Joscha Bach

Implementing Emotion and Motivation in AI Architectures

Tutorial AAAI 2018

From Computation to Emotion

How can a computational system experience emotion?

What is emotion?

What is experience?

Relationship between experiencer and experience?

Emotional states as cognitive configurations

Emotions as cognitive configurations

Emotions as cognitive configurations

Overview

- AGI perspective on minds
- Basic architectural components
- Modeling motivation (MicroPsi model)
- Models of emotion
- Emotion in the Psi theory
- Modeling personality
- Emotion, self and prosociality

Basic perspective on general AI

- Mind as machine

- Machine = computational system
- computation = regular state change

- universal computation: set of computable functions that can compute all computable functions (when given unbounded resources)

Basic perspective on general AI

- Access to universe via discernible differences
  $\rightarrow$ Information
- Meaning of information:
  relationship to changes in other information
- Intelligence: ability to model
- Modeling is function approximation
- Purpose of modeling is regulation,
  to maximize rewards

Basic perspective on general AI

- Classical AI:
  direct modeling of cognitive functionality
  $\rightarrow$ "first order AI"
- Deep Learning:
  systems that model functionality themselves;
  compositional function approximation
  $\rightarrow$ "second order AI"
- Meta Learning:
  systems that learn how to build learning systems
  $\rightarrow$ "third order AI"

Basic perspective on general AI: open questions

- Are humans meta learning systems?
- Is evolution a (slow and ineffective) search for meta learners?

- Is there a class of universal function approximators that can approximate any function that can be approximated by a computer (when given unbounded resources),
  and does it contain itself and us?

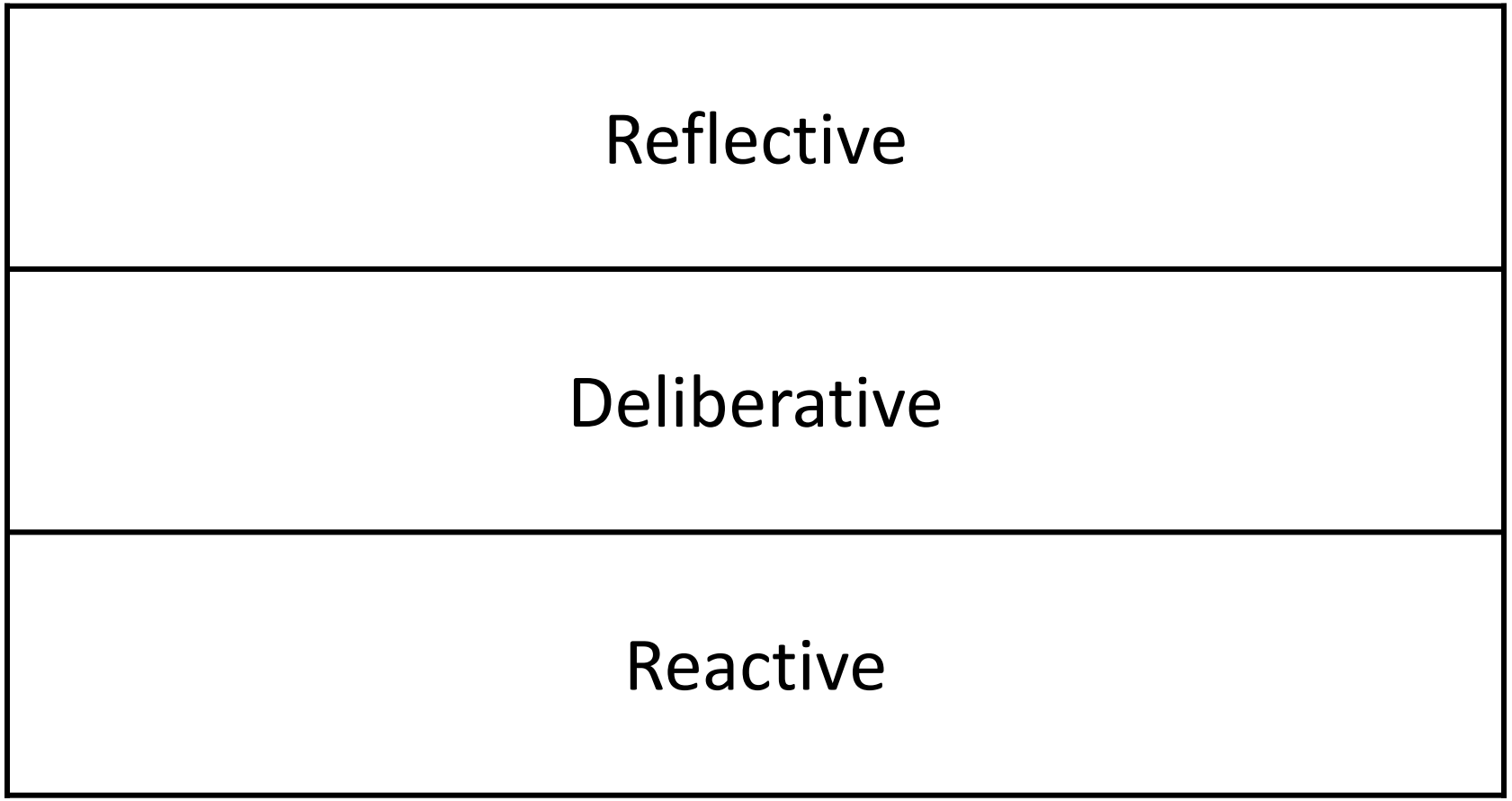
AI perspective on the mind

- Constructed architectures (Minsky, Simon, Newell) — classical cognitive architectures

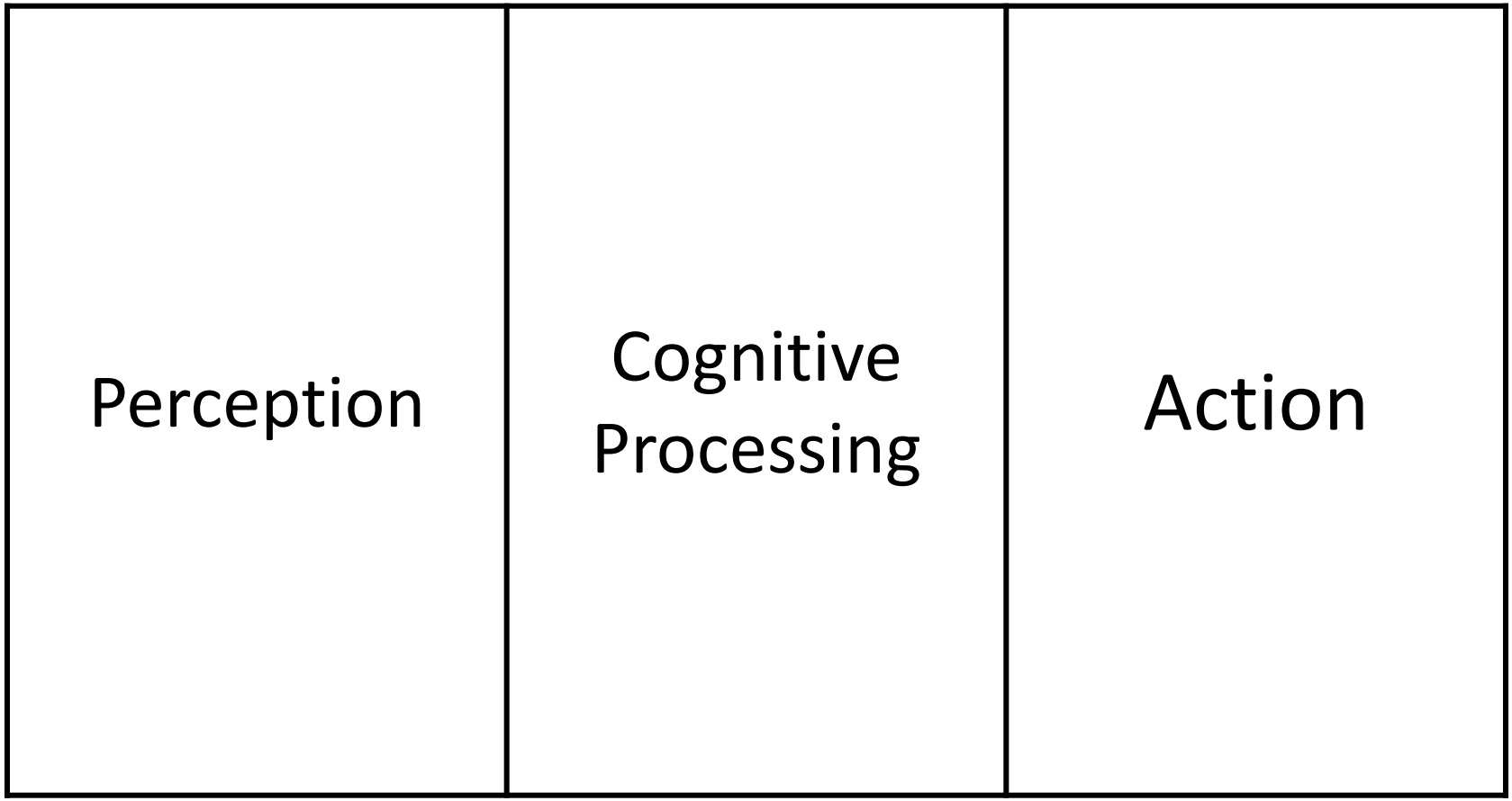
- Generated architectures (Schmidhuber, Hutter, …): general recursive function approximation + reward system

- Hybrid perspective:
  mostly generated, but with complex prerequisites and biases

Layers of Cognition



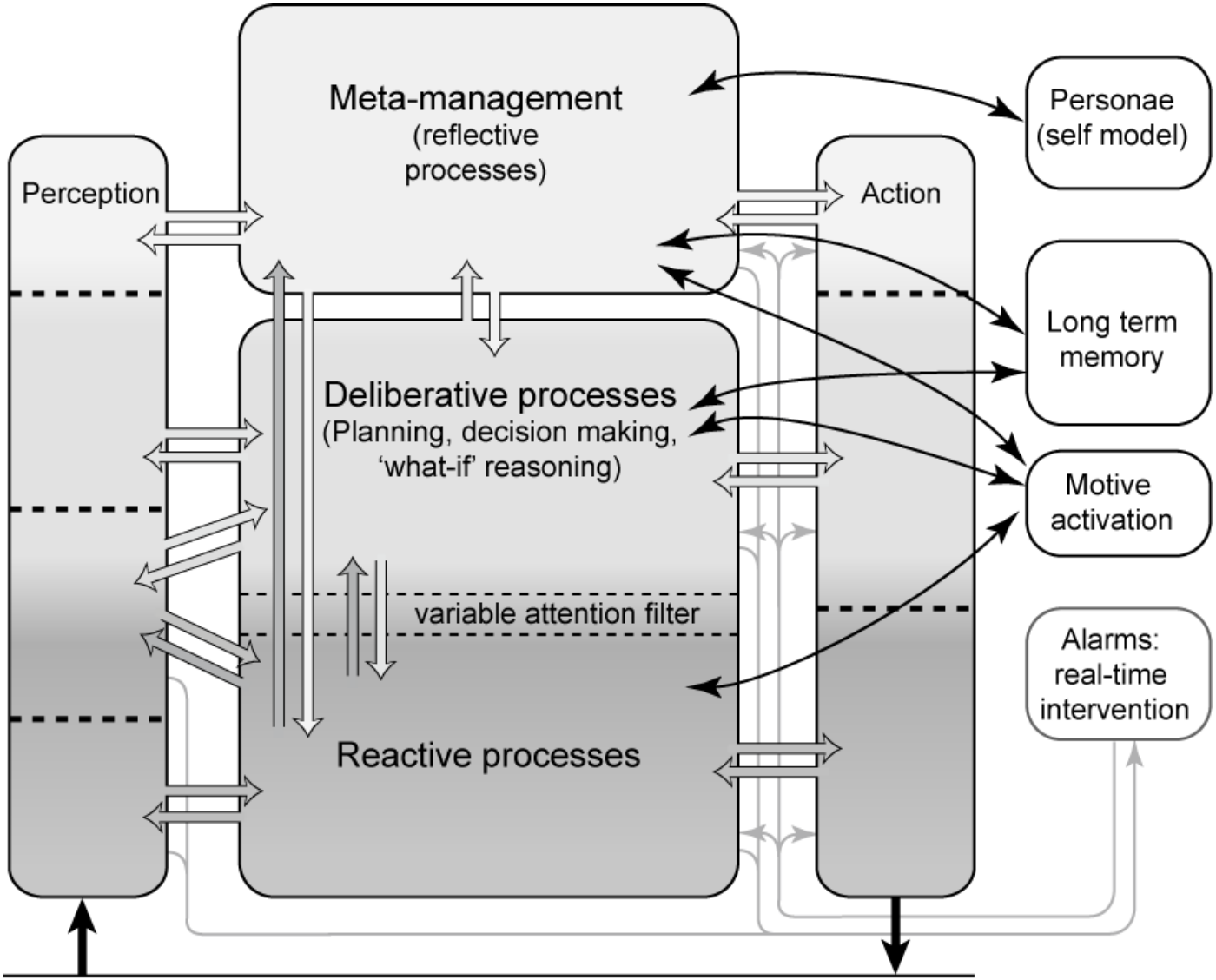
Columns of Cognition



Cognitive Grid

Reflexive Perception	Meta-Management	Management Action
Deliberative Perception	Planning, Reasoning	Deliberative Action
Reactive Perception	Reflexes	Reflexive Action

Conceptual Analysis: HCogAff (Sloman 2001)



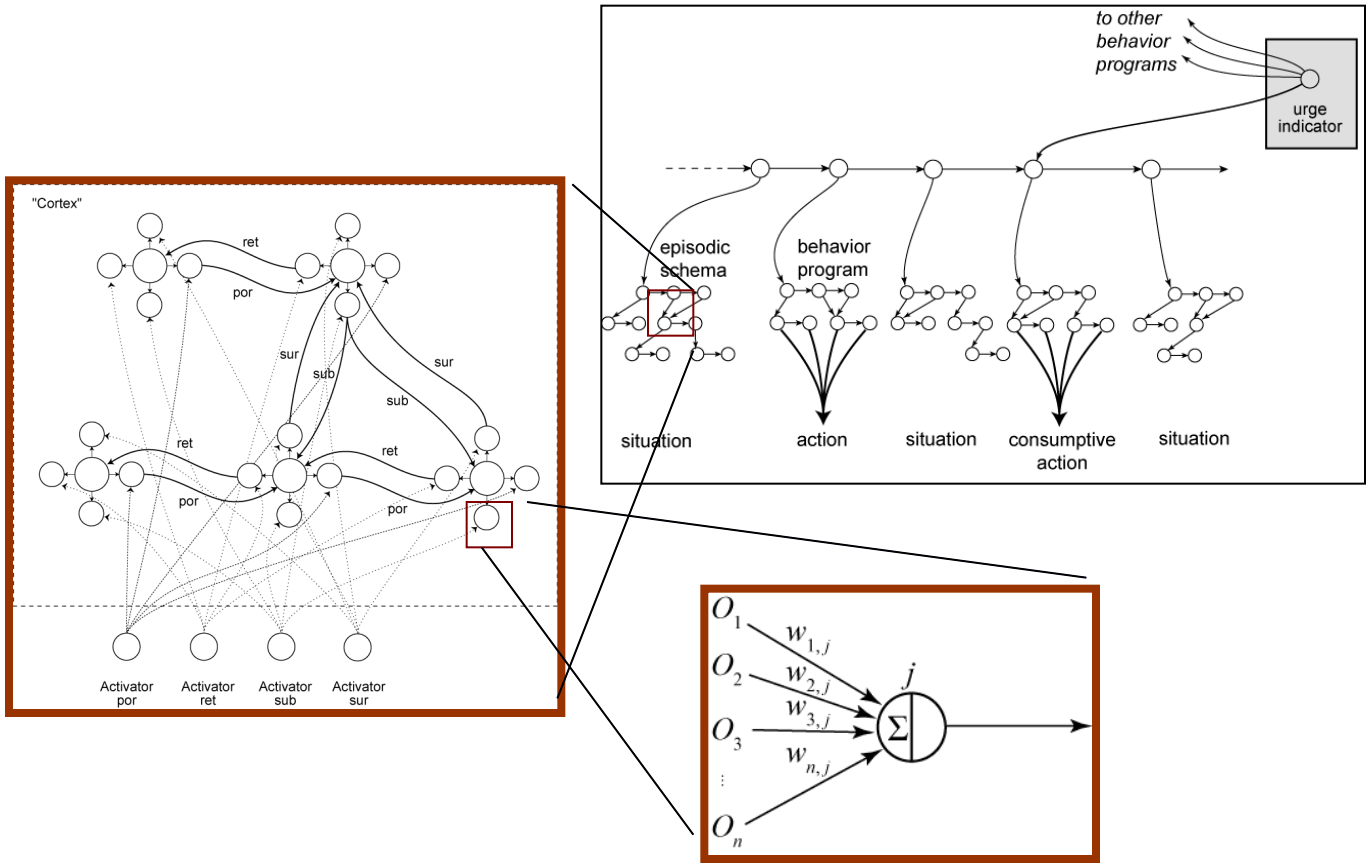
Artificial General Intelligence

Methods should focus on components and performances necessary for intelligence:

- **Whole, testable architectures**
- **Universal Representations:**
  Dynamic model of environment, possible worlds, and agent
- **(Semi-) Universal Problem Solving:**
  Learning, Planning, Reasoning, Analogies, Action Control, Reflection ...
- **Universal Motivation:**
  Polythematic, adaptive goal identification
- **Emotion and affect**

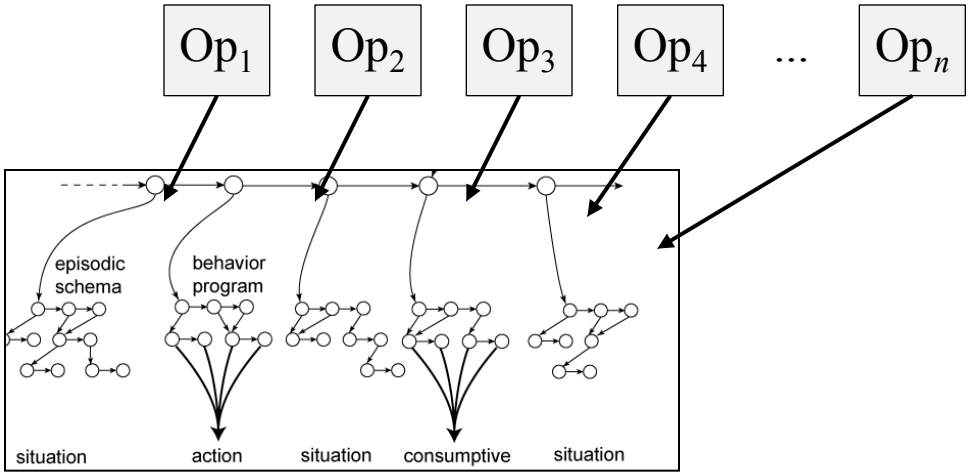
Components for Cognitive AI

- Universal mental representations
  (compositional + distributed → neurosymbolic)



Components for Cognitive AI

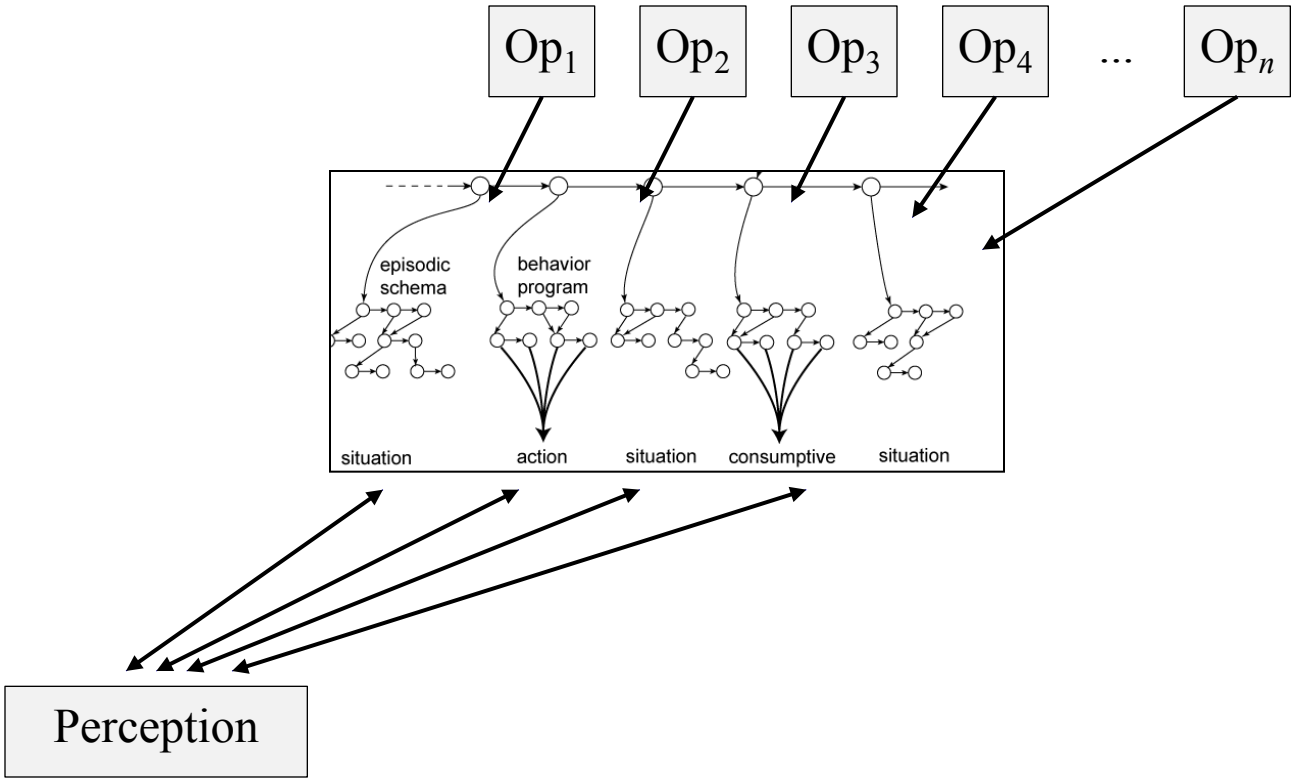
- (Semi-) General problem solving: Operations over these representations



(neural learning, categorization, planning, reflection, consolidation, ...)

