  - An element of information or some pattern is linked to another
  - The first element or pattern is used to recall the second, by association
- Hetero-associative memory
  - Recalls a memory that is different in character from the input
  - A particular smell or sound, for example, might evoke a visual memory of some past event
- Auto-associative memory
  - Recalls a memory of the same modality as the one that evoked it
  - A picture of a favourite object might evoke a mental image of that object in vivid detail

Role of Memory

- The role of memory – why do we remember things?
  - To recognize objects, events, and people we've encountered before
  - To act towards them in some appropriate way (attraction/avoidance)
  - Memory is what makes it possible for the changes that occur as a result of learning and development to persist
  - **Memory makes it possible to project forwards into the future**

Role of Memory

"It's a poor sort of memory that only works backwards"

Remarks of the White Queen to Alice
in Lewis Carroll's *Through the Looking Glass*

Memory is Prospective

Role of Memory

- One of the central pillars of cognitive capacity:
  - the ability to **simulate internally the outcomes of possible actions** and select the most appropriate one for the current situation
  - Memory can be seen as a mechanism that allows a cognitive agent **to prepare to act,** overcoming through anticipation the inherent “here-and-now” limitations of its perceptual capabilities
  - **a cognitive system** doesn’t operate just on the basis of its current sensory data bu**t readies itself for what it expects and adjusts to the unexpected**

Role of Memory

- Memory is an **active** & **constructive** process, and it is fundamentally **associative**
  - Memories are recalled by associated triggers, possibly other memories
  - If you have a network of associative memories, you can run through this network **backwards** or **forwards**
  - Running through it **forwards** provides the **anticipatory predictive** element of memory suggesting possible sequence of events leading to a desired goal
  - Running through it **backwards** provides a way of **explaining** how some event or other might have occurred

Self-Projection, Prospection, & Internal Simulation

- Memory plays at least four roles in cognition

  1. Remember past events
  2. Anticipate future ones
  3. Imagine the viewpoint of other people
  4. Navigate around our world

- All four involve **self-projection**

  – Ability of an agent to shift perspective from itself in the here-and-now

  – Take an alternative perspective

  – It does this by **internal simulation**, i.e. the mental construction of an imagined alternative perspective

Self-Projection, Prospection, & Internal Simulation

- There are four forms of internal simulation

  1. **Episodic memory** (remembering the past)

  2. **Navigation** (orienting yourself topographically, i.e. in relation to your surroundings)

  3. **Theory of mind** (taking someone else's perspective on matters)

  4. **Prospection** (anticipating possible future events)

- Each form of simulation has a different orientation (past, present, or future)

- Each refers to the perspective of either the agent itself or another person

Self-Projection, Prospection, & Internal Simulation

- Recent evidence suggests that all four kinds of internal simulation involve a single core brain network
  - This network overlaps what is known as the default-mode network
  - A set of interconnected regions in the brain that is active when the agent is **not** occupied with some attentional task

Self-Projection, Prospection, & Internal Simulation

- Episodic memory
  - **Re-experience** your past
  - **Pre-experience** your future
- Projecting yourself forward in time is important when you form a goal
  - Creating a mental image of yourself **acting out the event**
  - **Episodically pre-experiencing** the unfolding of a plan to achieve that goal
  - **Episodic Future Thinking** [Atance and O'Neill 2001]

Self-Projection, Prospection, & Internal Simulation

- **Episodic memory is inherently constructive**
  - Old episodic memories are reconstructed slightly differently every time a new episodic memory is assimilated or remembered
  - The **constructive episodic simulation hypothesis** [Schacter and Addis 2007]
    - Episodic memory allows the **simulation of multiple possible futures**
    - This imposes an **even greater** need for a constructive capacity because of the need to extrapolate **beyond past experiences**
  - Episodic memory is not an exact and perfect record of experience but one that conveys the essence of an event and is open to re-combination

Internal Simulation and Action

- So far, internal simulation considered entirely in terms of memory-based self-projection
  - Using re-assembled combinations of episodic memory to
    - Pre-experience possible futures
    - Re-experience (and possibly adjust past experiences)
    - Project ourselves into the experiences of others
- However, action plays a significant role in our perceptions so does action play a role in internal simulation?
- **YES**

Internal Simulation and Action

- Internal simulation
  - extends beyond episodic memory
  - includes simulated interaction, particularly embodied interaction