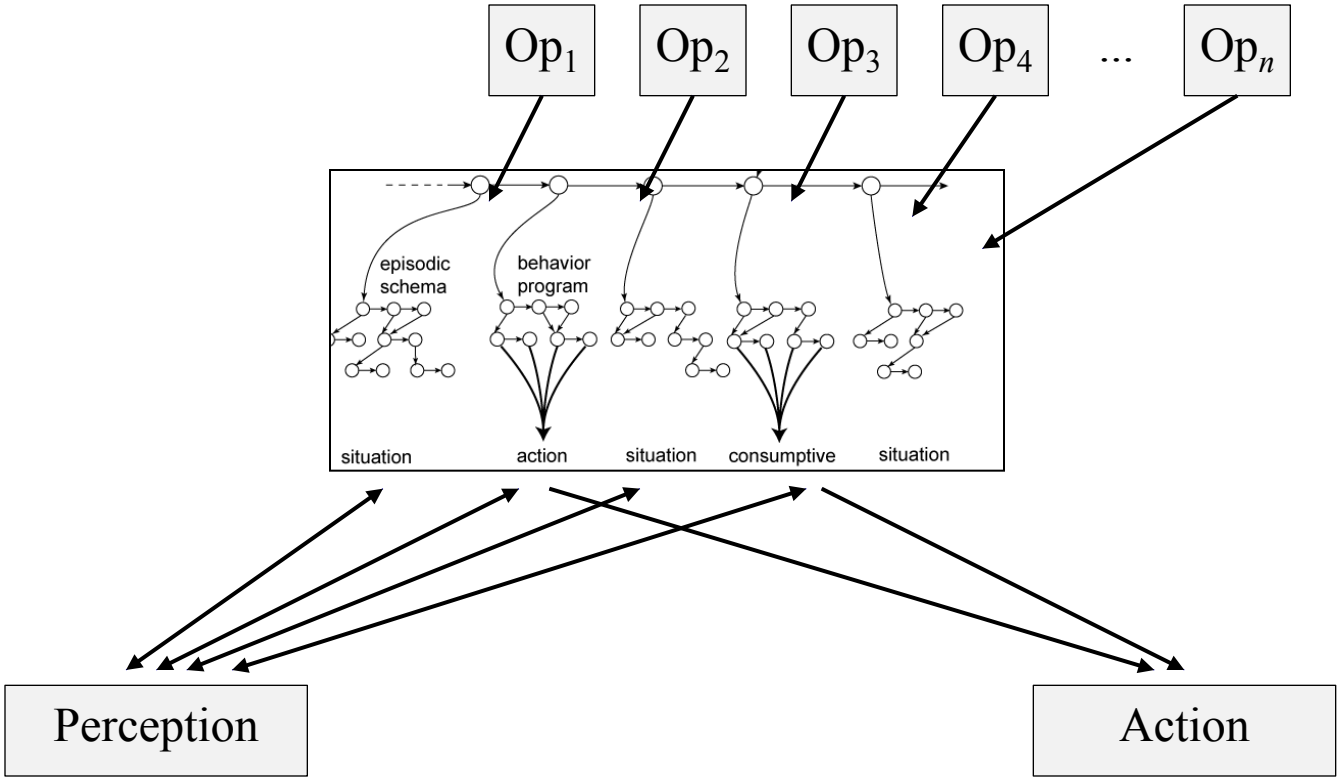
Components for Cognitive AI

- Perceptual grounding



Components for Cognitive AI

- Perceptual grounding and action



Components for Cognitive AI

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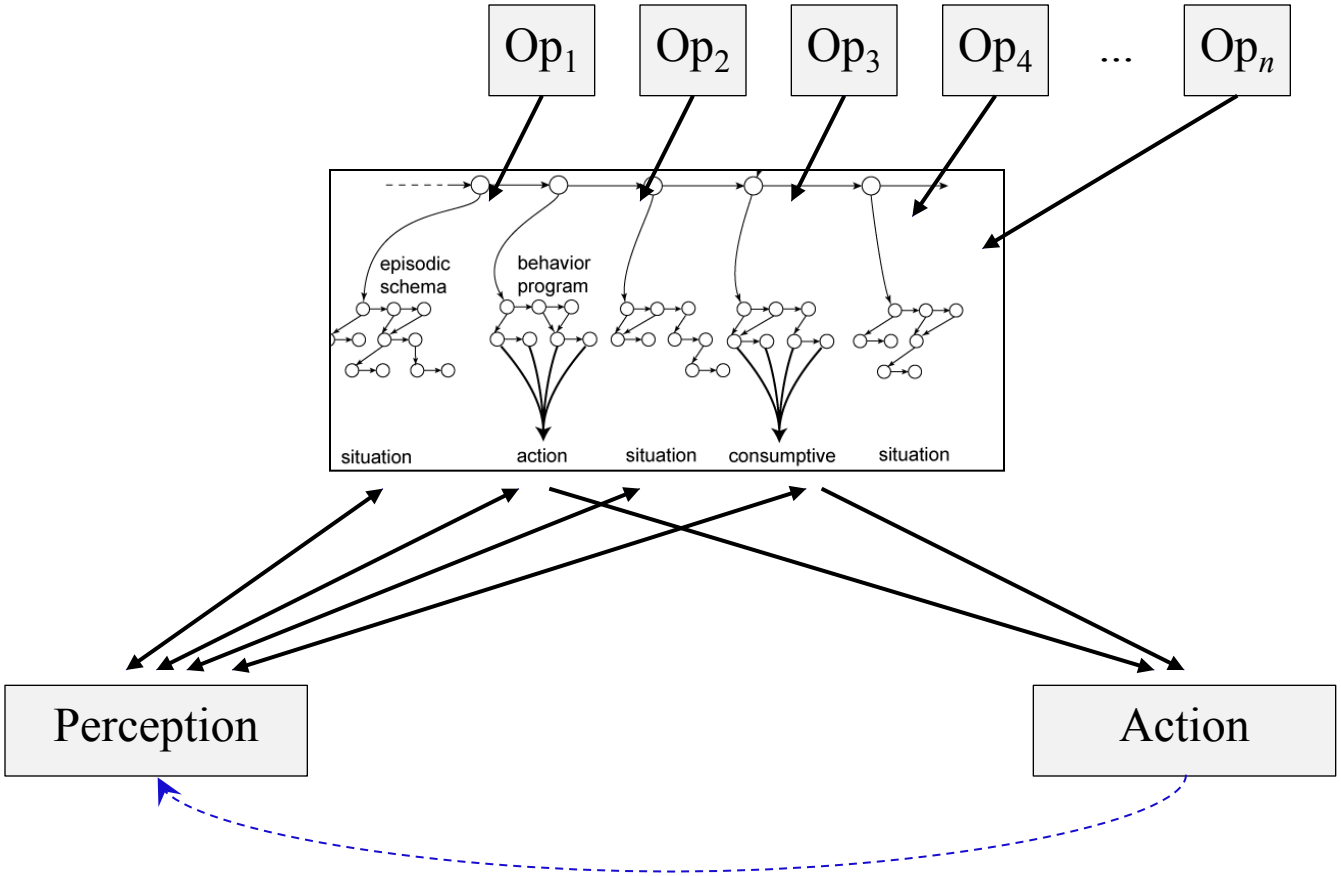
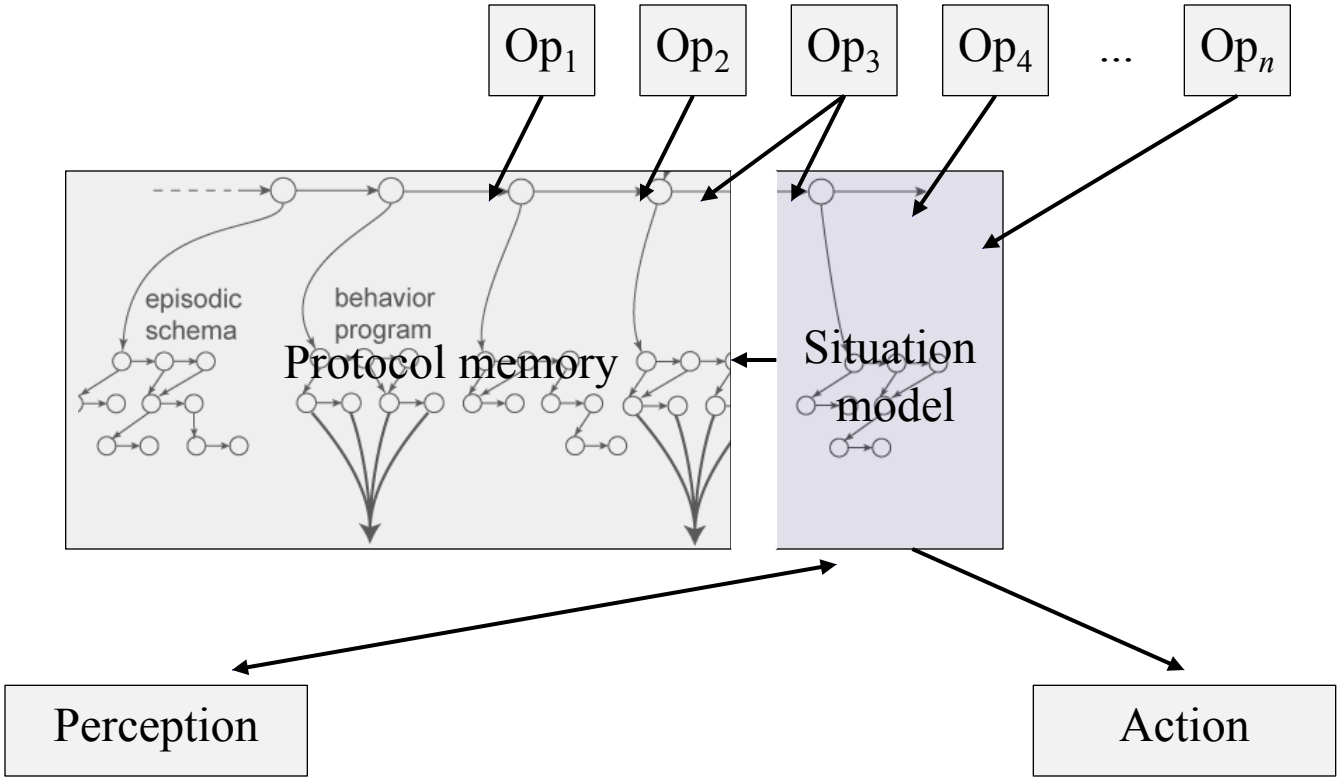


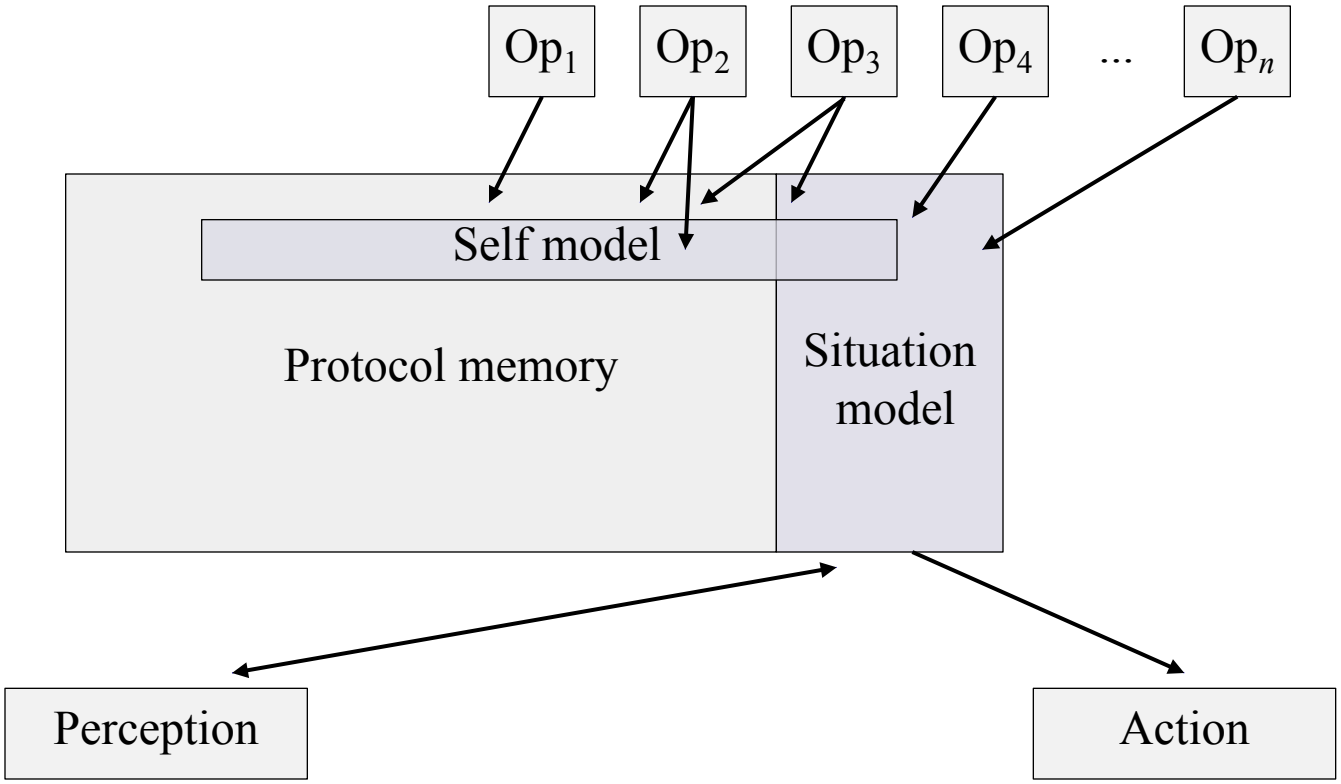
Components for Cognitive AI

- Model of current situation, and protocol of past situations



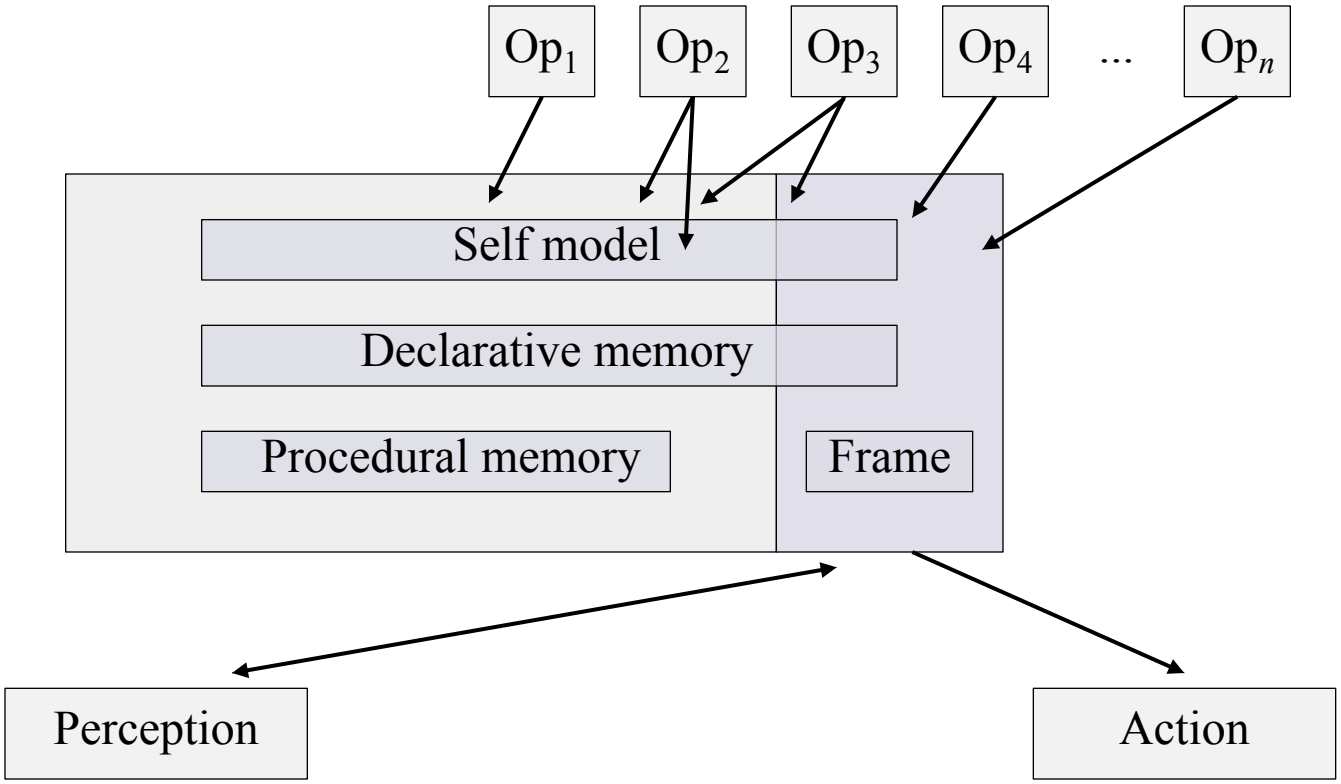
Components for Cognitive AI

- Model of self



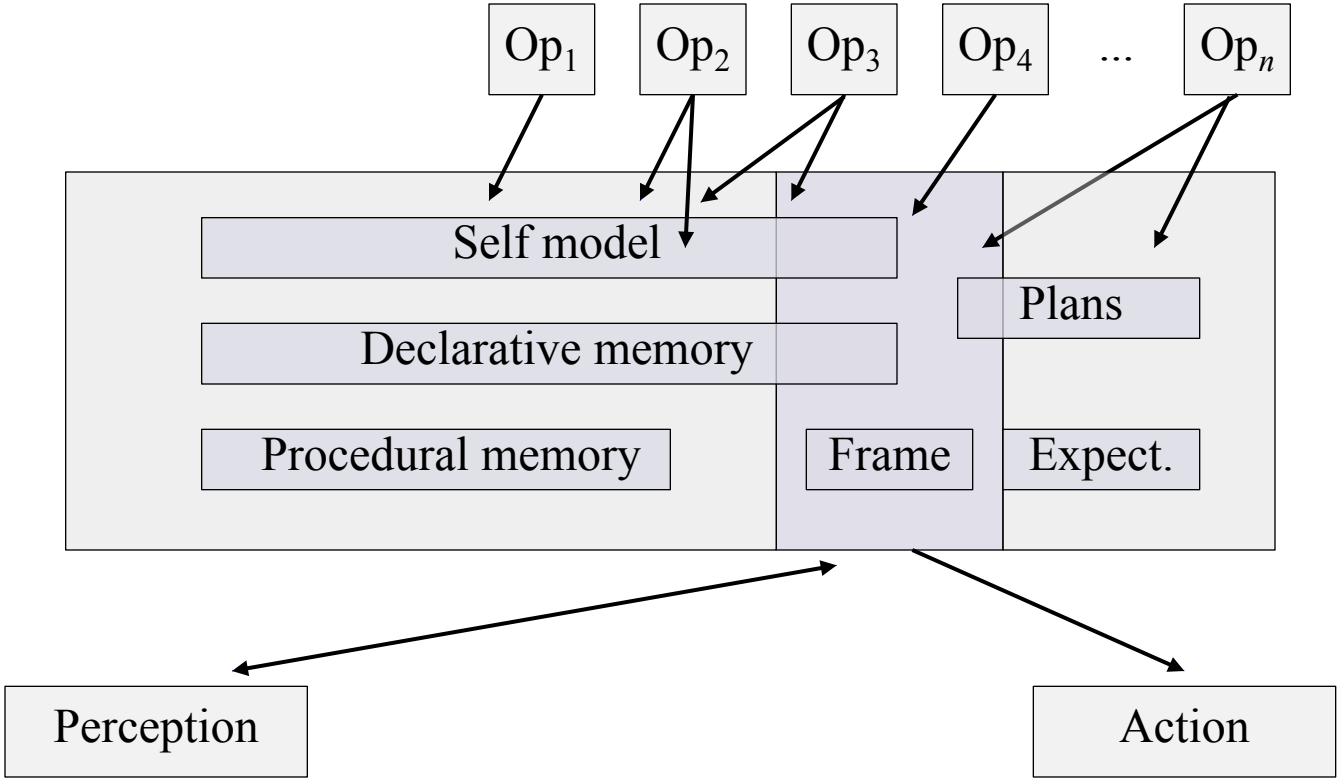
Components for Cognitive AI

- Abstractions of objects, episodes and types



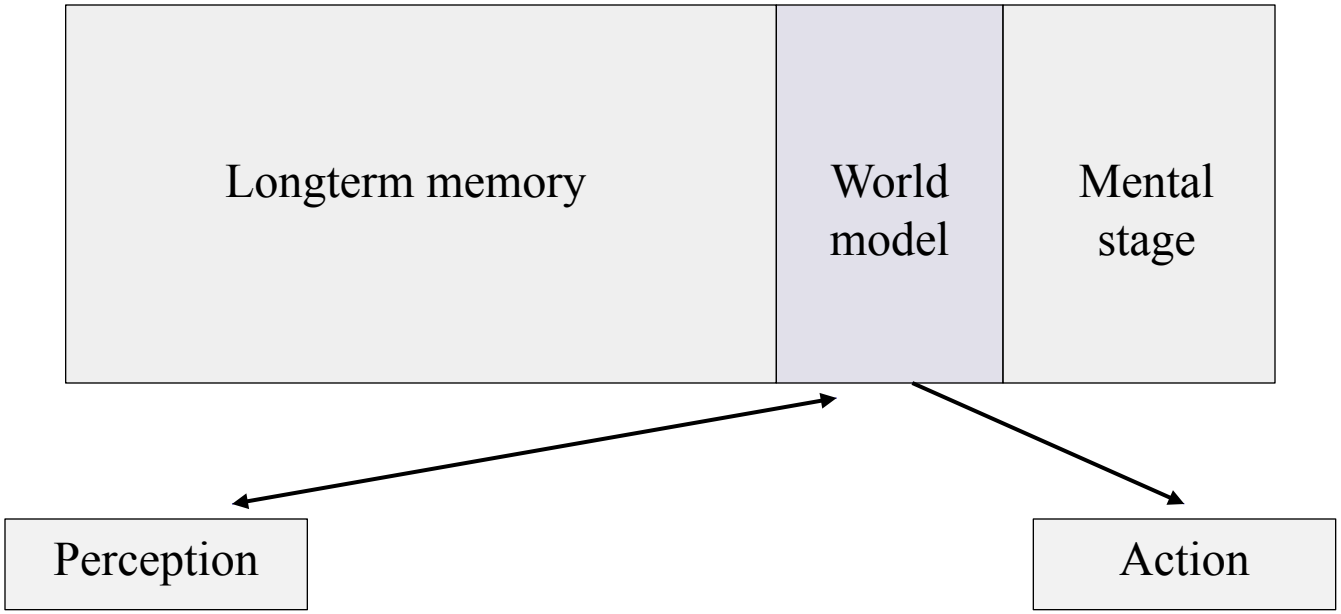
Components for Cognitive AI

- Anticipation of future developments



Components for Cognitive AI

- Action selection and executive control



Components for Cognitive AI

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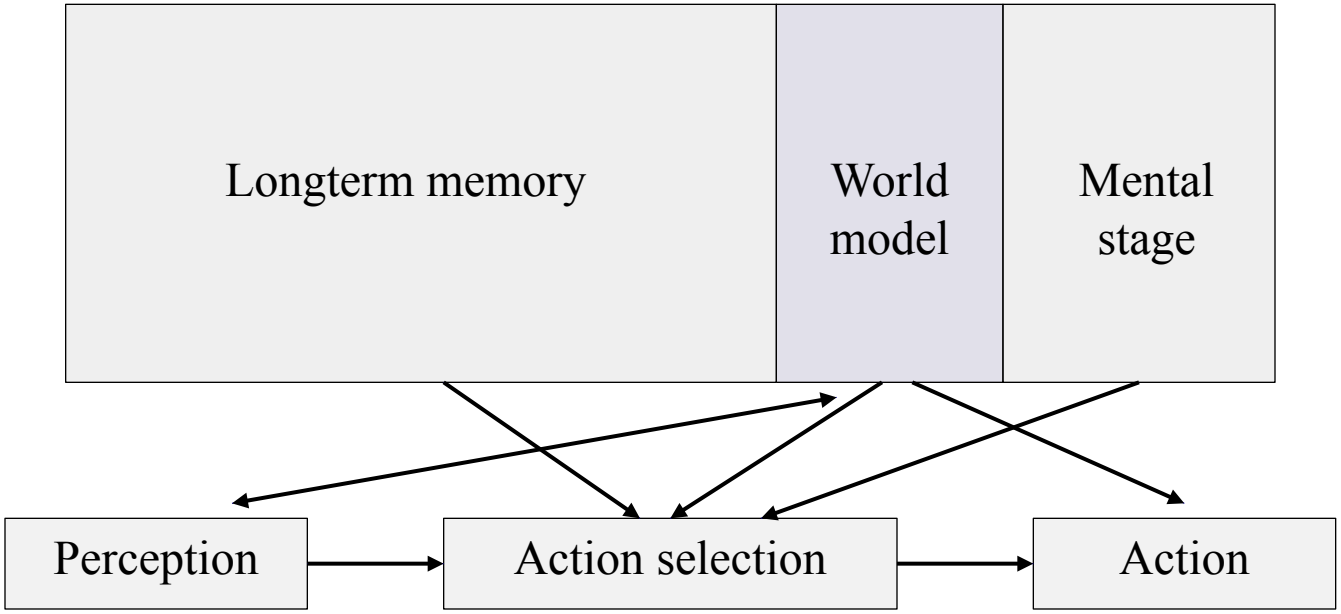
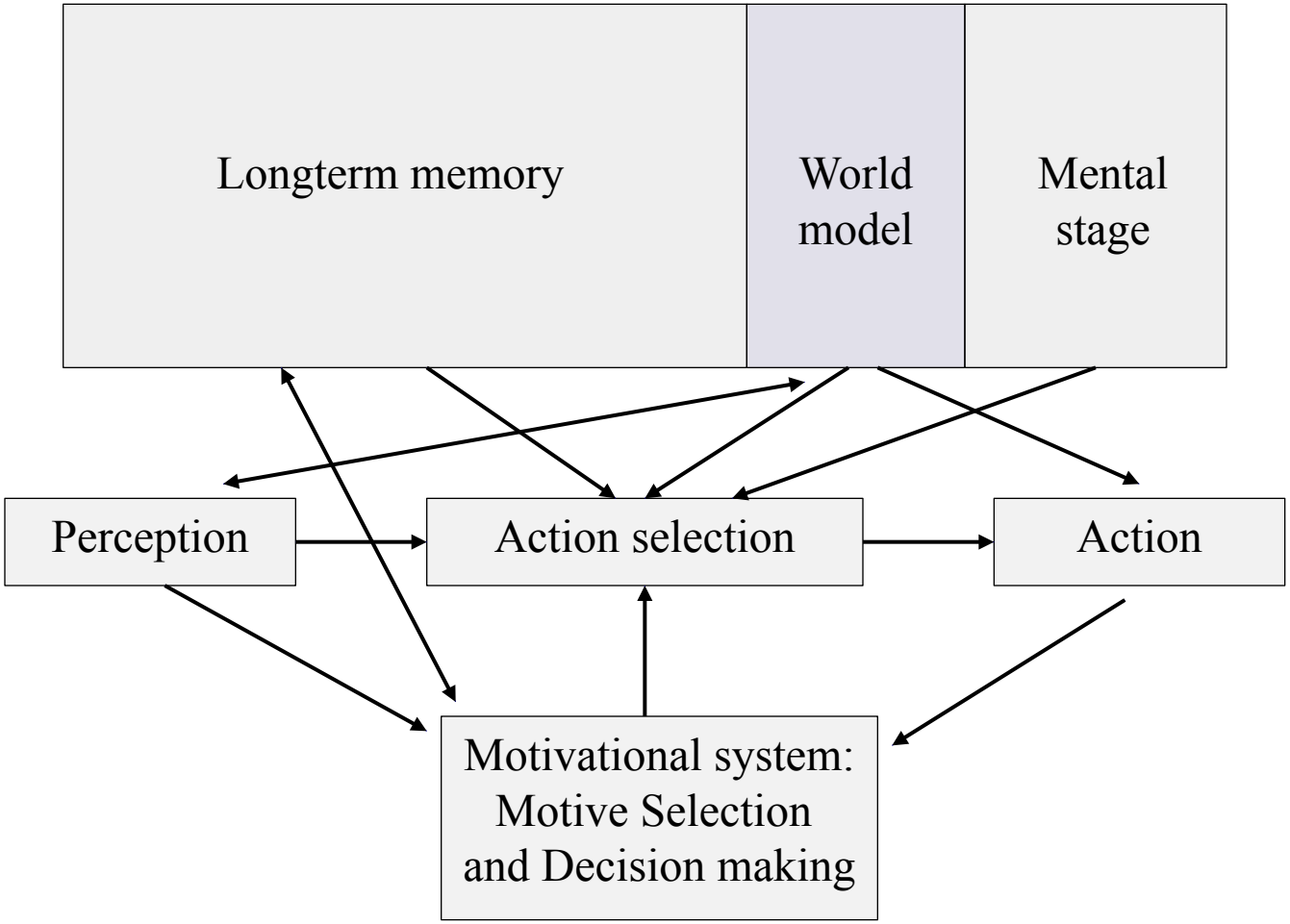