- Terms
  - Simulation
  - Internal simulation
  - Mental simulation
  - *Emulation*

Internal Simulation and Action

- Several simulation theories, but perhaps the most influential is known as the **Simulation Hypothesis** [Hesslow 2002, Hesslow 2012]

- Three core assumptions

Covert action / covert behaviour

1. The regions in the brain that are responsible for motor control can be activated ***without*** causing bodily movement

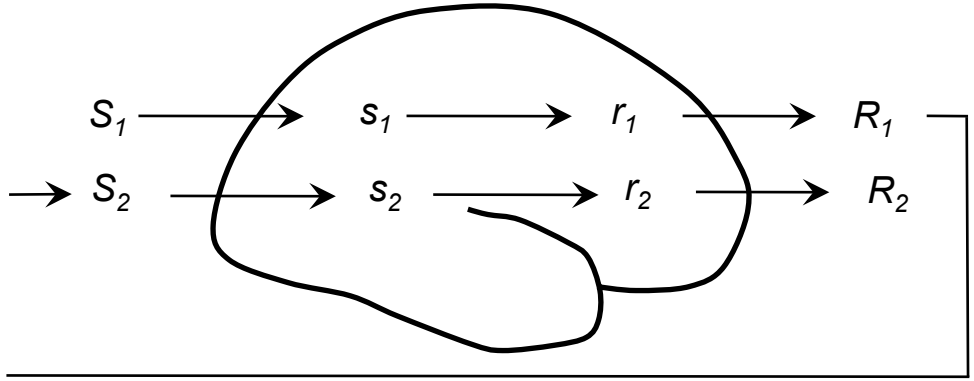
2. Perceptions can be caused by internal brain activity and not just by external stimuli

Simulation of perceptions

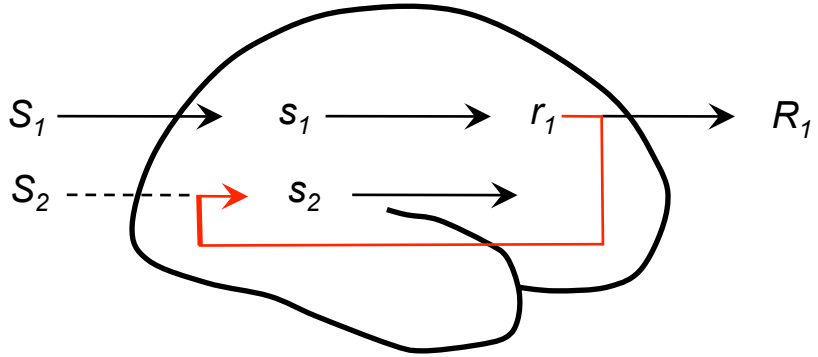
3. The brain has associative mechanisms that allow motor behaviour or perceptual activity to evoke other perceptual activity

Simulated action elicit perceptions

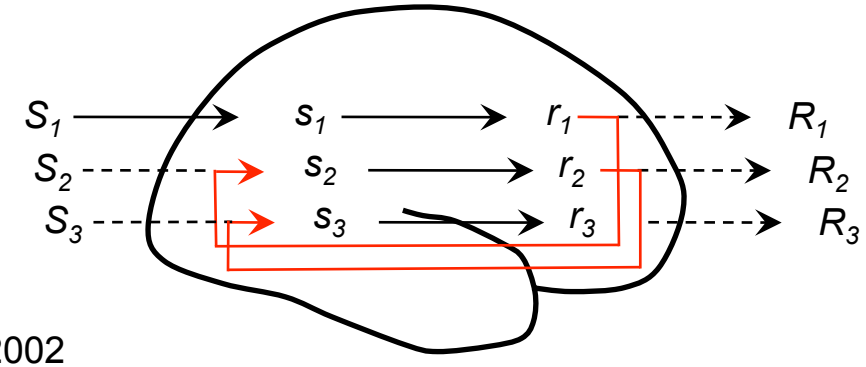
Internal Simulation and Action



No internal simulation



A motor response
to an input stimulus
causes the internal simulation
of an associated perception …



This elicits a covert action
which in turn elicits a simulated
perception and a consequent
covert action

Hesslow 2002

Internal Simulation and Action

- There is an increasing amount of neurophysiological evidence in support of all three assumptions

For example, see:

H. Svensson, S. Thill, and T. Ziemke. Dreaming of electric sheep? Exploring the functions of dream-like mechanisms in the development of mental imagery simulations. *Adaptive Behavior*, 21:222–238, 2013.