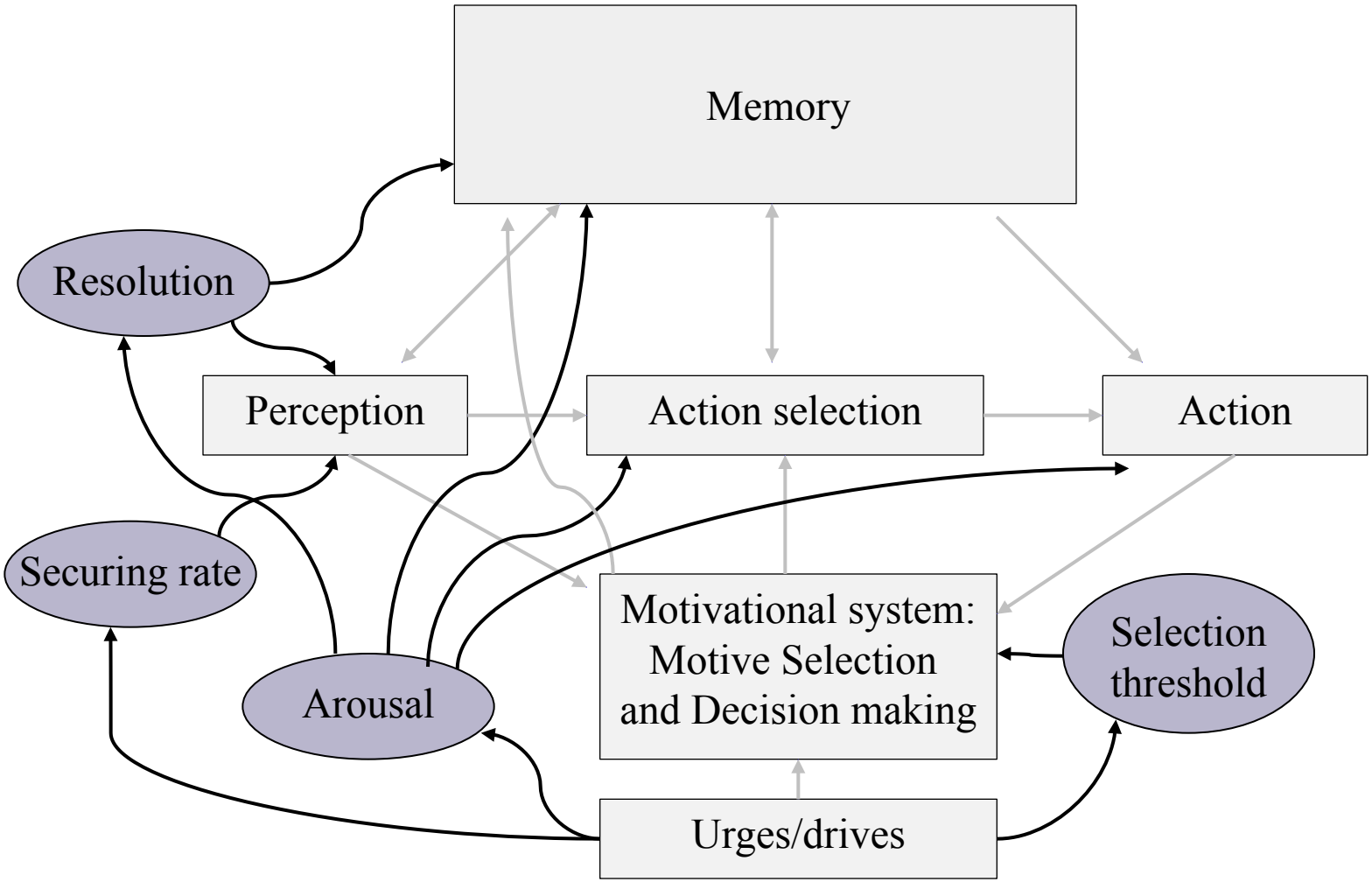
Components for Cognitive AI

- Universal motivation: autonomous identification of goals

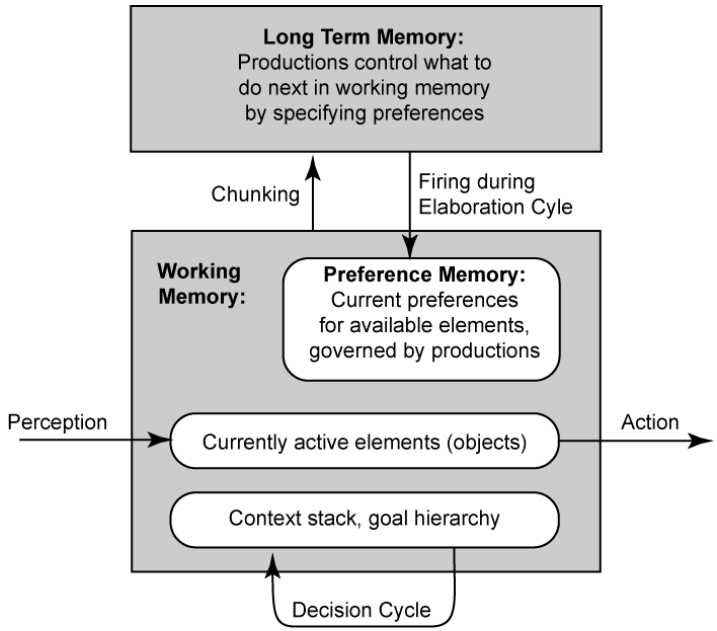


Components for Cognitive AI

- Emotional modulation and affect



Cognitive Architectures



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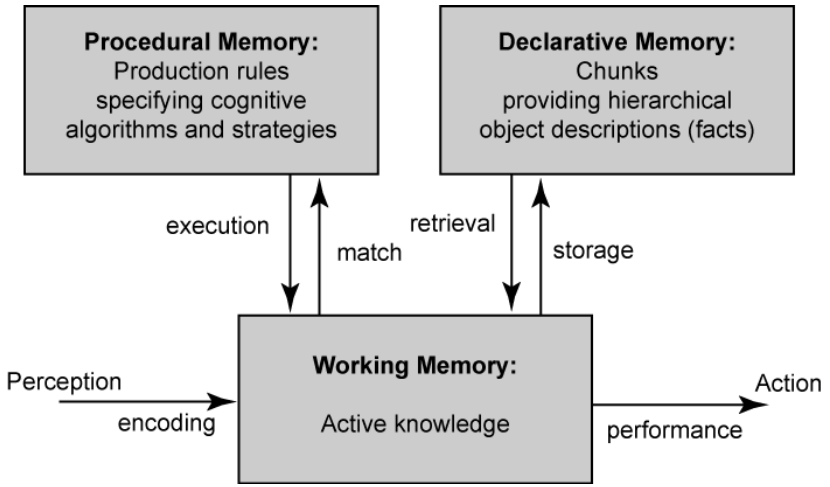
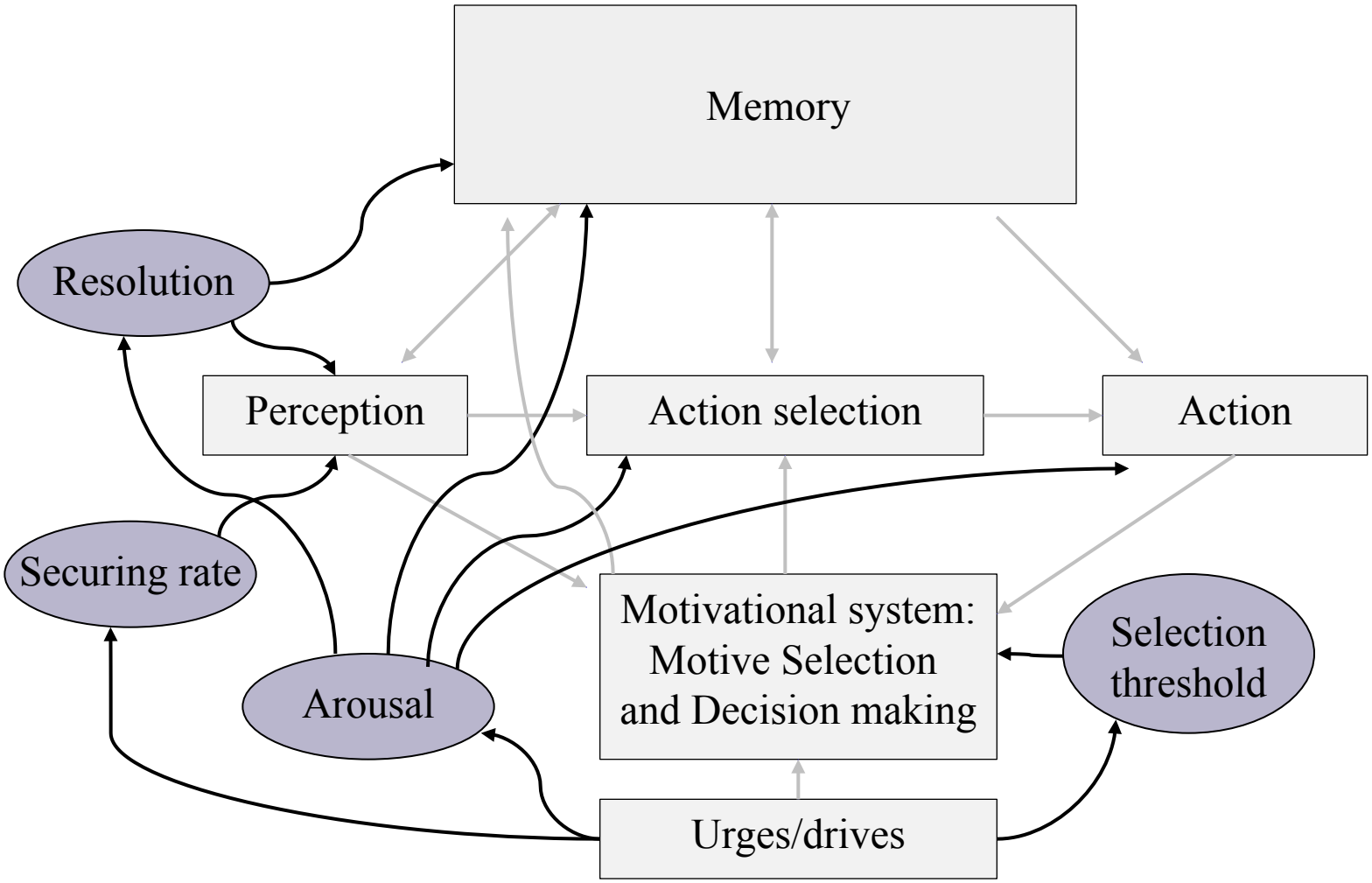


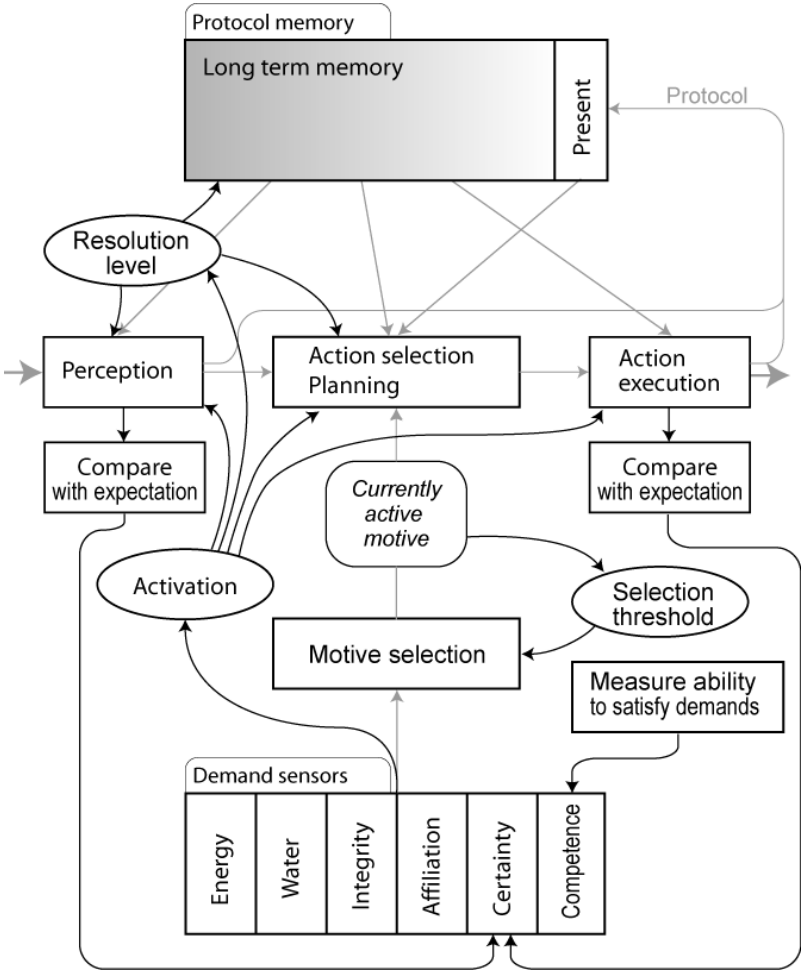
ACT-R

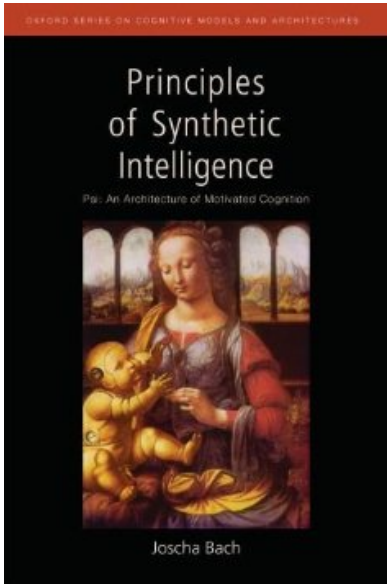
"Classical Cognitive Architectures" tend to focus on cognition as an isolated problem solving capability.

Components for Cognitive AI



MicroPsi architecture



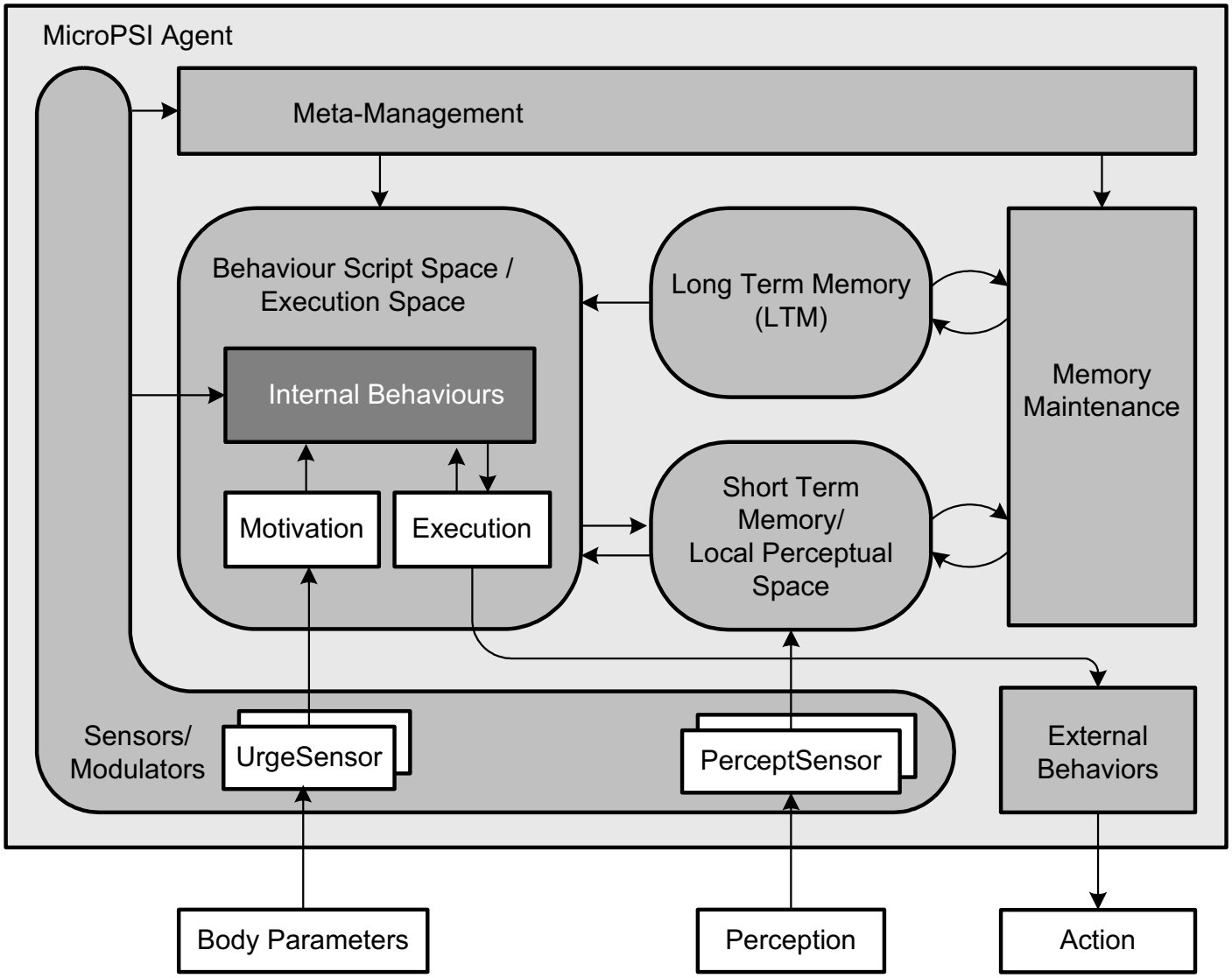


PSI theory

Principles of Synthetic Intelligence

(Dörner 1999; Bach 2003, 2009)

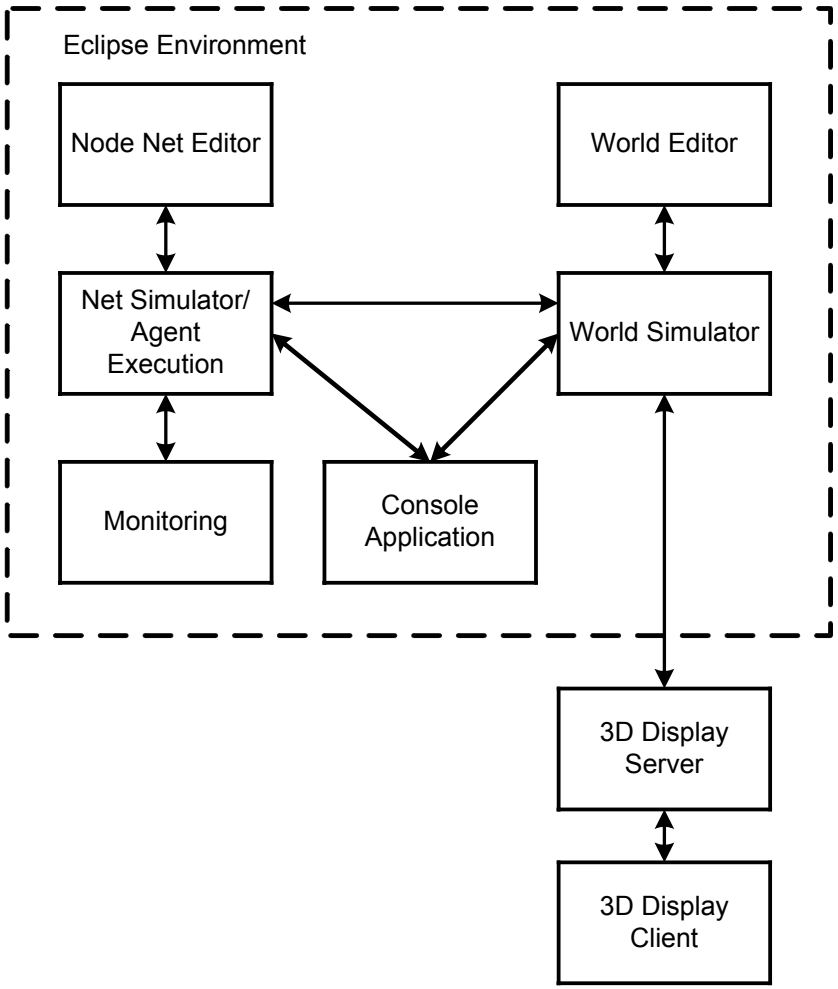
MicroPsi Architecture–simplified



Agent Functionality

- Episodic learning
- Goal-directed behavior, motivational system
- Emotional modulation
- Hypothesis based perception
- Simple planning
- Execution of hierarchical plans

Implementation: MicroPsi (Bach 03, 05, 04, 06)



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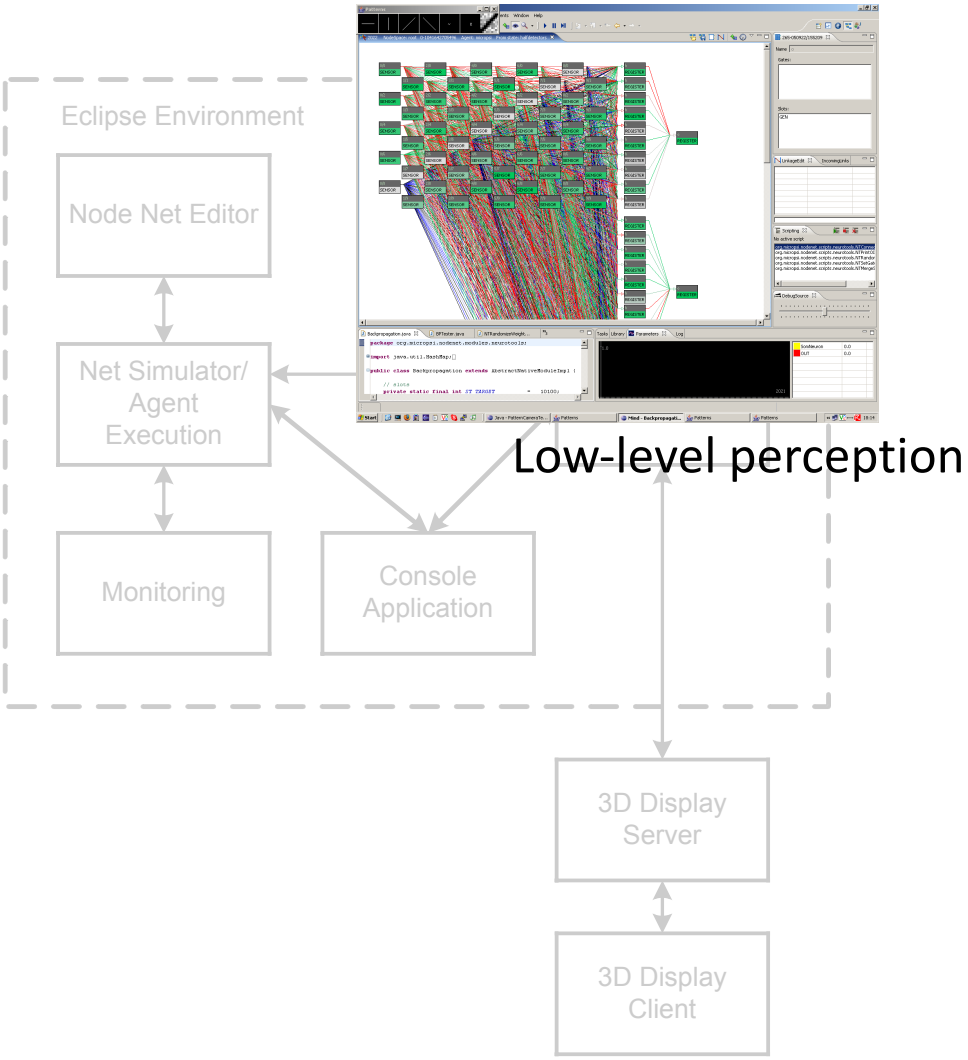