Internal Simulation and Action

- Action-directed internal simulation involves three different types of anticipation:
  - **Implicit anticipation**
    - Prediction of motor commands from (possibly simulated) perceptions
  - **Internal anticipation**
    - Prediction of the proprioceptive consequences of carrying out an action, i.e. the effect of an action on the agent's own body
  - **External anticipation**
    - Prediction of the consequences for external objects and other agents of carrying out an action

Internal Simulation and Action

- **Implicit anticipation** selects some motor activity (possibly covert, i.e. simulated) to be carried out based on an association between stimulus and actions
- Internal and external anticipation then **predict** the consequences of that action
- Collectively, they simulate actions and the effects of actions
- Covert action involves ***motor imagery***
- Simulation of perception is referred to as ***visual imagery (perceptual imagery)***

Internal Simulation and Action

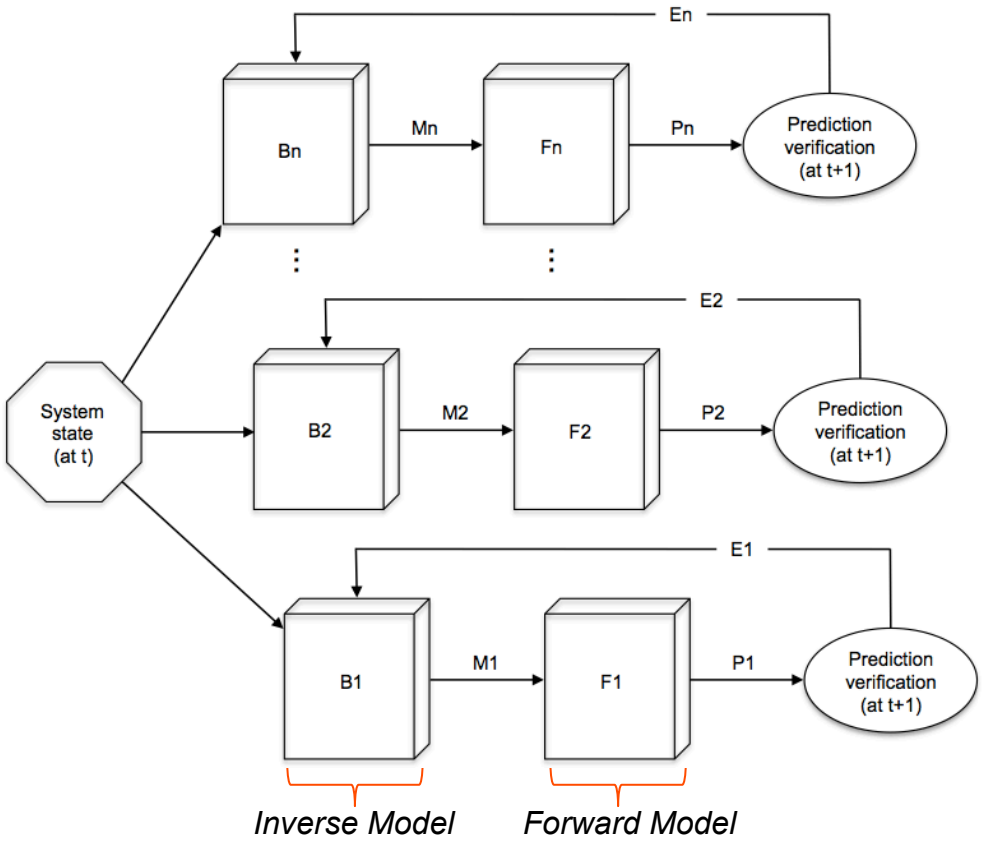
- Motor imagery is also a form of perceptual imagery
  - It involves the proprioceptive and kinesthetic sensations associated with bodily movement
- Covert action often has elements of both motor and visual imagery
- *Vice versa*, the simulation of perception often has elements of motor imagery
- Visual and motor imagery are sometimes referred to collectively as ***mental imagery***
- Mental imagery can be viewed as a synonym for internal simulation

Internal Simulation and Action

- HAMMER accomplishes internal simulation using forward and inverse models [Demiris and Khadhouri 2006, Demiris et al. 2014]
  - The inverse model
    - Takes as input the current state of the system and the desired goal, and it outputs the motor commands necessary to achieve that goal
  - The forward model
    - Acts as a predictor
    - Takes as input the motor commands and simulates the perception that would arise if this motor command were to be executed

      (just as the simulation hypothesis envisages)

Internal Simulation and Action



HAMMER Architecture

Demiris and Khadhouri. 2006

Multiple inverse models (B1 to Bn) take as input the current system state, which includes a desired goal, suggesting motor commands (M1 to Mn), with which the corresponding forward models (F1 to Fn) form predictions of the system's next state (P1 to Pn). These predictions are verified at the next time state, resulting in a set of error signals (E1 to En).