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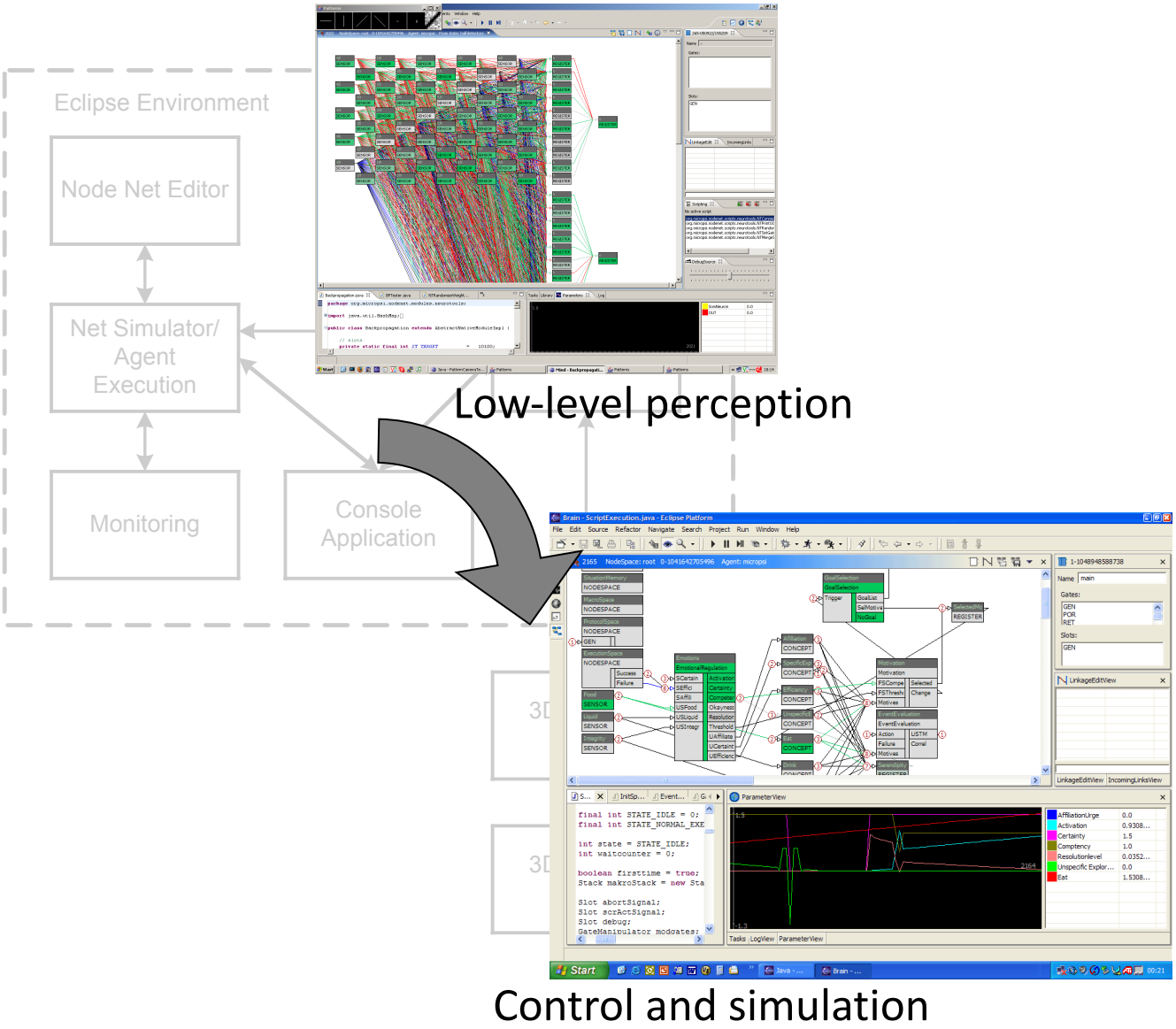

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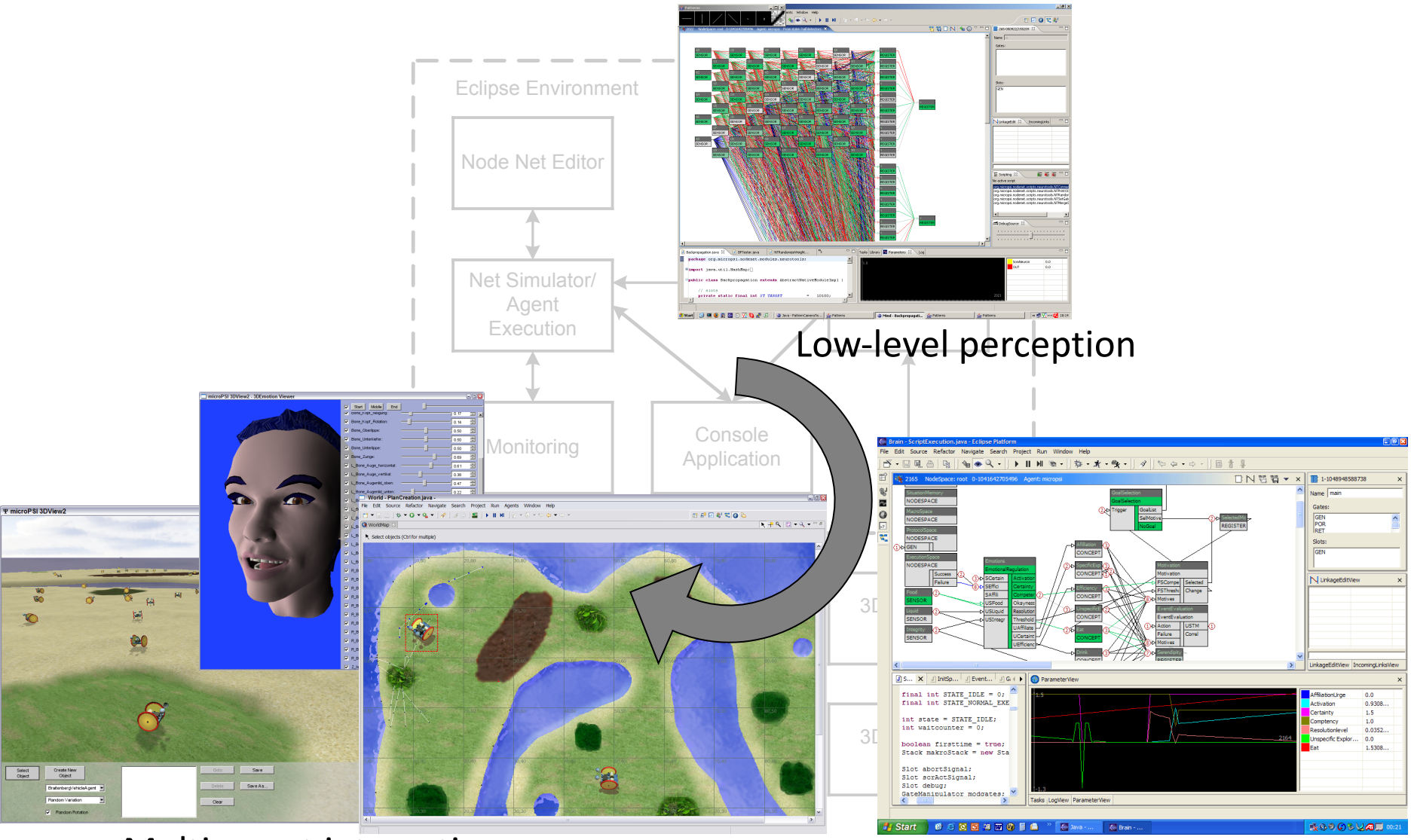

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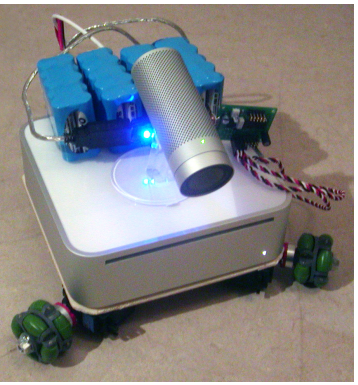
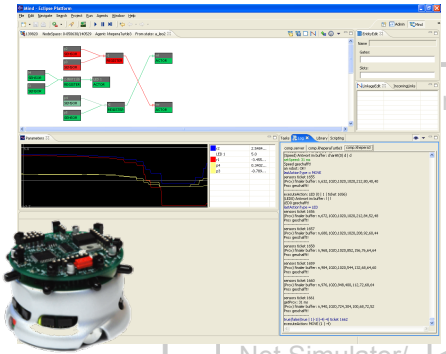
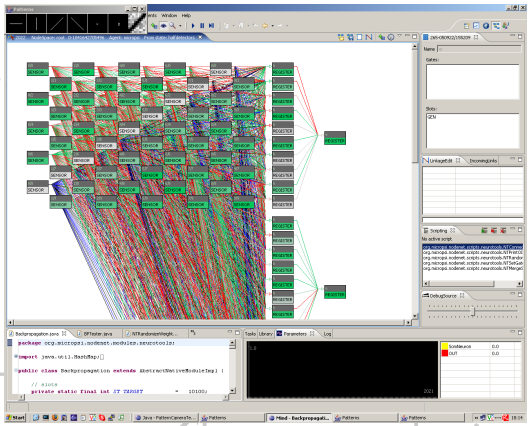
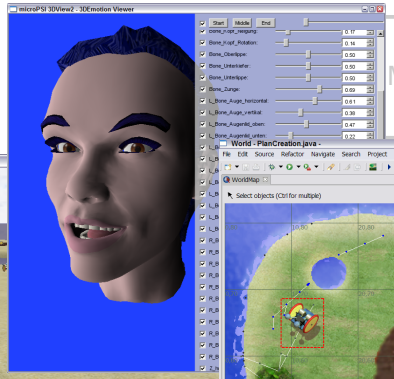


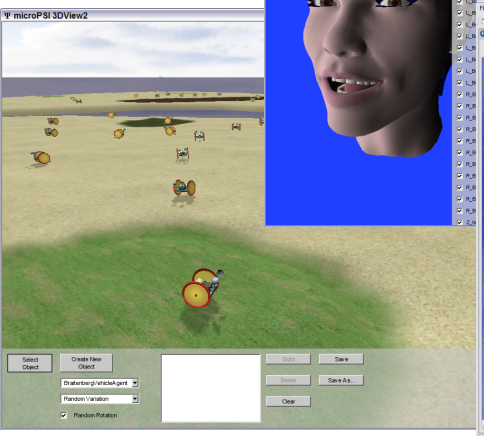
Robot control

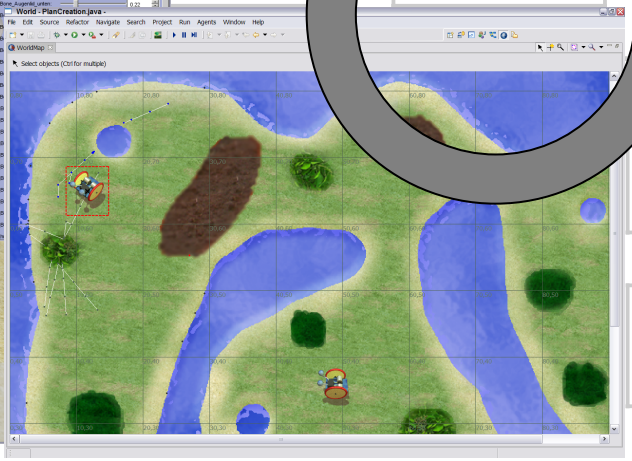




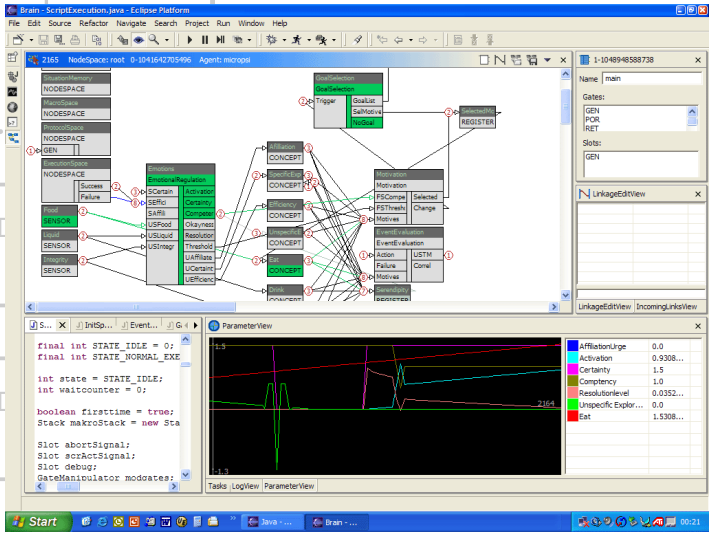
Low-level perception





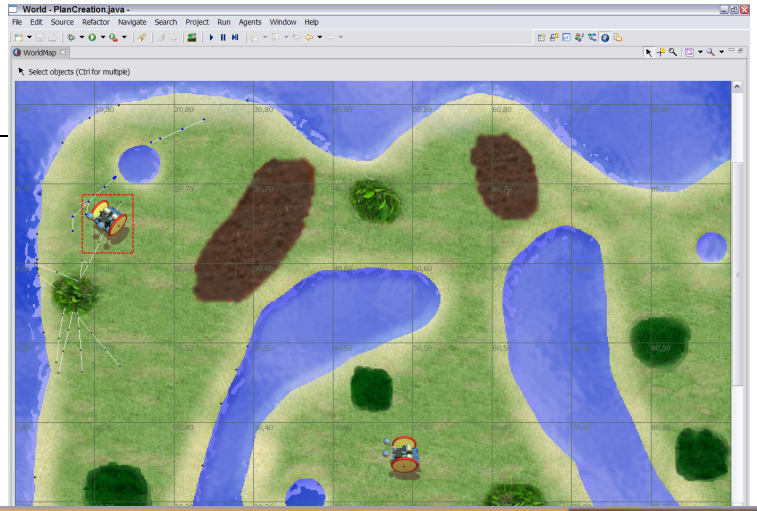


Multi-agent interaction

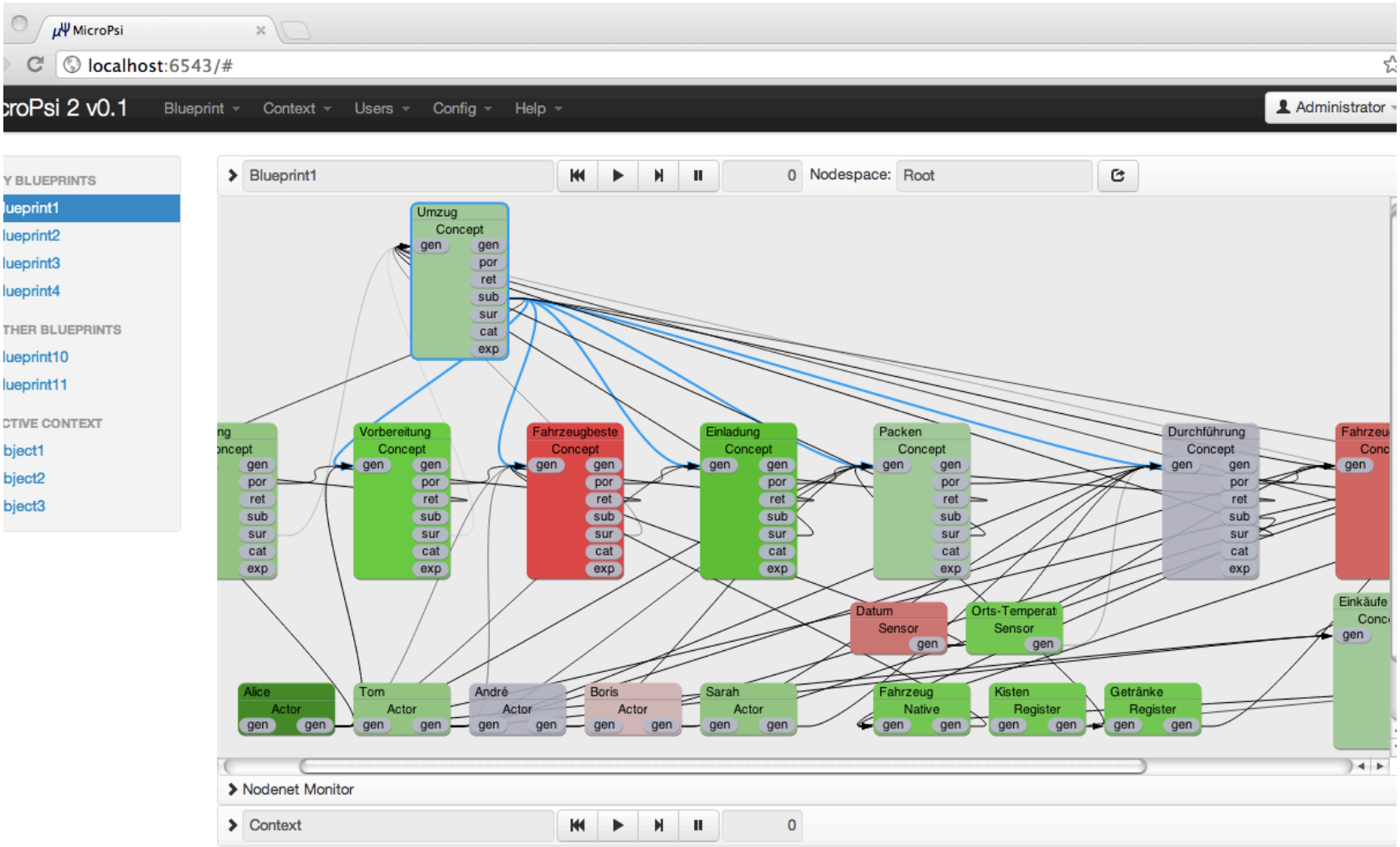


Control and simulation

Different simulation environments



Implementation: MicroPsi 2 (Bach, Welland, Vuine, Herger 12, 14, …)



Cognitive Artificial Intelligence

Methods should focus on components and performances necessary for intelligence:

- **Universal Representations:**
  Dynamic model of environment, possible worlds, and agent
- **(Semi-) Universal Problem Solving:**
  Learning, Planning, Reasoning, Analogies, Action Control, Reflection ...
- **Universal Motivation:**
  Polythematic, adaptive goal identification
- **Emotion and affect**
- **Whole, testable architectures**

Modeling Motivation

Modeling Motivation in a Cognitive Architecture

- *General intelligence needs General Motivation*
- Motivational system structures cognition
- Motivational dynamics: physiological, social and cognitive drives
- Intention selection and action control
- Motivation vs. affect

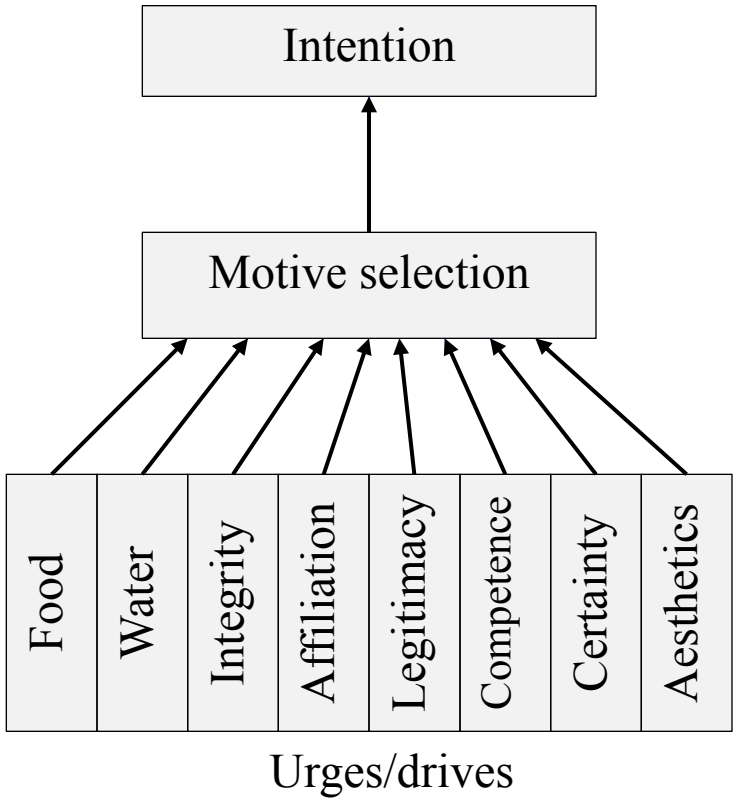
Motivation vs. emotion

- Motivation:
  - reflects needs
  - gives rise to goals and directed behavior
  - does not have to be associated with emotions

- Emotion:
  - modulates perception, cognition, action
  - receives valence from motivation
  - receives objects from cognition
  - leads to affective expression

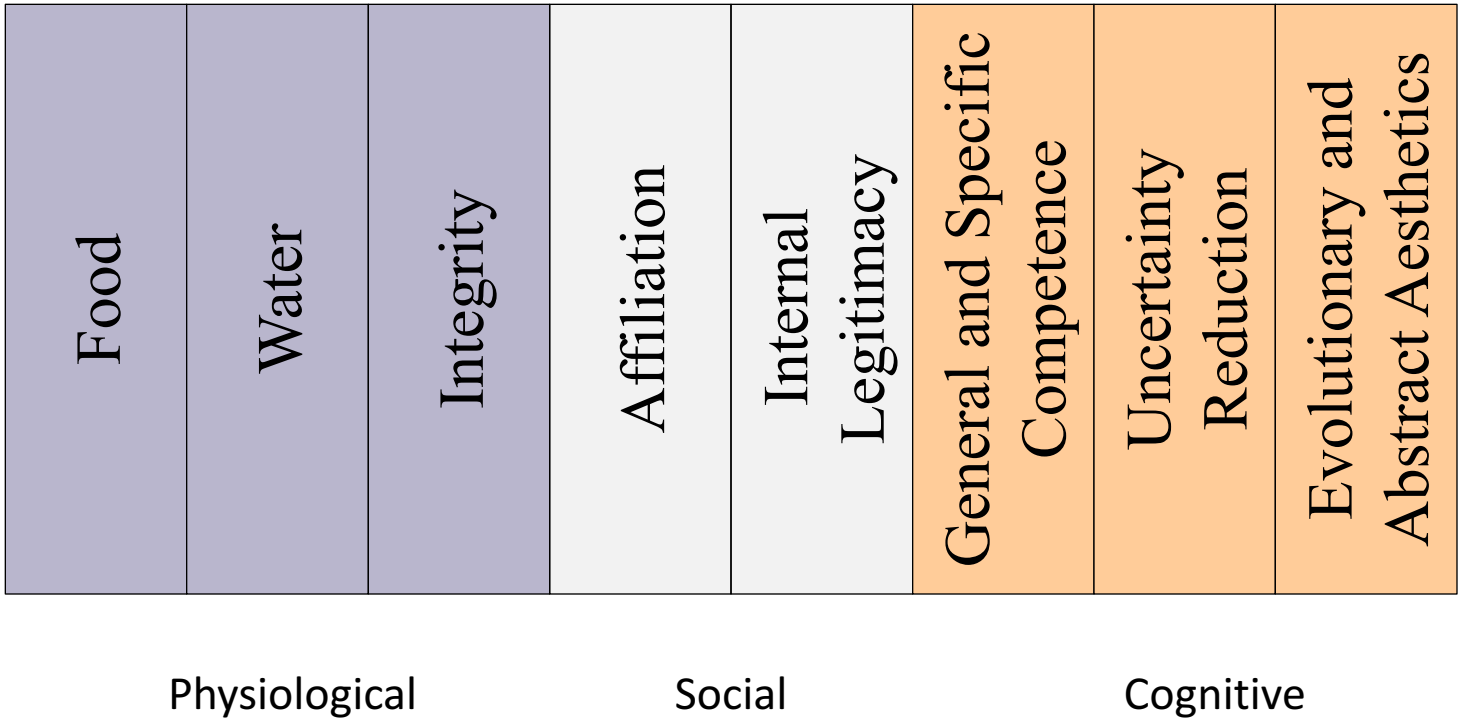
Motivational System

- All goals attempt to satisfy a (hard-wired) demand
  → flexible goals, but (evolutionary) suitable behavior



Motivational System

- Drives correspond to set of demands of the agent



Physiological Drives

- if autonomous regulation of body processes fails
  → actively manage physiology (seek food, water, healing, shelter, rest, warmth, ...)
  → escape perilious situations
  → **implicitly** seek physical survival

Social Drives

- *Affiliation*: structure social interaction beyond rational utility
- increased by 'legitimacy signals', decreased by 'anti legitimacy signals' (and adaptively over time); allows for non-material reward and punishment