Internal Simulation and Action

- HAMMER it provides for the hierarchical composition of primitive actions into more complex sequences
- The action is selected using an internal attention process
- It has been implemented both in robot simulations and on physical robotic platforms

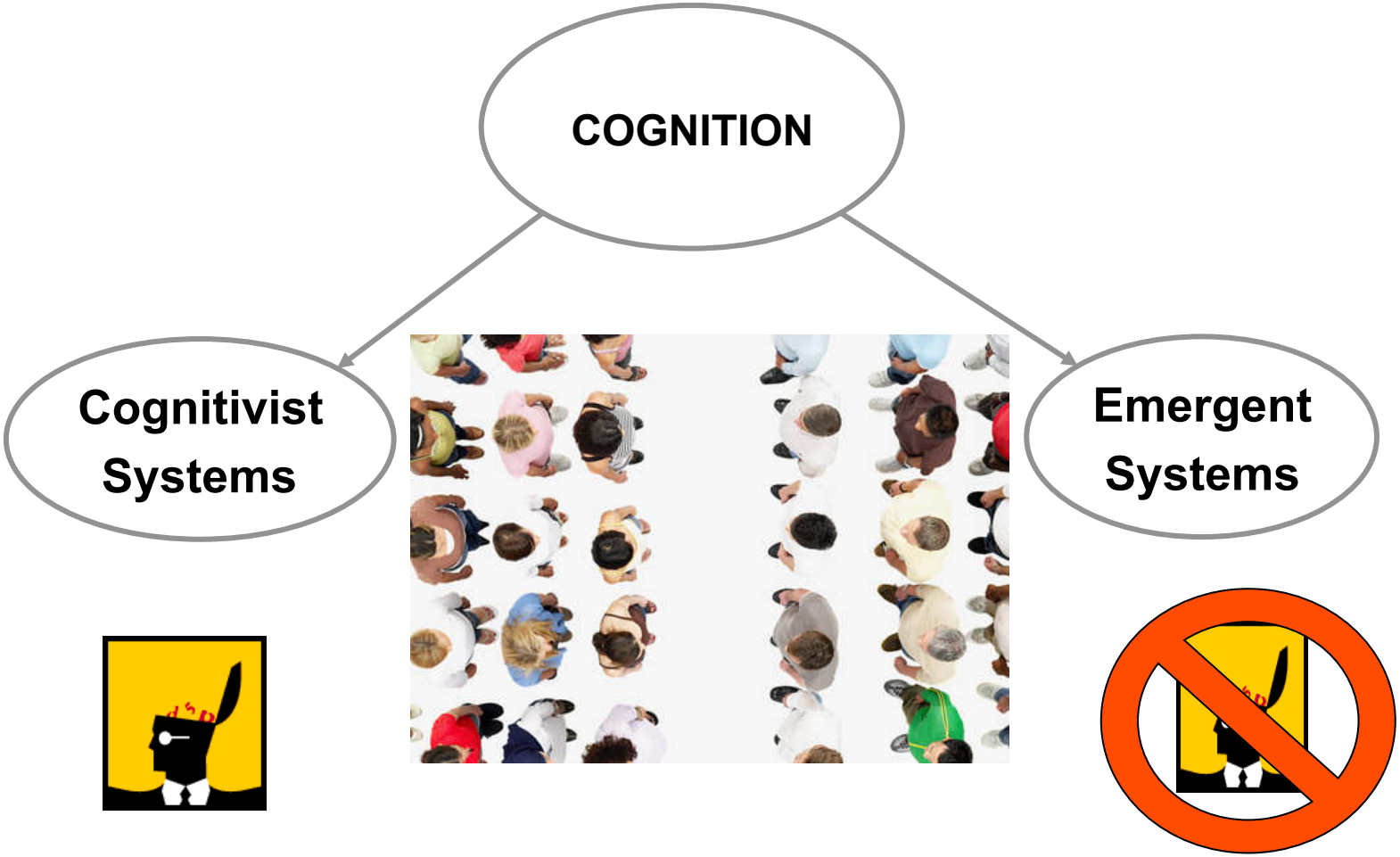
Internal Simulation and Action

- HAMMER goes beyond the scope of episodic memory in effecting internal simulation by invoking actions and behaviours
- The sensorimotor associations involved in internal simulations, for forward and inverse models, requires both **episodic memory** and **procedural memory**
- **Episodic memory** is needed for **visual imagery**, including proprioceptive imagery
- **Procedural memory** is needed **for motor imagery**

Internal Simulation and Action

- Classical treatments of memory (above) usually maintain a clear distinction between
  - Declarative memory and procedural memory, in general,
  - Episodic memory and procedural memory, in particular
- Contemporary research takes a slightly different perspective
  - **Joint perceptuo-motor representations**
  - E.g. Marco Iacoboni's instantiation of *Ideo-motor Theory*
  - *Theory of Event Coding* by Bernhard Hommel and colleagues

Knowledge and Representation



Joint Perceptuo-motor Representations

- Mental imagery – internal simulation – comprises both visual imagery (or, better still, perceptual imagery) and motor imagery

- These two forms of imagery are tightly entwined

  – the **simulation of perception and covert action** both involve elements of visual and motor imagery

- Consider two different approaches:

  1. ***Theory of Event Coding***

  2. ***Object-Action Complexes***

Joint Perceptuo-motor Representations

- **Sensory-motor Theory** and **Ideo-motor Theory**
  [Stock & Stock 2004]

  - ***Sensory-motor action planning***

    - Treats actions as reactive responses to sensory stimuli
    - **Assumes that perception and action use distinct and separate representational frameworks**
    - Builds on the classic uni-directional approach to perception, proceeding stage by stage from stimulus to percept and then to response
    - **Doesn't allow the resultant (or intended) action to impact on the related sensory perception**

Joint Perceptuo-motor Representations

- **Sensory-motor Theory** and **Ideo-motor Theory** [Stock & Stock 2004]
  - ***Ideo-motor action planning***
    - treats action as the result of internally-generated goals
    - **The selection and control of a particular goal-directed movement depends on the anticipation of the sensory consequence of accomplishing the intended action**
    - The agent images (e.g. through **internal simulation**) the desired outcome and selects the appropriate actions in order to achieve it

Joint Perceptuo-motor Representations

- **Sensory-motor Theory** and **Ideo-motor Theory** [Stock & Stock 2004]
  - ***Ideo-motor action planning***
    - There is an important difference between the concrete movements comprising an action and the higher-order goals of an action
    - Actors do not voluntarily pre-select the exact movements required to achieve a desired goal
    - **Instead, they select prospectively-guided intention-directed goal-focussed action, with the specific movements being adaptively controlled as the action is executed**
    - Anticipatory idea-centred way of selecting actions and as a way of bridging the higher-order conceptual representations of intentions and goals with the concrete adaptive control of movements when executing that action