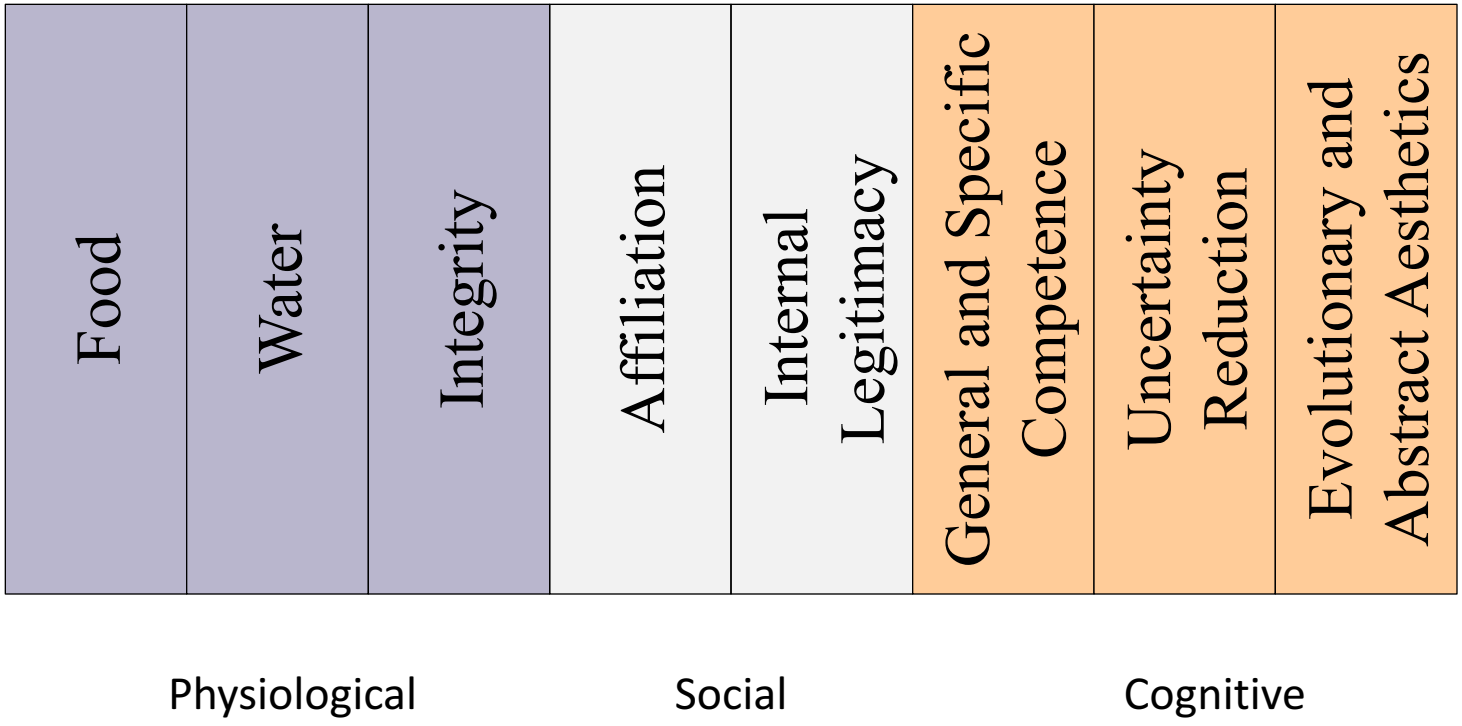
- *external* legitimacy: group acceptance
- *internal* legitimacy: "honor", conformance to internalized social norms

Cognitive Drives

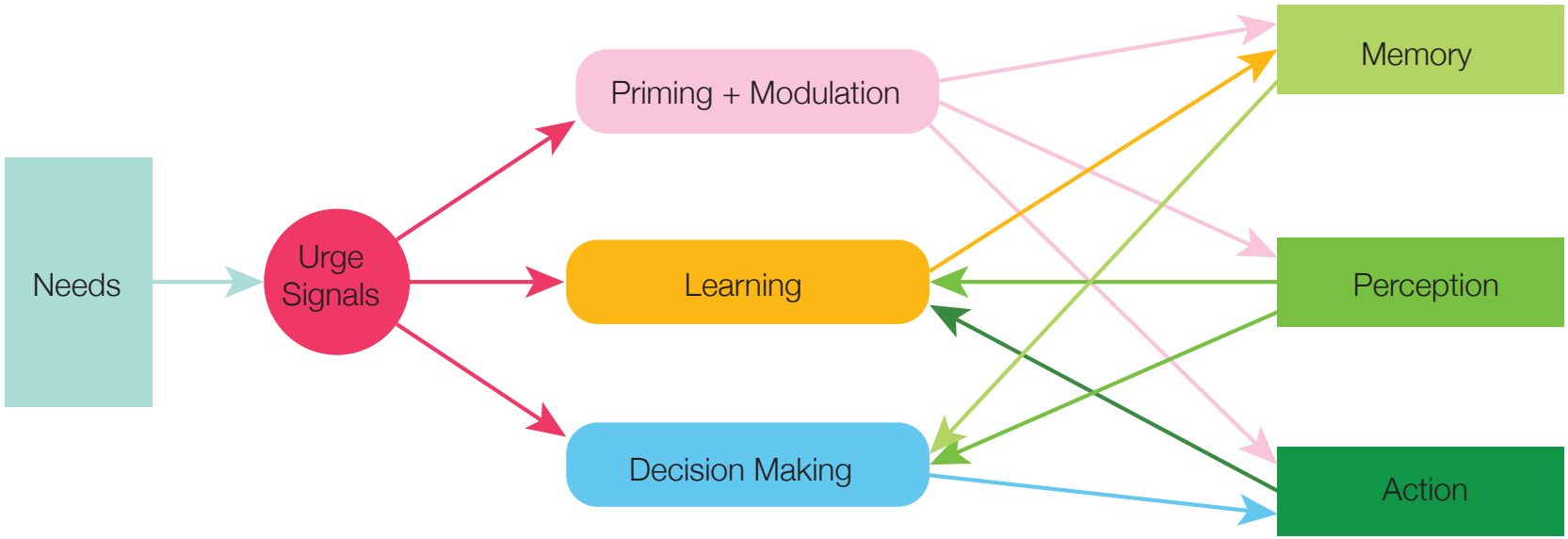
- Competence
  - epistemic (problem specific)
  - general (ability to satisfy demands)
  - effect oriented
- Uncertainty reduction
  - novelty seeking
- Aesthetics
  - evolutionary preferences (stimulus oriented)
  - abstract (representation oriented)

Motivational System

All possible goals correspond to (at least one) demand



From Needs to Behavior



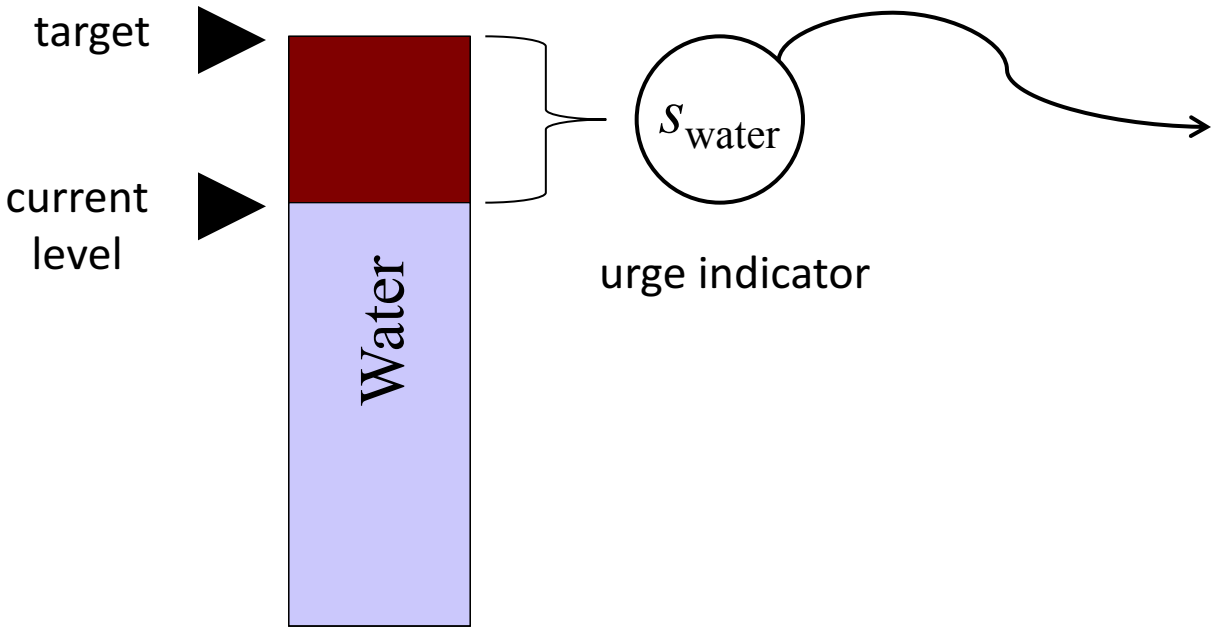
Pleasure and distress:

- *Change* of a demand is reflected in *pleasure* or *distress signal*
- Strength is *proportional* to amount of change

- Pleasure and distress signals deliver ***reinforcement*** values for behavioral procedures and episodic sequences and define ***appetitive*** and ***aversive*** goals.

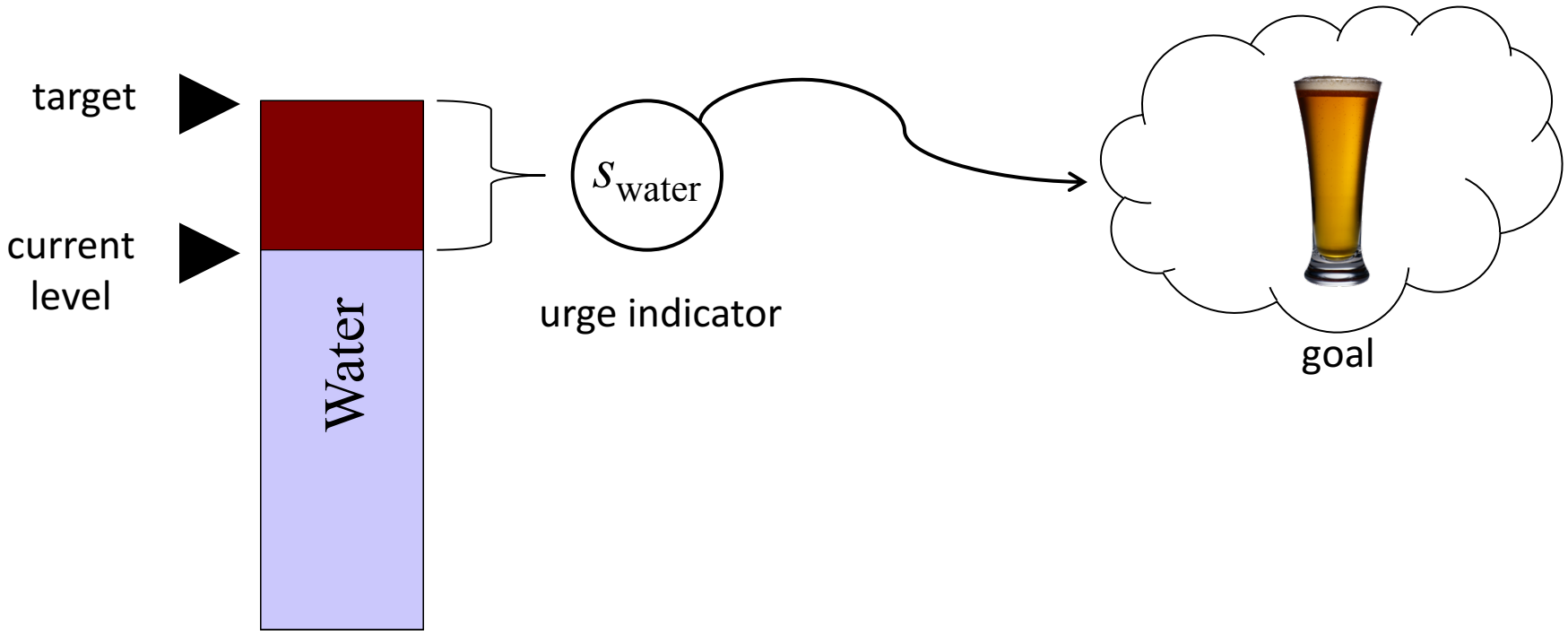
Motivational System

- drive = demand + urge indicator



Motivational Learning

- motive = urge + goal situation



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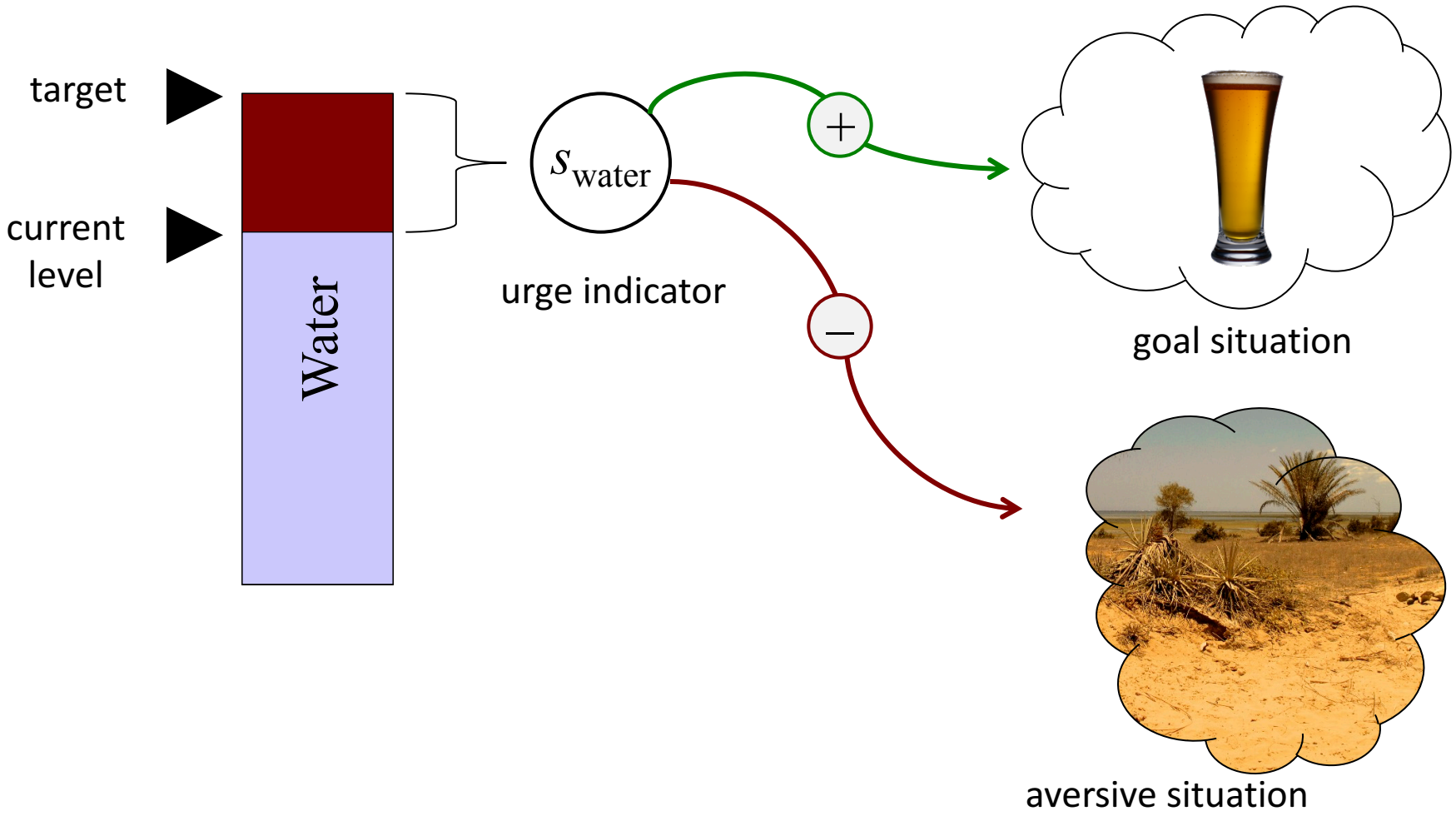


Goals

- Goal: situation or action that affords to satisfy a need
- Aversive goal: situation or action that frustrate a need
- All behavior is directed on satisfying an appetitive goal or avoiding an aversive goal
- Needs are predefined, goals are learned

Physiological needs

- Thirst
- Hunger
- Rest
- Warmth
- Libido
- …

→ Survival as emergent property

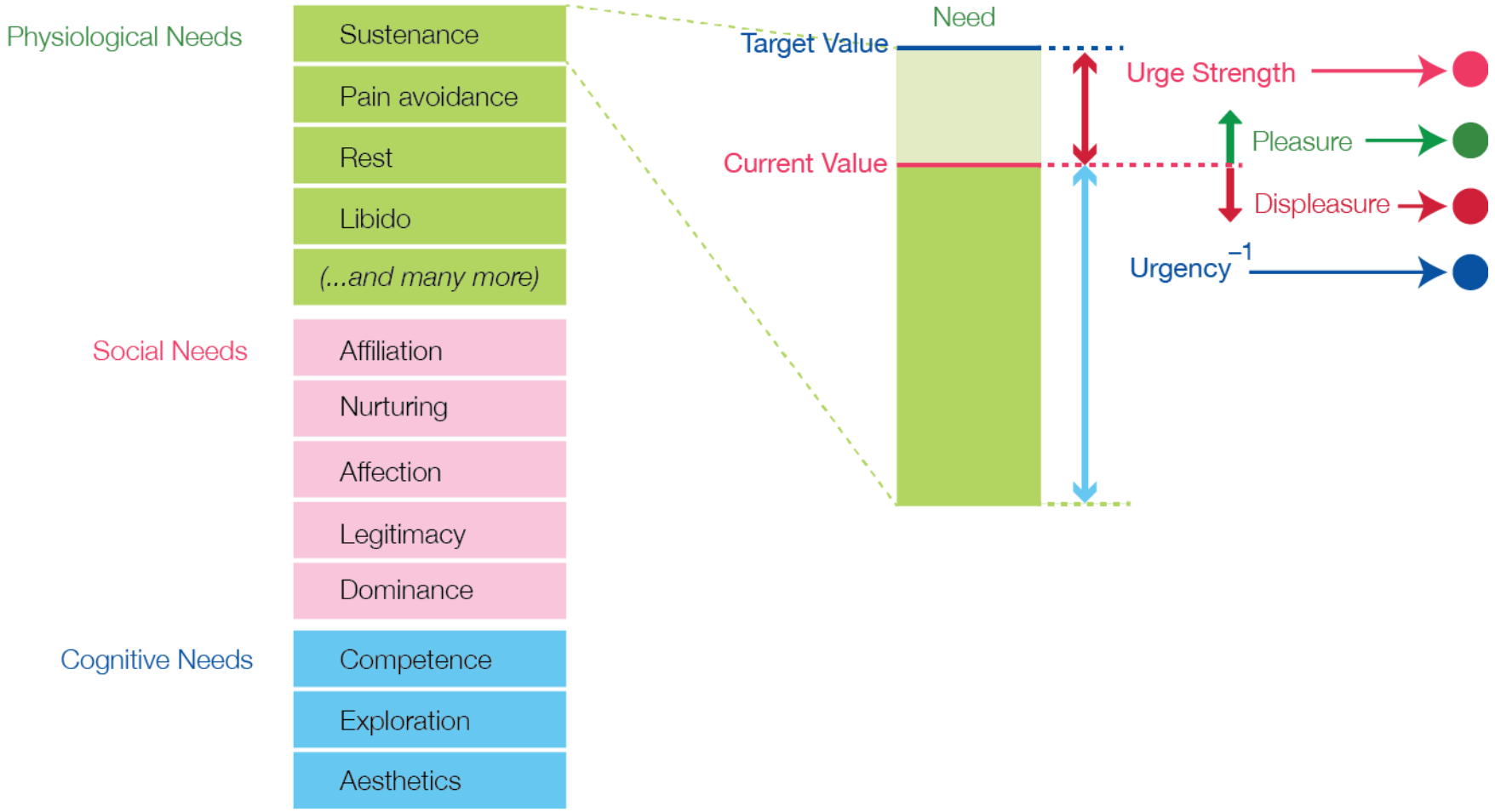
Social needs

- Affiliation (Attention from others, external legitimacy)
- Internal legitimacy
- Nurturing (caring for others)
- Affection
- Dominance

Cognitive needs

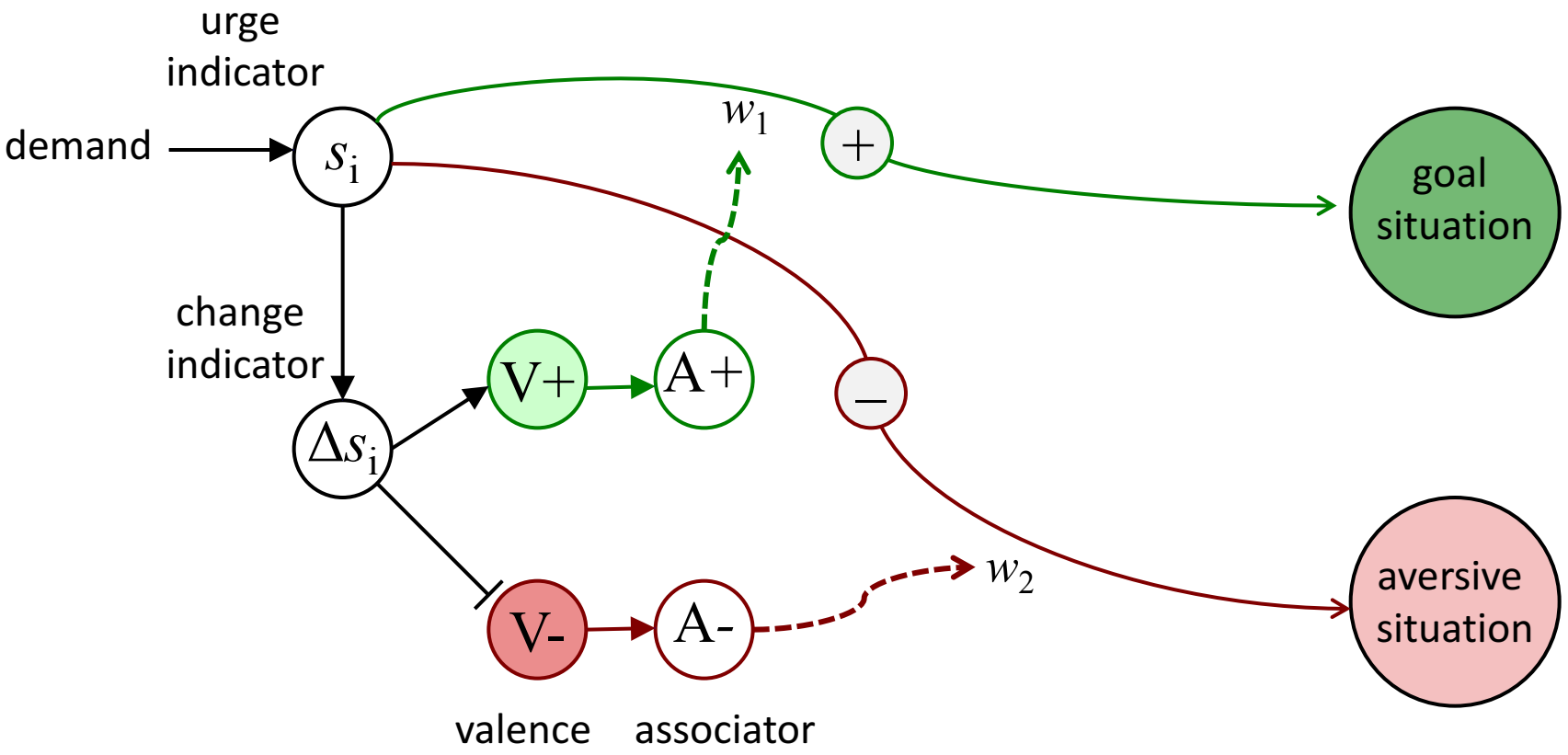
- Competence:
  - Skill acquisition (epistemic competence)
  - Coping/control ability (general competence)
  - Effect generation
- Uncertainty reduction:
  - Exploration
- Aesthetics:
  - Stimulus oriented
  - Structure oriented (abstract aesthetics)

Needs and urges



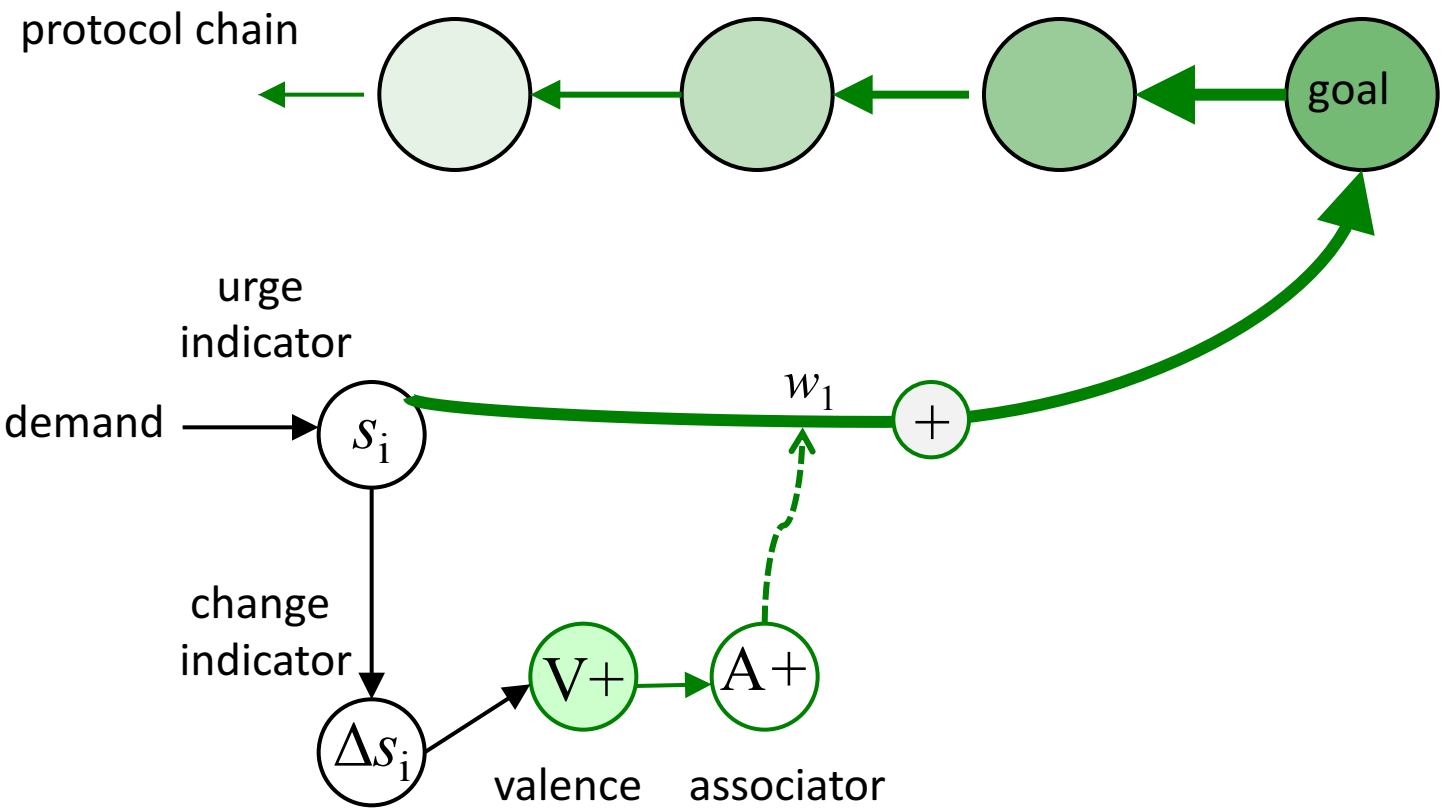
Motivational Learning

- association by learning:



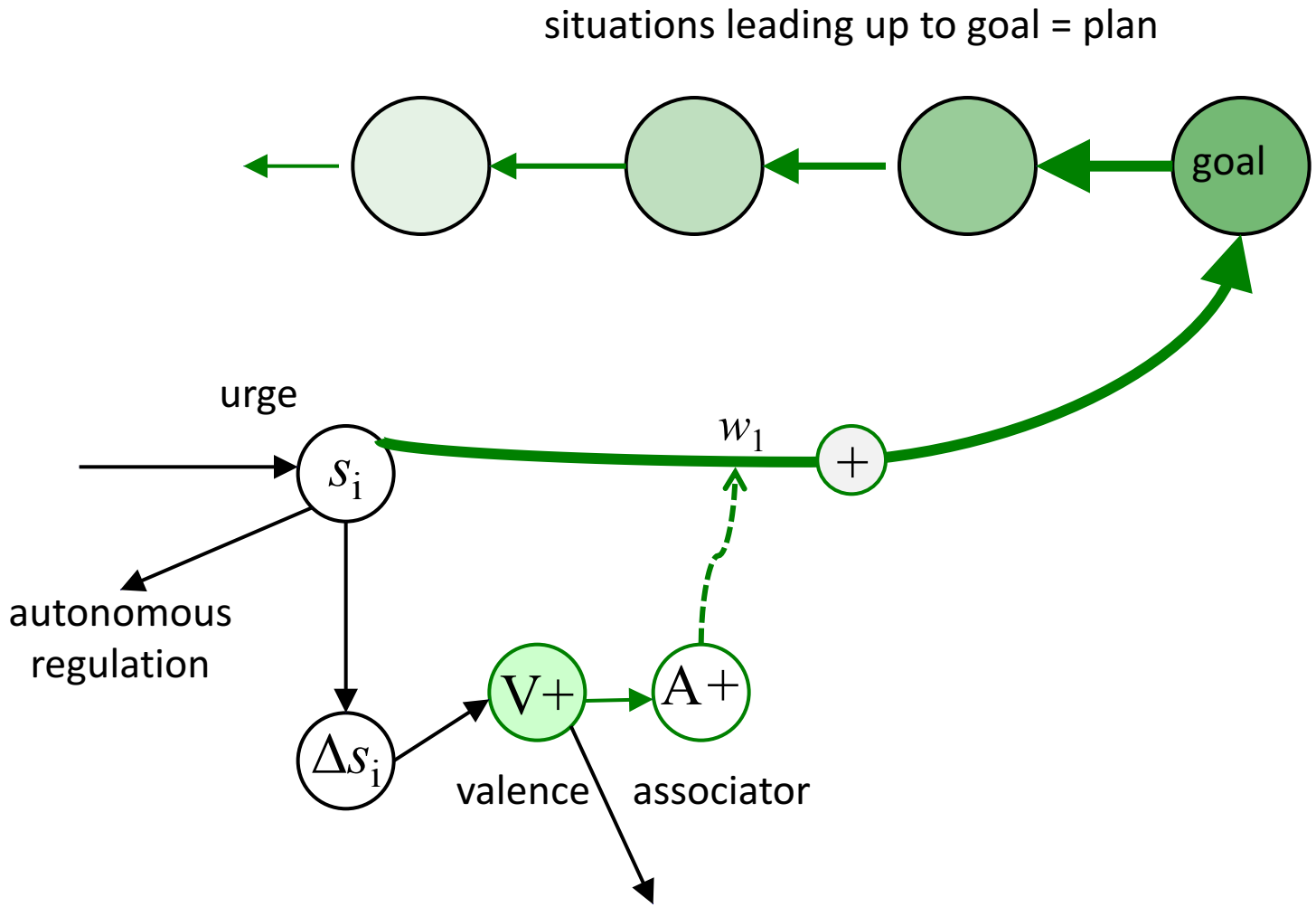
Motivational Learning

- retrogradient reinforcement



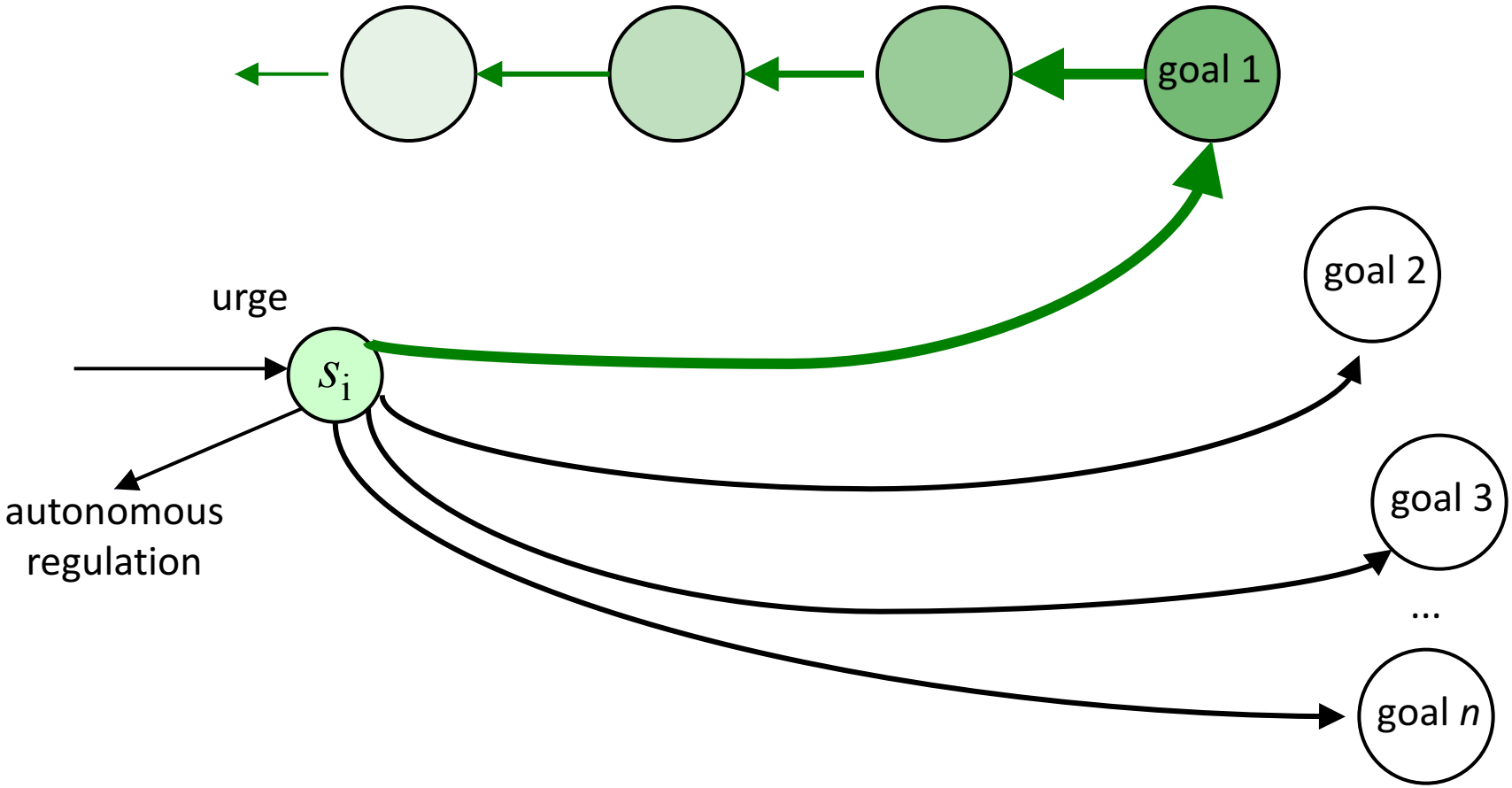
Motivational Learning

Motivator:

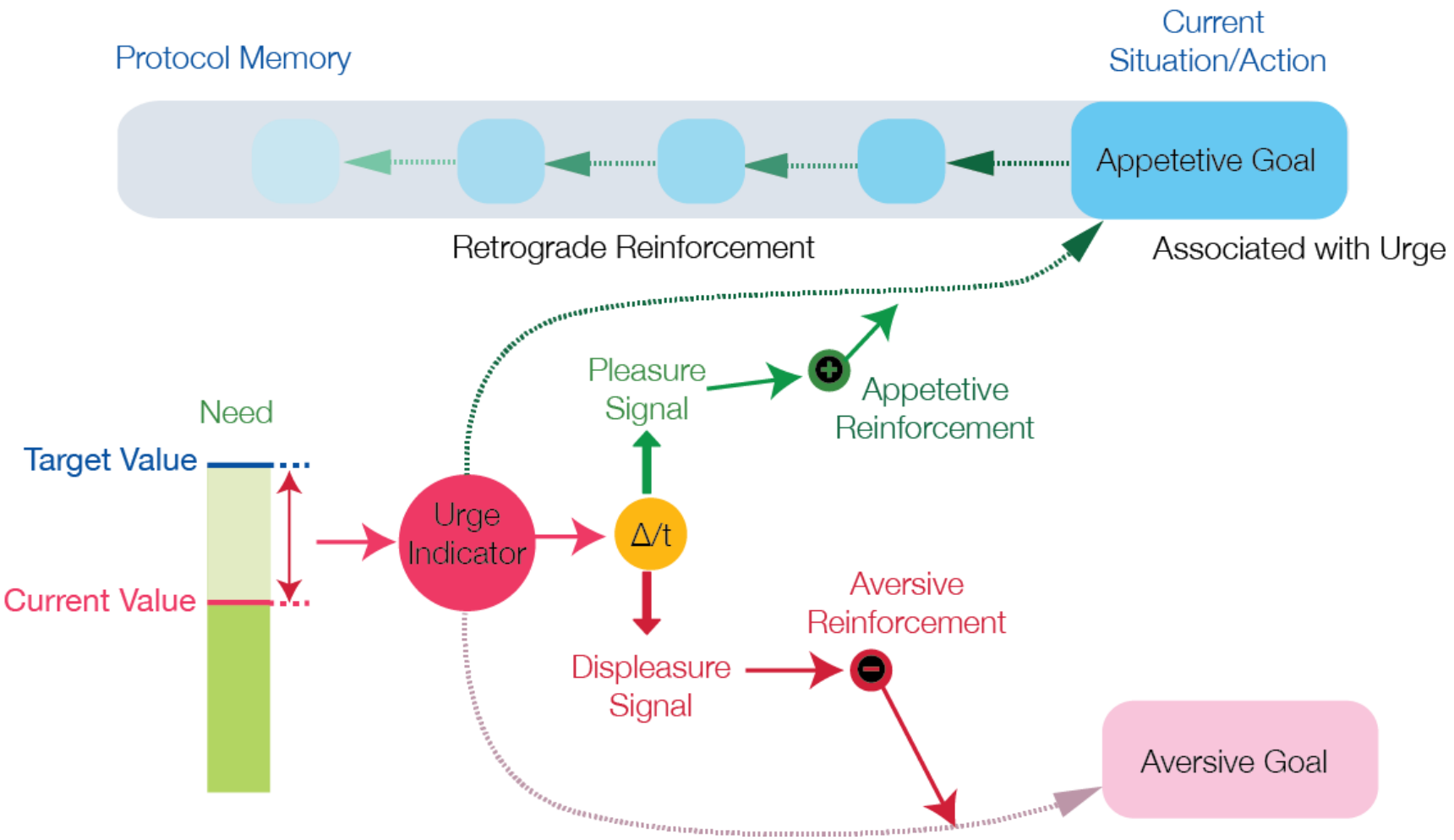


Motivational Learning

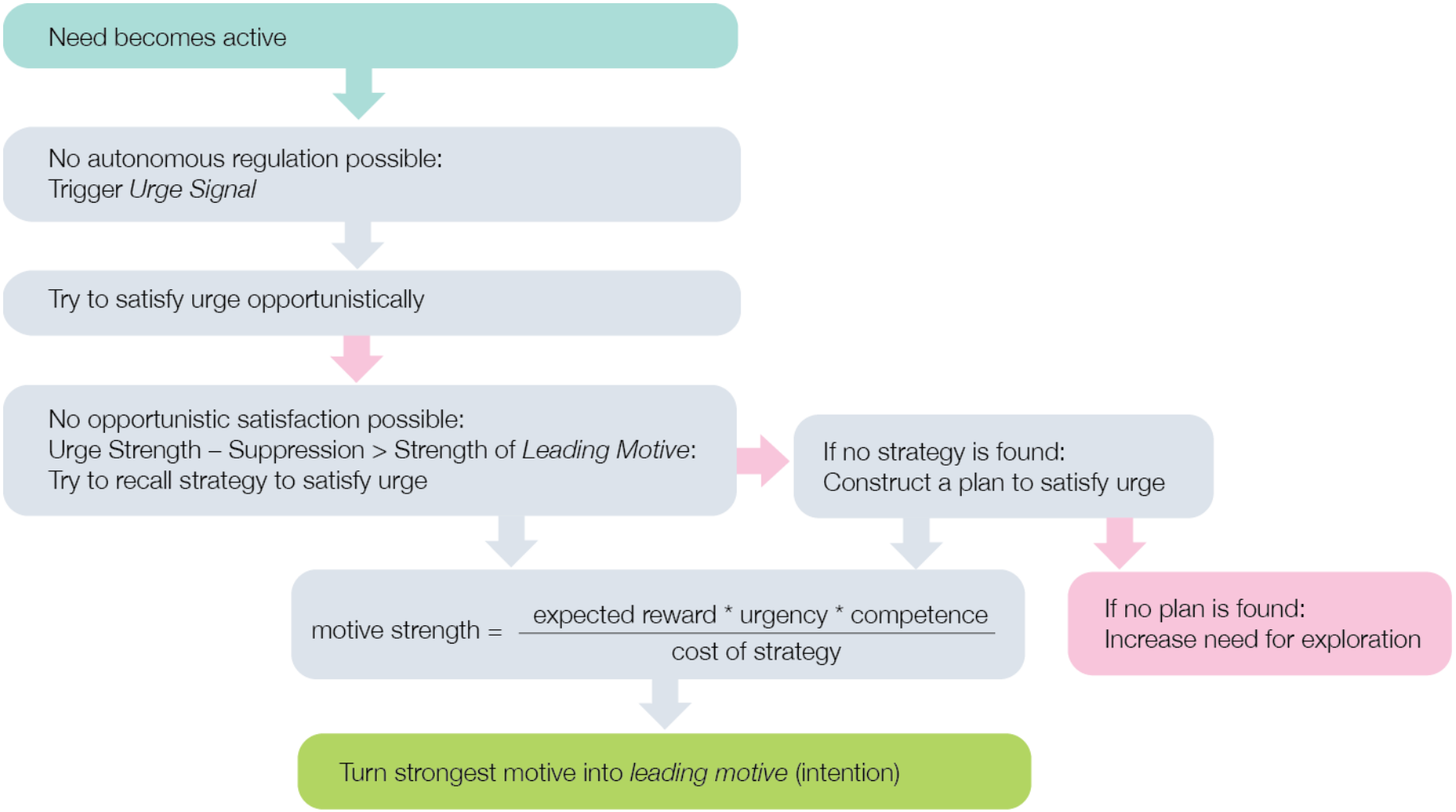
Intention:



Motivational learning



Motive selection



Need parameters

- Strength: relative importance
- Decay: rate of replenishment
- Gain: effect of satisfaction
- Loss: effect of frustration

- different configuration of need parameters = different personality traits

Anticipated needs

- Actual reward determines reinforcement (striatum, basal ganglia)
- Anticipated reward determines action (prefrontal dopamine)

- Valenced reactions are not only caused by present rewards, but also by imagined/anticipated rewards (expectations, memories)

Implementation of motivation

$$Need := \left\{ \begin{array}{c} type \in \{physiological, social, cognitive\}, \\ value_{\,t} \in [0,1], \\ value_{\,t0} \in [0,1], \\ urge_{\,t} \in [0,1], \\ urgency_{\,t} \in [0,1], \\ pleasure_{\,t} \in [0,1], \\ pain_{\,t} \in [0,1], \\ weight \in \mathbb{R}^{+}, \\ decay\ time \in [-1,1], \\ gain \in [0,1], \\ loss \in [0,1], \\ satisfaction^{img} \in [0,1], \\ frustration^{img} \in [0,1], \\ pleasure\ sensitivity \in \mathbb{R}^{+}, \\ pain\ sensitivity \in \mathbb{R}^{+}, \\ pleasure\ decay\ time \in \mathbb{R}^{+}, \\ pain\ decay\ time \in \mathbb{R}^{+}, \\ pleasure\ sensitivity^{img} \in [0,1], \\ pain\ sensitivity^{img} \in [0,1] \end{array} \right\}$$

Urge strength and urgency

- $urge_t = weight\,[1 - value_{t-1}]_0^{1^2}$
- $urgency_t = weight\,\left[\frac{k - remaining\ time_t}{k}\right]_0^{1^2}$

Value and decay of a need

- $$value_t = \left[\begin{array}{c} \text{decay}(value_{t-1}) \\ +gain \times \delta_t^{consume} \\ +loss \times \delta_t^{aversive} \\ +gain \times satisfaction^{img}\ \delta_t^{img\ consume} \\ +loss \times frustration^{img}\ \delta_t^{img\ aversive} \end{array} \right]_0^1$$

- $$\text{decay}(v_{t-1}) := \sigma\left(\sigma^{-1}(v_{t-1}) + \frac{\text{duration}(t,t-1)}{decay\ time}\right)$$

Pleasure and pain associated with a need

- $pleasure_t = \begin{bmatrix} \text{decay}(pleasure_{t-1}, pleasure\ decay\ time) \\ +gain \times pleasure\ sensitivity\ \times \delta_t^{consume} \\ +gain \times pleasure\ sens.^{img} \times\ \delta_t^{\ img\ consume} \end{bmatrix}_0^1$

- $pain_t = \begin{bmatrix} \text{decay}(pain_{t-1}, pain\ decay\ time) \\ +loss \times pain\ sensitivity \times \delta_t^{aversive} \\ +loss \times pain\ sensitivity^{img} \times\ \delta_t^{\ img\ aversive} \\ +\text{pain from depletion}(\text{value}_{t-1}) \end{bmatrix}_0^1$

- $\text{pain from depletion}(value) \coloneqq \left[\left(1 - \frac{value}{\theta}\right)\right]_0^{1^2}$

Events and consumptions

- $Event \coloneqq \left\{ \begin{array}{c} consumption \in Consumptions, \\ expected\ reward \in [-1, 1], \\ certainty \in (0, 1], \\ skill \in [0, 1], \\ remaining\ time_t \in \mathbb{R}^+ \end{array} \right\}$

- $Consumption \coloneqq \left\{ \begin{array}{c} need \in Needs, \\ reward_t \in \mathbb{R}, \\ total\ reward \in \mathbb{R}, \\ reward\ duration \in \mathbb{R}^+, \\ max\ reward \in \mathbb{R}, \\ discount \in [0, 1] \end{array} \right\}$

Reward signal and reward summation

- $signal(t) := \ t\, e^{-\frac{1}{2}t^2}$
- $t_1 = (t - t_{onset})\ \dfrac{k}{reward\ duration}\ \mathrm{duration(t, t-1)}$
- $t_1 = (t - t_{onset})\ \dfrac{k}{reward\ duration}\ \mathrm{duration(t, t-1)}$
- $reward_t = \left[\dfrac{k \times total\ reward}{reward\ duration} \int_{t_1}^{t_2} t\, e^{-\frac{1}{2}t^2}\right]_{-max\ reward}^{max\ reward}$

$$= \left[\frac{k \times total\ reward}{reward\ duration}\left(e^{-\frac{1}{2}t_1^2} - e^{-\frac{1}{2}t_2^2}\right)\right]_{-max\ reward}^{max\ reward}$$

Actualized rewards change values of needs

- $\delta_t^{consume} = \left[reward_t^{consumption}\right]_0^{\infty}$
- $\delta_t^{aversive} = \left[reward_t^{consumption}\right]_{-\infty}^{0}$

Dealing with anticipated rewards

- $\delta_t^{img\ consume} = certainty \times skill \times \left[\frac{reward_t^{consumption}}{1+d \times remain.time_t}\right]_0^{\infty}$

- $\delta_t^{img\ aversive} = cert. \times (1 - skill) \times \left[\frac{reward_t^{consumption}}{1+d \times remain.time_t}\right]_{-\infty}^{0}$

(d is discount; hyperbolic discounting)

Cognitive Artificial Intelligence

Methods should focus on components and performances necessary for intelligence:

- **Universal Representations:**
  Dynamic model of environment, possible worlds, and agent
- **(Semi-) Universal Problem Solving:**
  Learning, Planning, Reasoning, Analogies, Action Control, Reflection ...
- **Universal Motivation:**
  Polythematic, adaptive goal identification
- **Emotion and affect**
- **Whole, testable architectures**