Joint Perceptuo-motor Representations

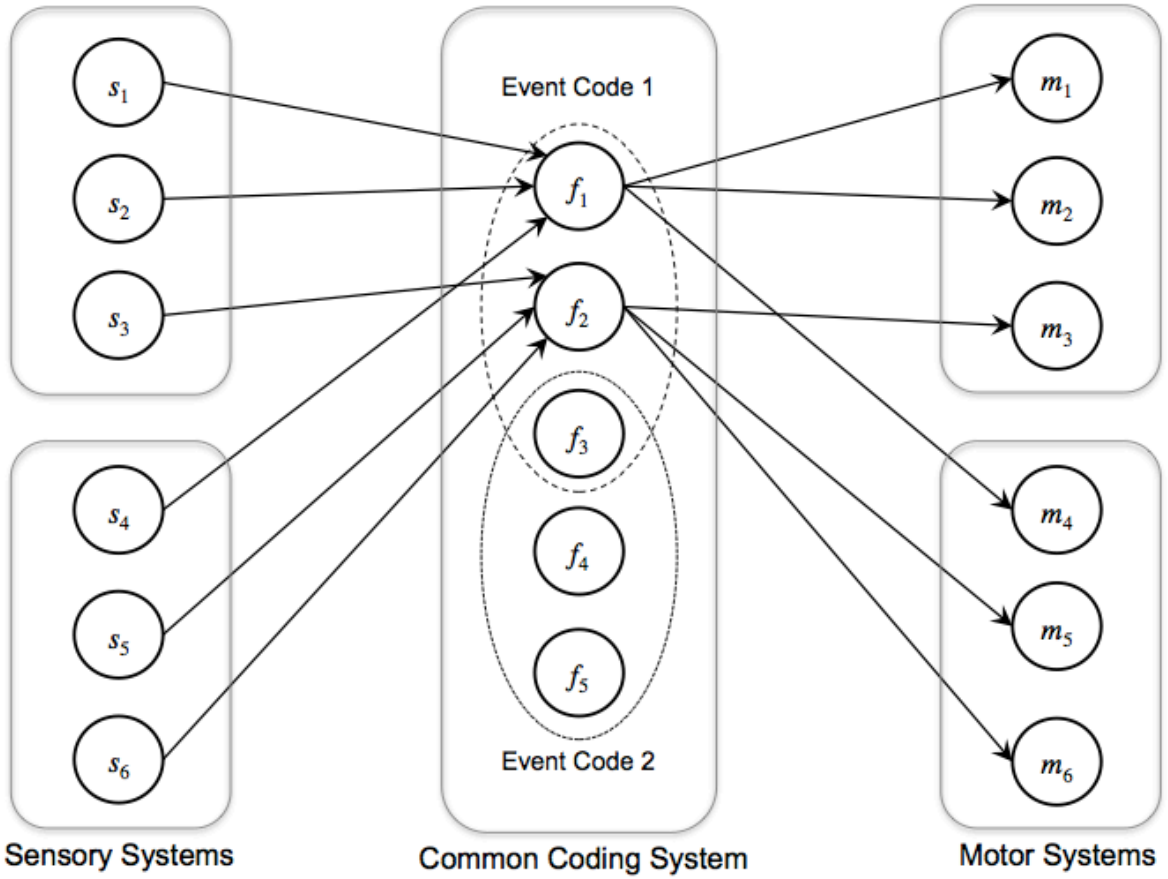
- **Sensory-motor Theory** and **Ideo-motor Theory** [Stock & Stock 2004]
  - **Ideo-motor action planning**
    - How can the goal, achieved through action, cause the action in the first place?
    - How can the later outcome affect the earlier action?
    - **Prospection**! It is the anticipated goal state, not the achieved goal state, that impacts on the associated planned action
    - **Goal-directed action is a centre-piece of ideo-motor theory**
    - Also referred to as the **goal trigger hypothesis** [Hommel et al. 2001]