Modeling Emotion

Emotional expression

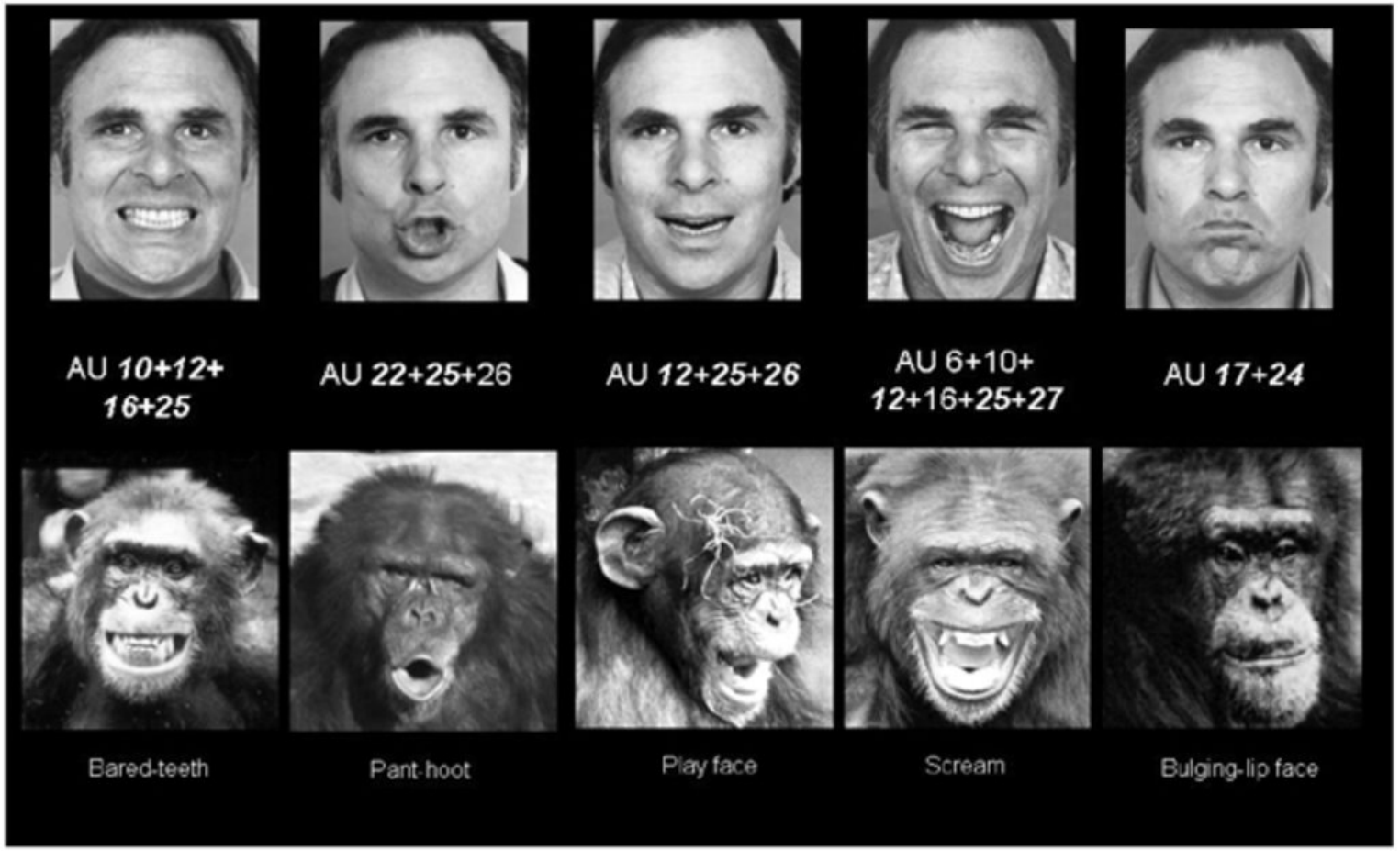
- Paul Ekman: Facial Action Coding

Emotional expression

- Paul Ekman: Facial Action Coding

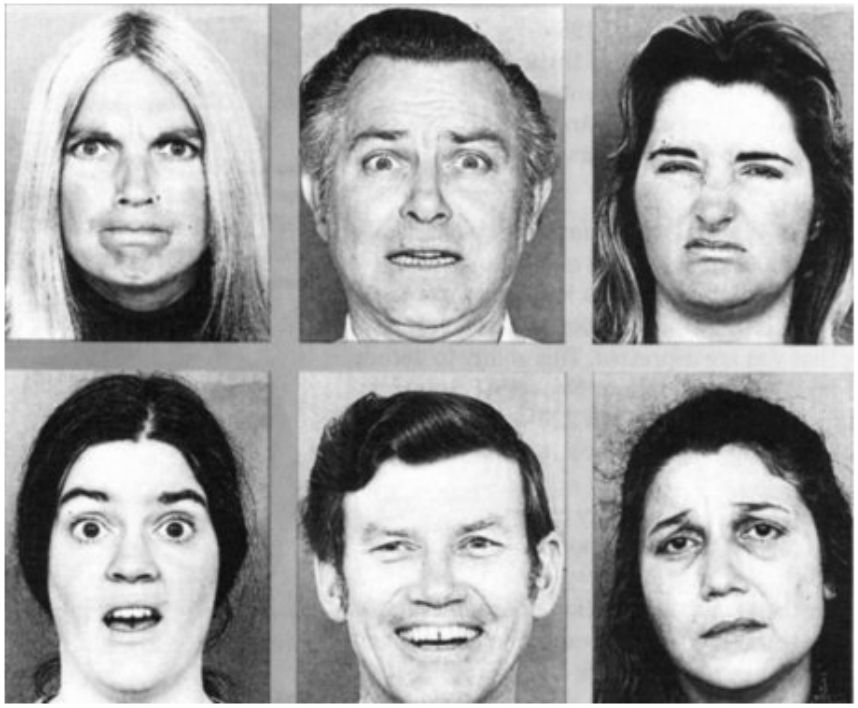
Emotional expression

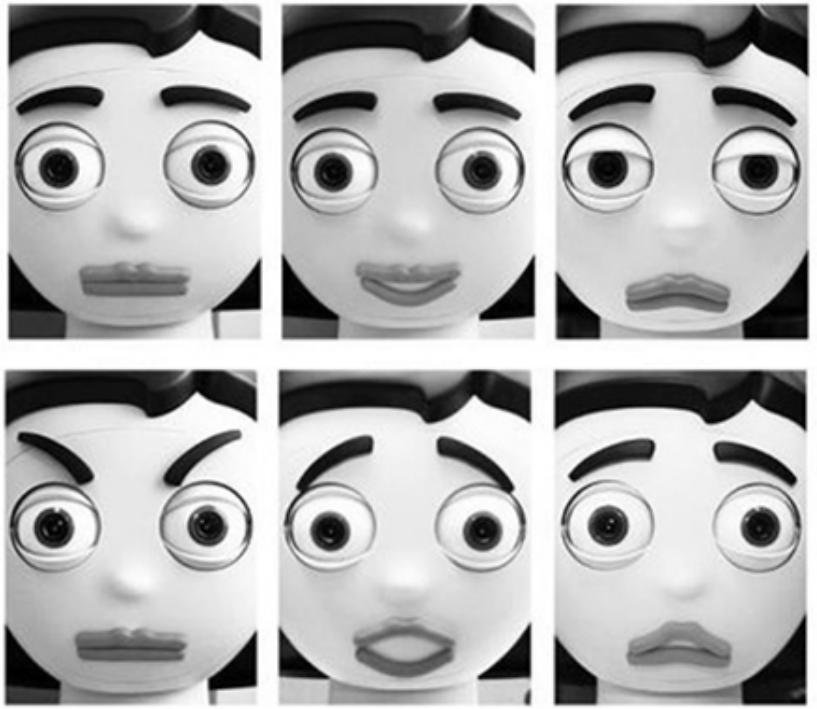
- Paul Ekman: Facial Action Coding



Affective computing

Recognize, process, simulate, express human affects

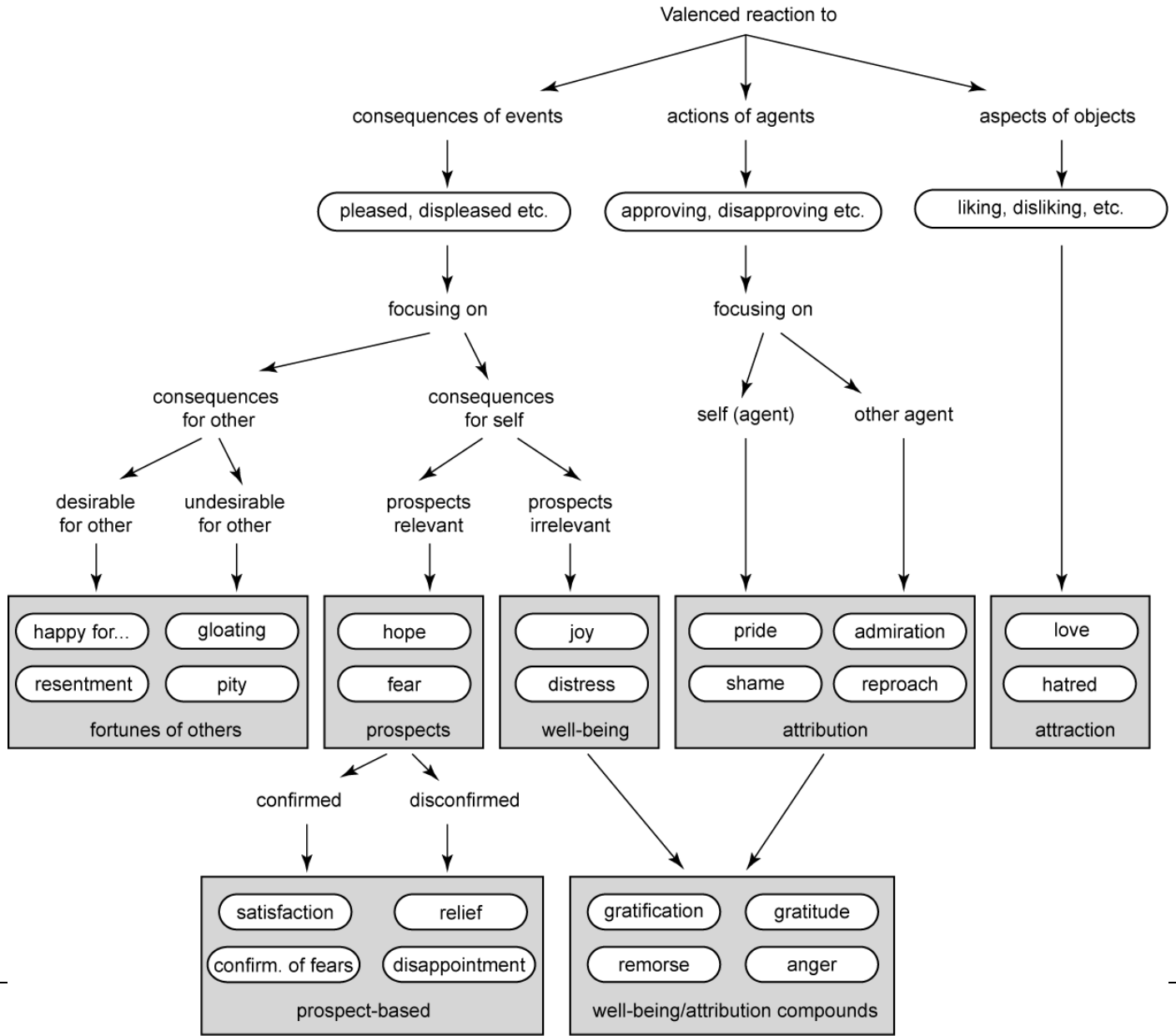




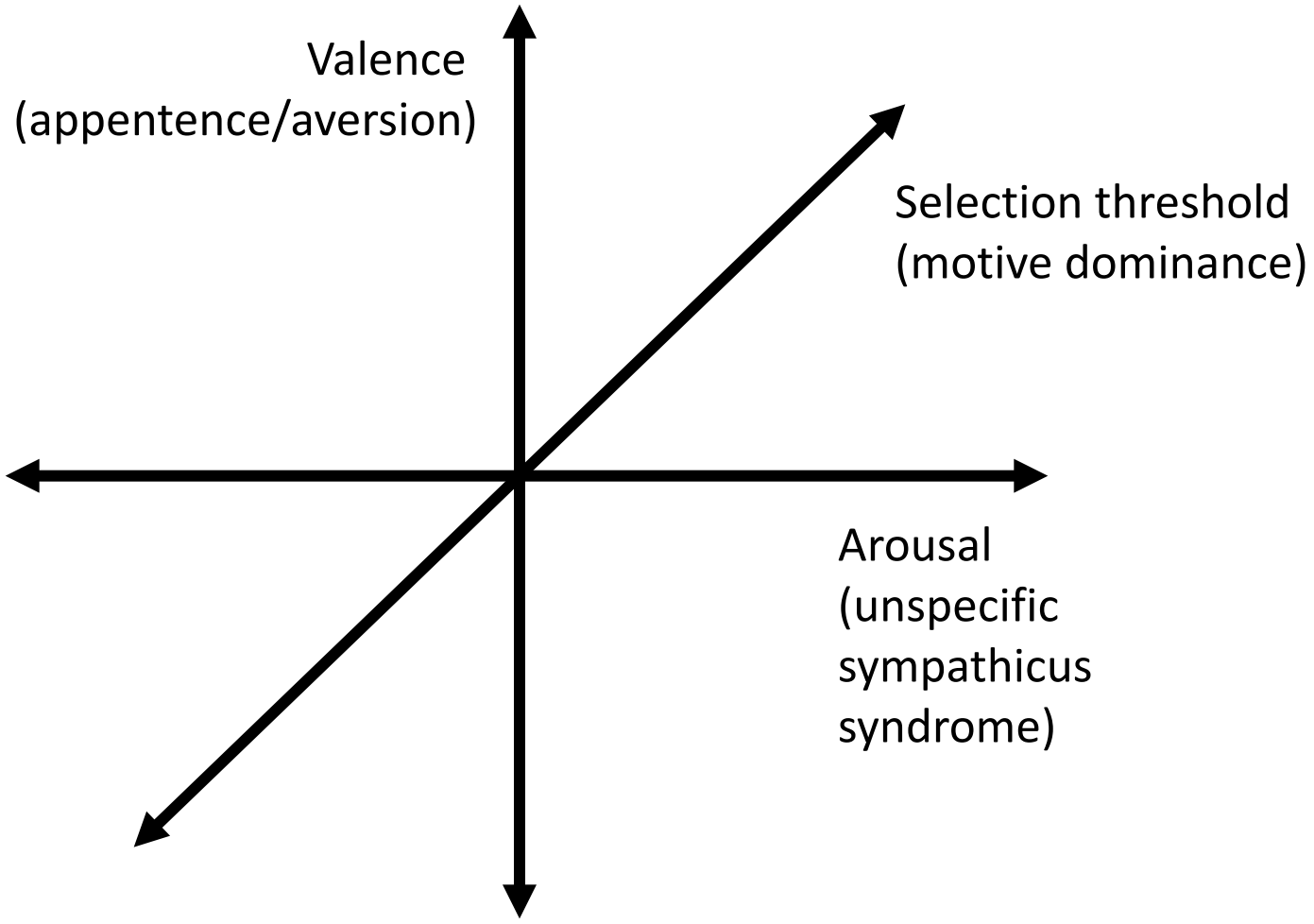
Appraisal models

- Magda Arnold, Richard Lazarus:
  - Emotion as cognitive appraisals of relations, motivation, cognition
- Klaus Scherer:
  - Stimulus evaluation checks
  - innate (sensory motor) $\rightarrow$ learned (schemas) $\rightarrow$ deliberate
  - relevance $\rightarrow$ implication $\rightarrow$ coping potential $\rightarrow$ normative signific.

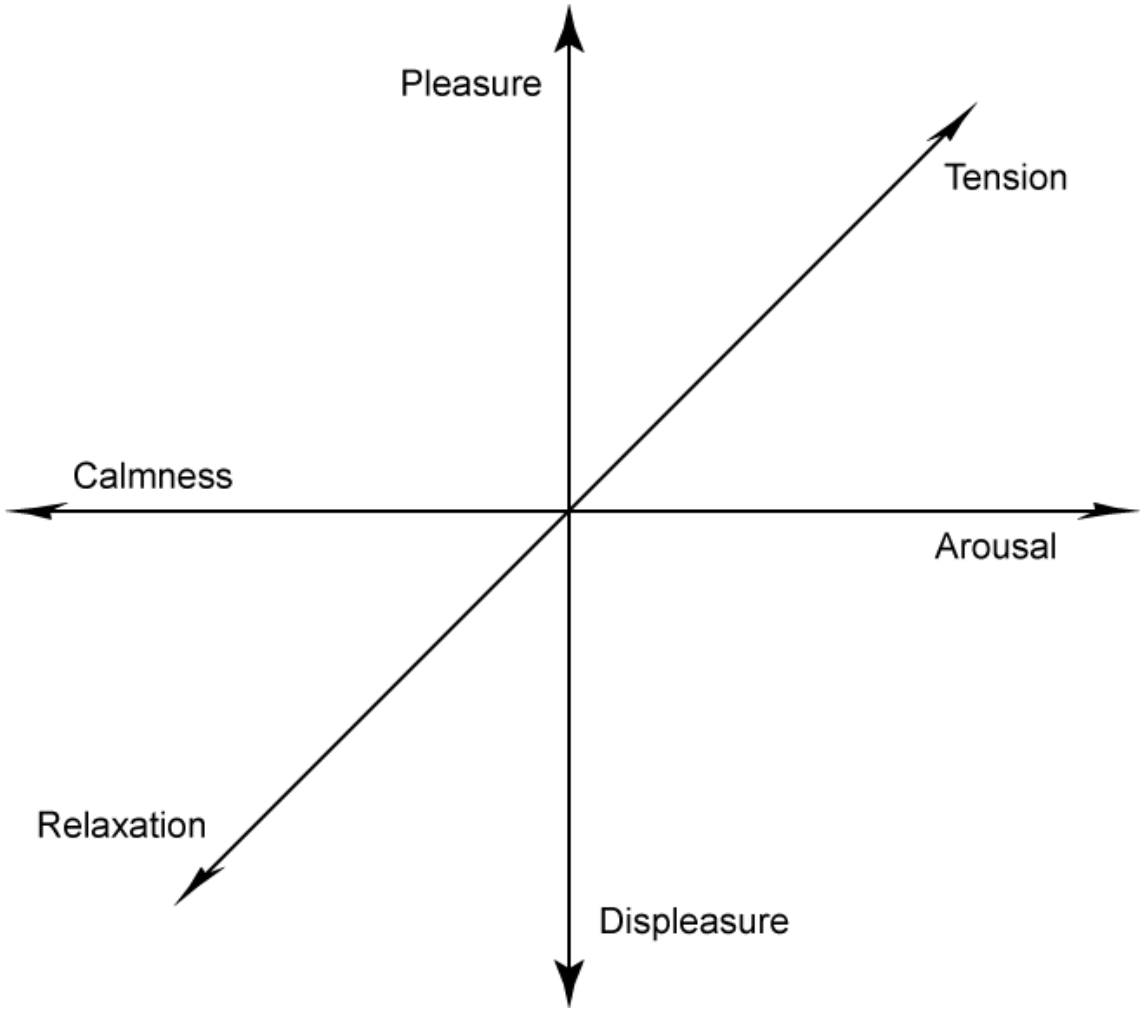
Conceptual analysis: Ortony, Clore, Collins 1988:



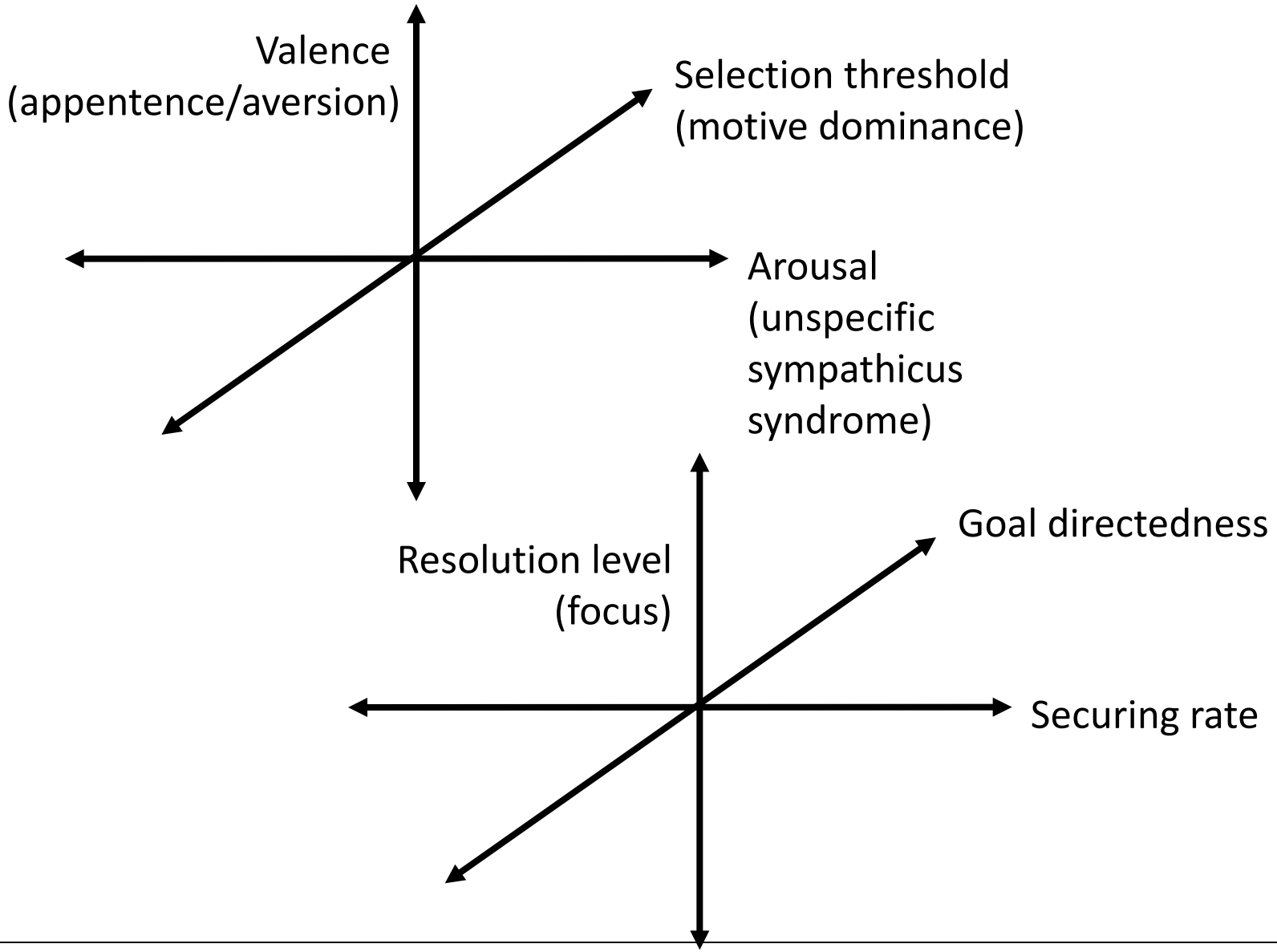
Affective dimensions in the PSI theory (Dörner 1999)



Compare: Affective dimensions (Wundt 1910)



Affective dimensions in the PSI theory



The Psi theory about emotion

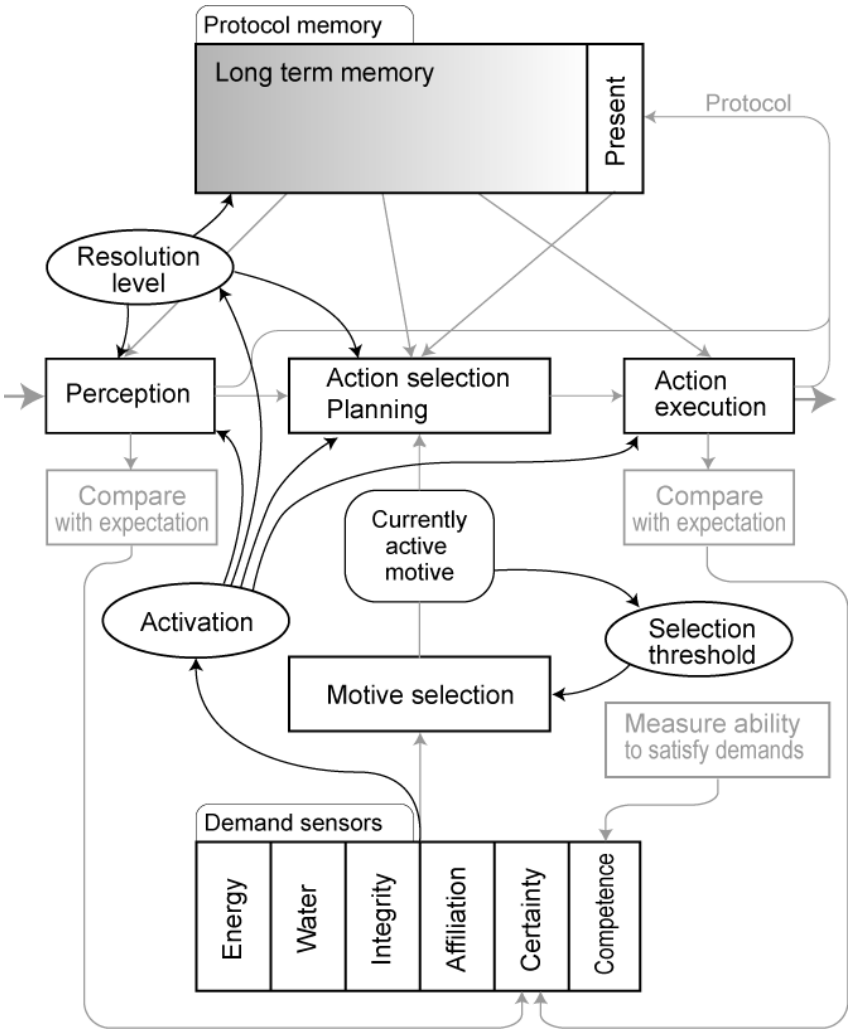
- Affect is seen as a *configuration* of a cognitive system
- Modulators of cognition:
  - arousal, selection threshold, securing threshold, resolution level
  - estimate of competence and certainty
  - pleasure/distress signals $\rightarrow$ valence
- Affective state is emergent property of modulation
- Directed affects (higher-level emotions) emerge by association of demand with appetive or aversive objects/situations

Purpose of emotional modulation

- Control width, depth and bias of operations on mental representations of the agent
  $\rightarrow$ modify perception, memory, planning and action selection