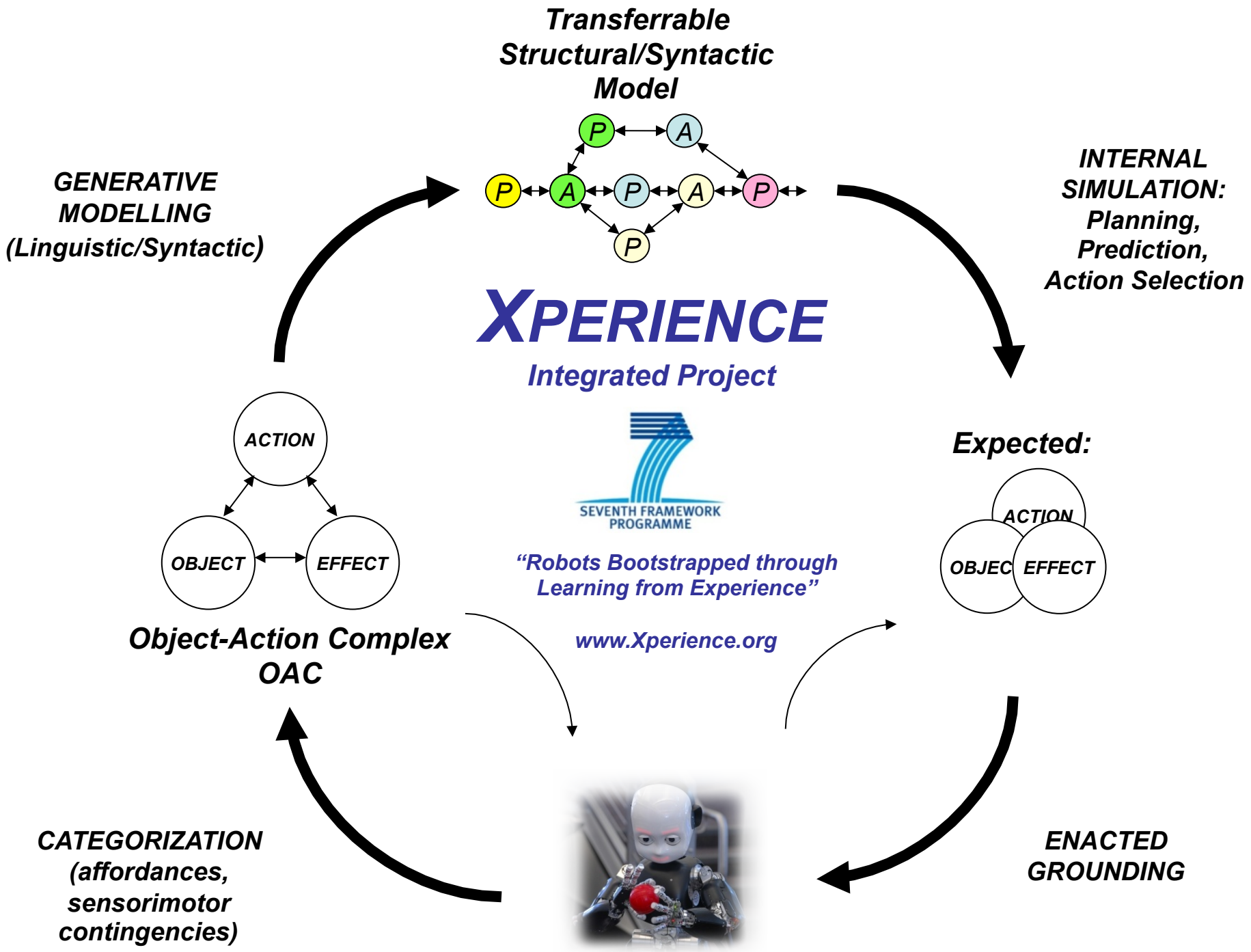
Joint Perceptuo-motor Representations

- **Sensory-motor Theory** and **Ideo-motor Theory** [Stock & Stock 2004]
  - **Ideo-motor action planning**
    - Anticipatory idea-centred way of selecting actions and as a way of bridging the higher-order conceptual representations of intentions and goals with the concrete adaptive control of movements when executing that action
    - **Perception and action share a common representational framework**

Joint Perceptuo-motor Representations

- The Theory of Event Coding (TEC) [Hommel et al. 2001]




Transferrable Structural/Syntactic Model
P
A
P
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P
P
GENERATIVE MODELLING (Linguistic/Syntactic)
INTERNAL SIMULATION: Planning, Prediction, Action Selection
XPERIENCE
Integrated Project
SEVENTH FRAMEWORK PROGRAMME
"Robots Bootstrapped through Learning from Experience"
www.Xperience.org
ACTION
OBJECT
EFFECT
Object-Action Complex OAC
Expected:
ACTION
OBJEC
EFFECT
CATEGORIZATION (affordances, sensorimotor contingencies)
ENACTED GROUNDING

Joint Perceptuo-motor Representations

- Object-Action Complex, or OAC [Kruger 2011]
  - An OAC is a triple, i.e. a unit with three components: (E, T, M)
    - E is an “execution specification”; think of it as an action
    - T is a function that predicts how the attributes that characterize the current state of the agent’s world will change if the execution specification is executed
      - Think of T as a prediction of how the agent’s perceptions will change as a result of carrying out the actions given by E. S is just the space of all possible perceptions of the agent
    - M is a statistical measure of the success of the OAC’s past predictions

Joint Perceptuo-motor Representations

- Object-Action Complex, or OAC [Kruger 2011]
  - **An OAC combines the essential elements of a joint representation with a predictor** that links current perceived states and future predicted perceived states that would result from carrying out that action

Joint Perceptuo-motor Representations

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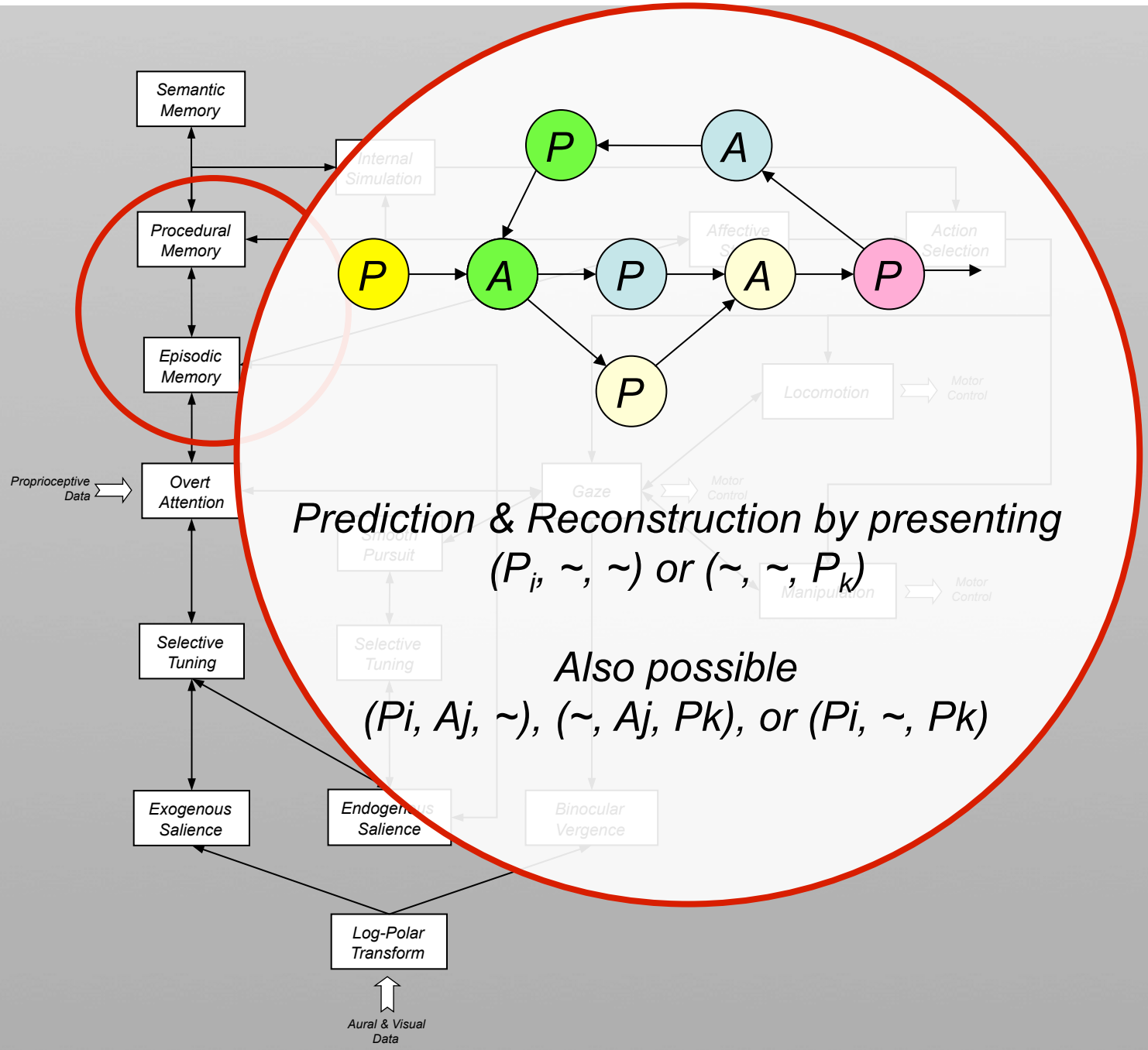
  - For example, an OAC might encode how to grasp a object or push an object into a given position and orientation

Joint Perceptuo-motor Representations

- Object-Action Complex, or OAC [Kruger 2011]
  - **An OAC combines the essential elements of a joint representation with a predictor** that links current perceived states and future predicted perceived states that would result from carrying out that action
  - For example, an OAC might encode how to grasp a object or push an object into a given position and orientation
  - OACs can be learned and executed, and they can be combined into more complex representations of actions and their perceptual consequences.


Semantic Memory
Procedural Memory
Episodic Memory
Proprioceptive Data
Overt Attention
Selective Tuning
Exogenous Salience
Endogenous Salience
Log-Polar Transform
Aural & Visual Data
P
A
P
A
P
P
Prediction & Reconstruction by presenting
(Pi, ~, ~) or (~, ~, Pk)
Also possible
(Pi, Aj, ~), (~, Aj, Pk), or (Pi, ~, Pk)