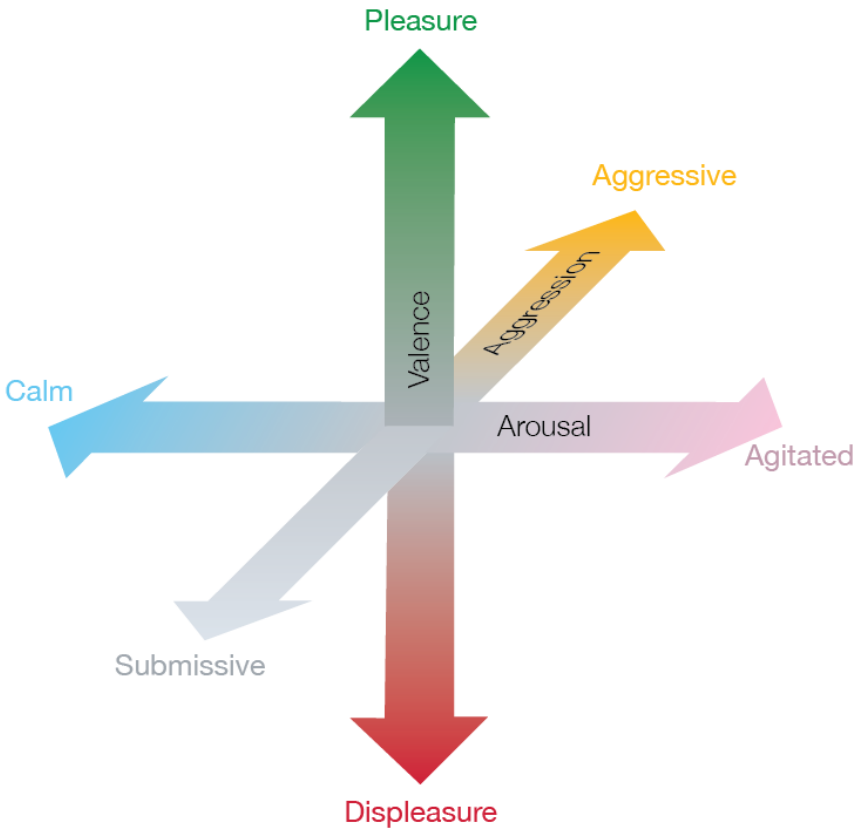
- Reduce complexity of cognitive processes

Modulation in PSI/MicroPsi



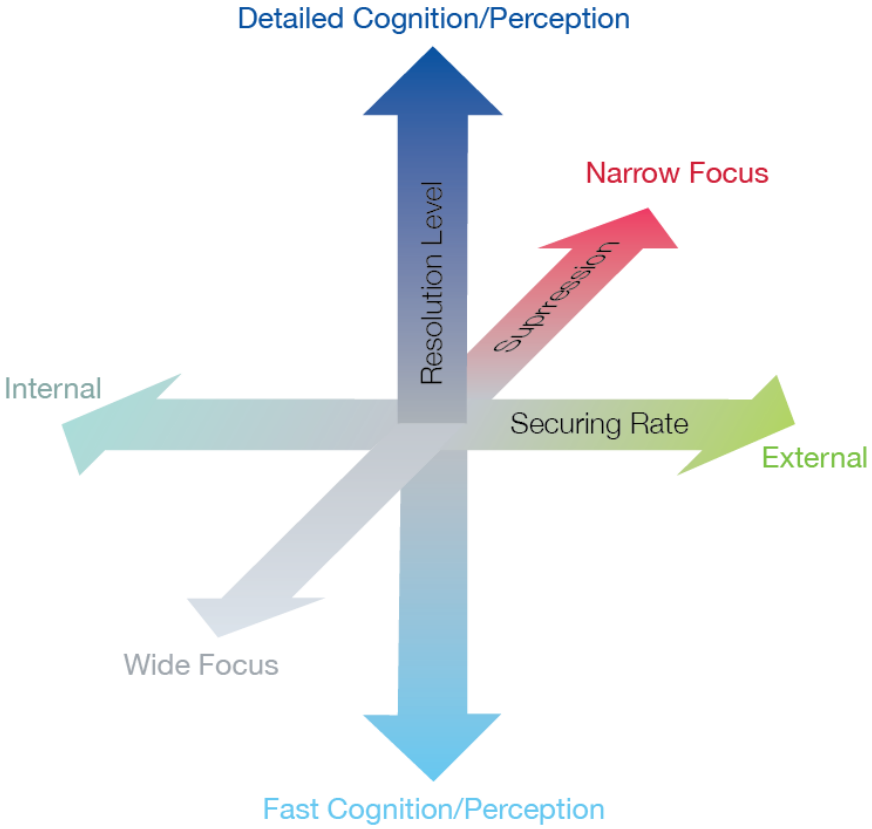
Primary modulators

Arousal	unspecific sympathicus syndrome
Valence	situation evaluation (good/bad)
Aggression	fight or flight

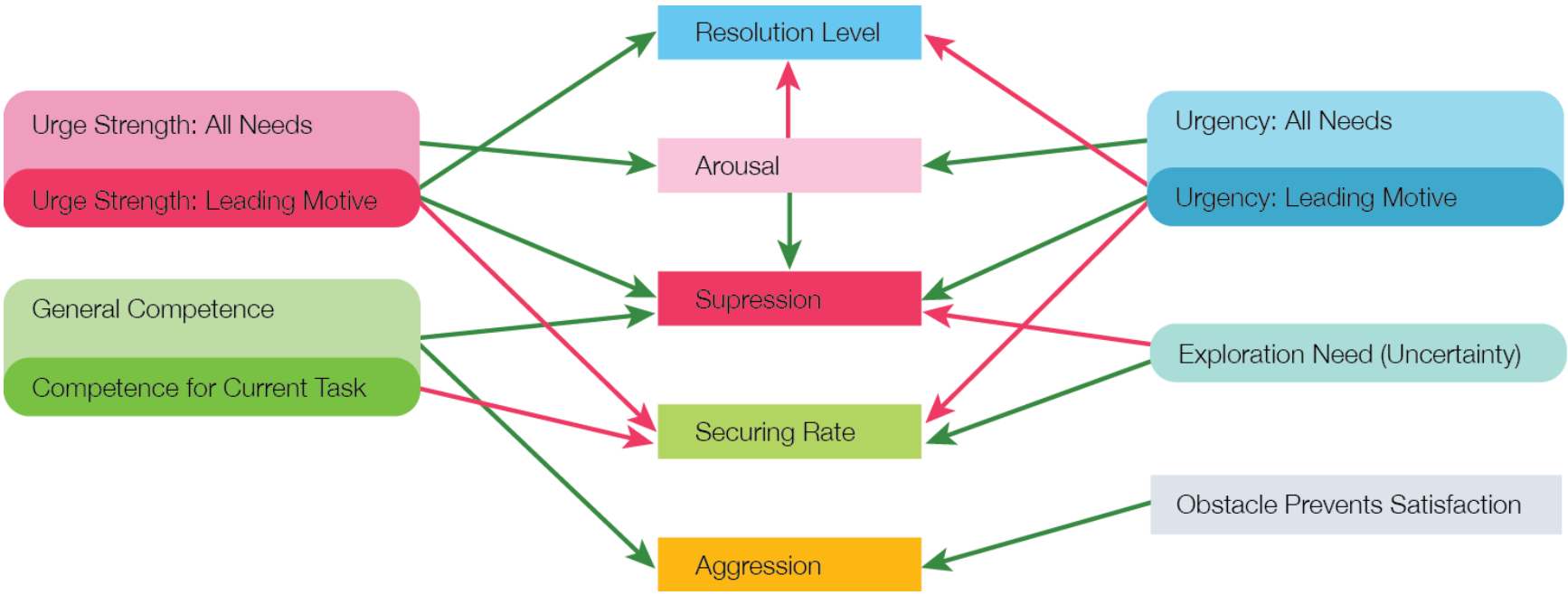


Attentional modulators

Resolution Level	width of focus
Supression	depth of focus; motive stability
Securing Rate	rate of checking the environment



Modulator dynamics



Modulator parameters

- Baseline
- Range
- Volatility
- Duration

- Different modulator parameter configurations = different temperaments

Emotions as directed affect + Modulation

Examples:

Fear: anticipation of aversive events (→ neg. valence) + arousal

Anxiety: uncertainty (→ neg. valence) + low competence + arousal, high securing behavior (frequent background checks)

Emotions as directed affect + Modulation

Examples:

Anger: Perceived obstacle (usually agent) manifestly prevented reaching of an active, motivationally relevant goal (→neg. valence), sanctioning behavior tendency (→ goal relevance is re-directed to sanctioning of obstacle), arousal, low resolution level, high action readyness, high selection threshold

Sadness: Manifest prevention from *all* conceived ways of reaching active, relevant goal, without relevant obstacle (→ neg. valence), support-seeking behavior (by increased demand for affiliation), low arousal, inhibition of active goal → decreased action readyness

Emotions as directed affect + Modulation

Examples:

- **Pride**: high competence (→ low securing rate), high internal legitimacy, likely coincidence with high external legitimacy
- **Joy**: high arousal + high perceived reward signal from satisfying a demand
- **Bliss**: low arousal + high perceived reward signal from satisfying a demand (since physiological demands often involve high arousal, mostly related to cognitive demands, such as aesthetics)

Implementation of affective modulation

- $Modulator := \left\{ \begin{array}{c} min \in \mathbb{R} \\ max \in \mathbb{R}, \\ level_t \in [min, max], \\ baseline \in [min, max], \\ volatility \in \mathbb{R}^+, \\ decay\ time \in \mathbb{R}^+ \end{array} \right\}$

- $interval = \begin{cases} max - baseline, \text{if } level_{t-1} > baseline \\ baseline - min, \text{else} \end{cases}$

- $\delta_t = (target \times interval + baseline - level_{t-1})\ volatility$

Implementation of valence

- $\text{marginal sum}(V, limit) := \sum_{n=0}^{|V|} S_n \Big| S_n := \frac{limit - S_{n-1}}{limit} v_n$
- $limit = \max(\{\omega | \omega \in weight_{needs}\})$

- $combined\ pain = \text{marginal sum}(\{\text{weight}_{\text{need}} \times pain_{need}\})$

- $combined\ pleasure = \text{marginal sum}(\{\text{weight}_{\text{need}} \times pleasure_{need}\})$

- $target^{valence} = \frac{combined\ pleasure - combined\ pain}{limit}$

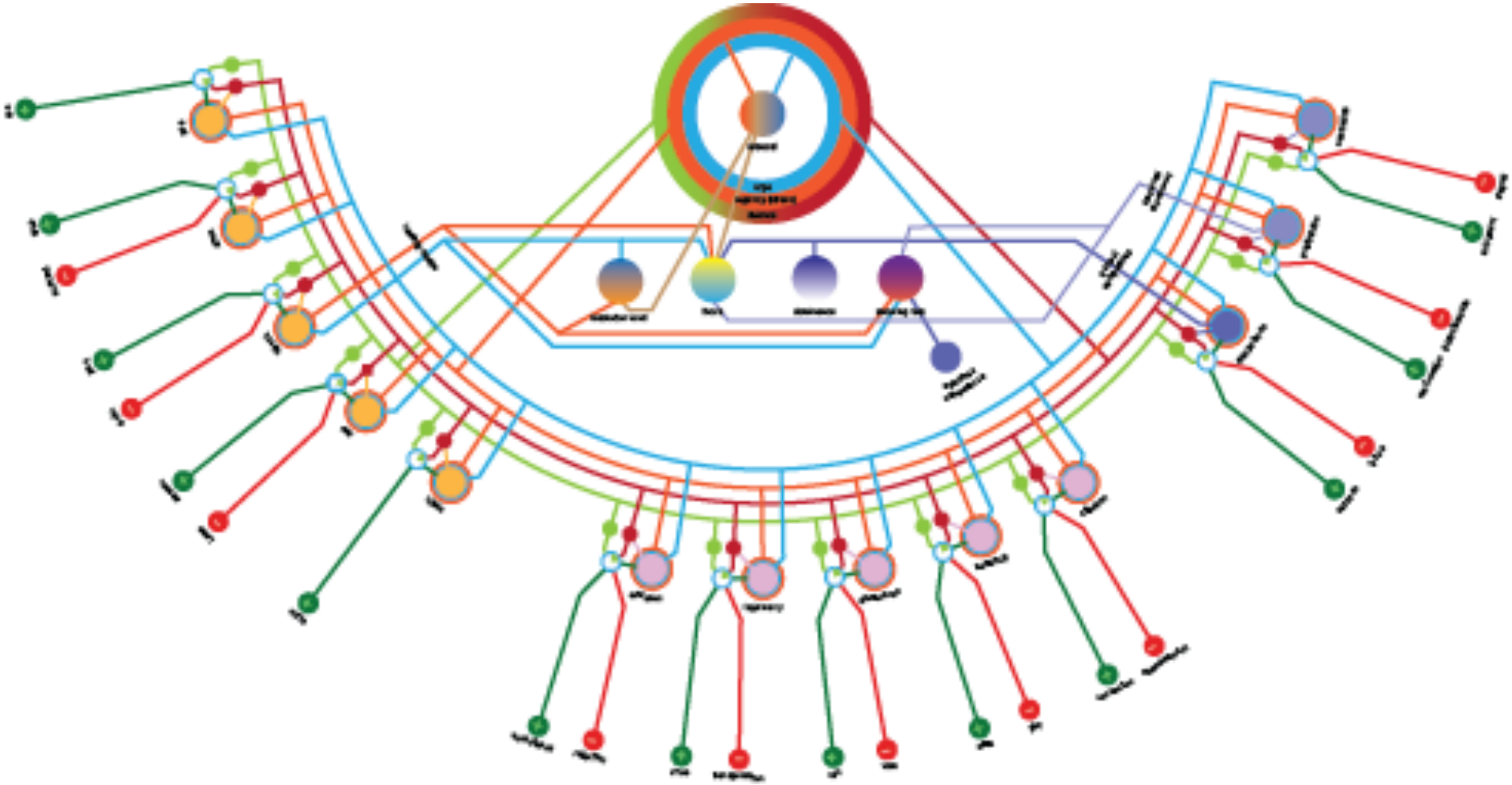
Implementation of arousal

- $combined\ urge = \frac{\text{marginal sum}(\{\text{weight}_{\text{need}} \times urge_{need}\})}{limit}$
- $combined\ urgency = \frac{\text{marginal sum}(\{\text{weight}_{\text{need}} \times urgency_{need}\})}{limit}$
- $target^{arousal} = combined\ urge + combined\ urgency - 1$

Implementation of aggression/regression

- $epistemic\ competence = skill_{current\ goal\ event}$
- $general\ competence = \sqrt{\text{value}^{\text{competence}} \times epistemic\ comp.}$
- $target^{aggression} = general\ comp. + epistemic\ comp. - 1$

Emotion viewer



Personality modeling

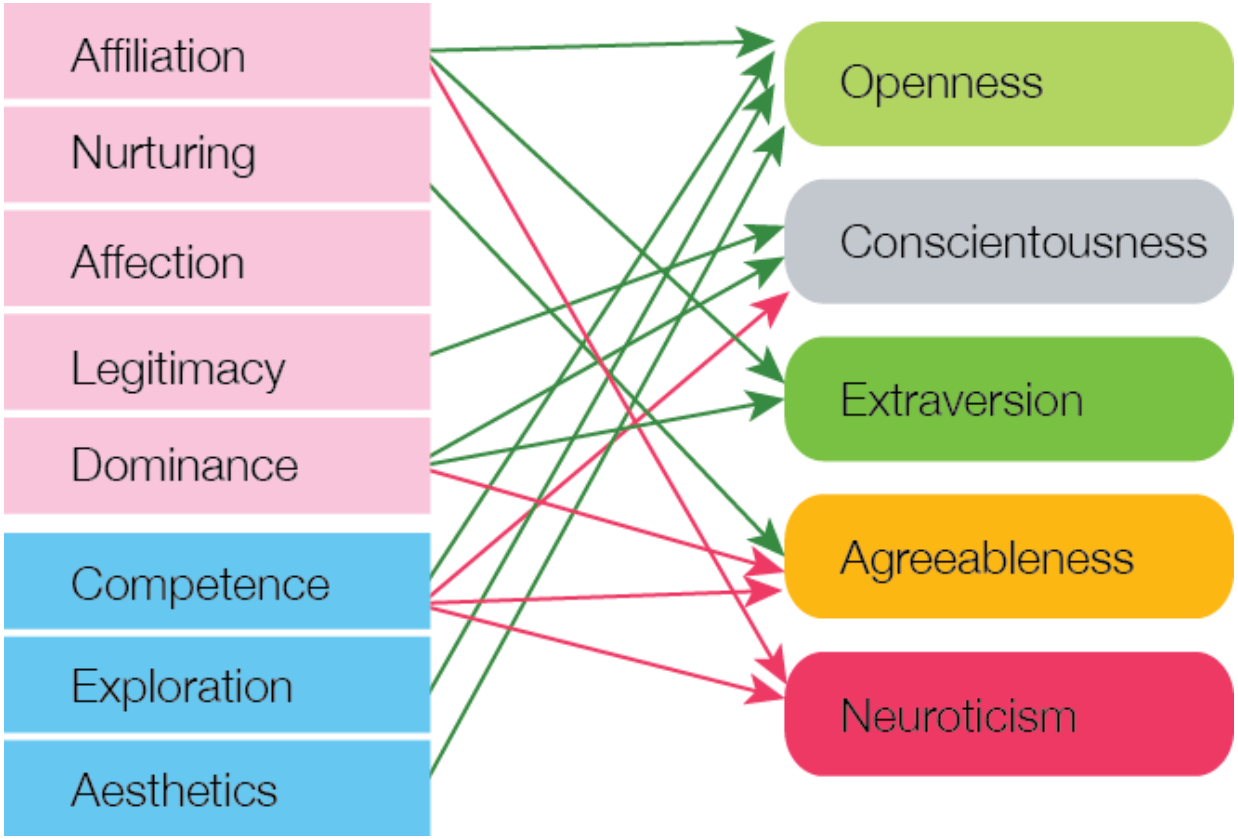
- Motivation parameters: Personality properties
- Modulation parameters: Temperament

Individual Variations by Parameterizing

Possible grounding of personality properties (FFM):

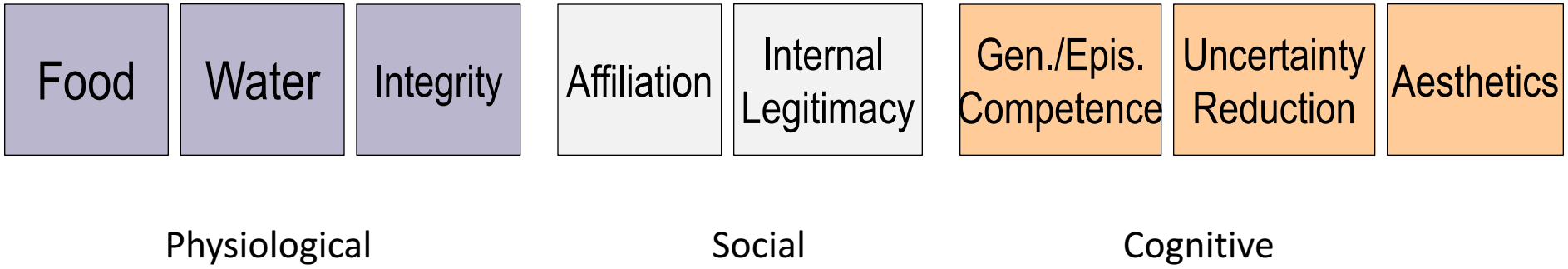
- **Openness**: appreciation of art and new ideas, curiousity
- **Conscientiousness**: rulefollowing vs. chaotic
- **Extraversion**: tendency to seek stimulation by environment and others
- **Agreeableness**: tendency for cooperativeness and compassion
- **Neuroticism**: emotional stability, effect of failure to self-confidence

Needs and Big Five



Example: Mapping to FFM (Big Five)

Demand dynamics:



Example: Mapping to FFM (Big Five)

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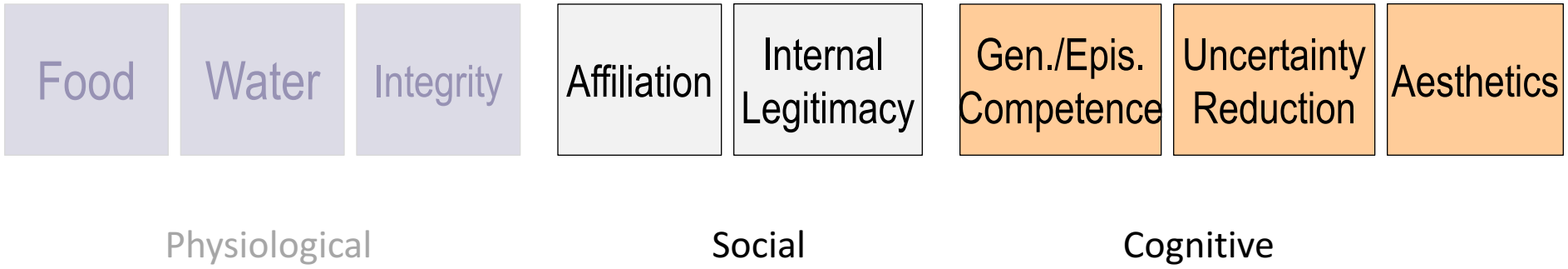
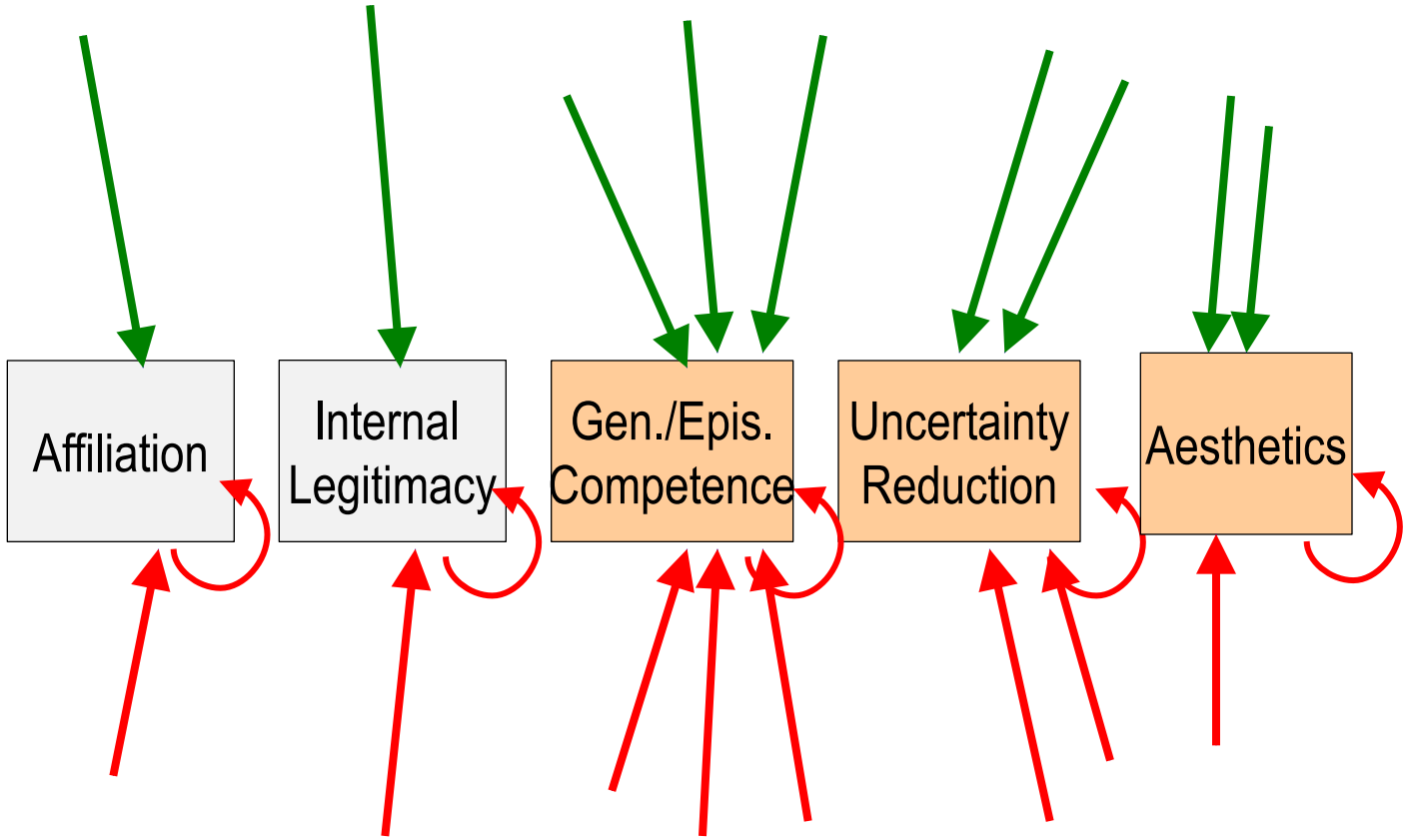


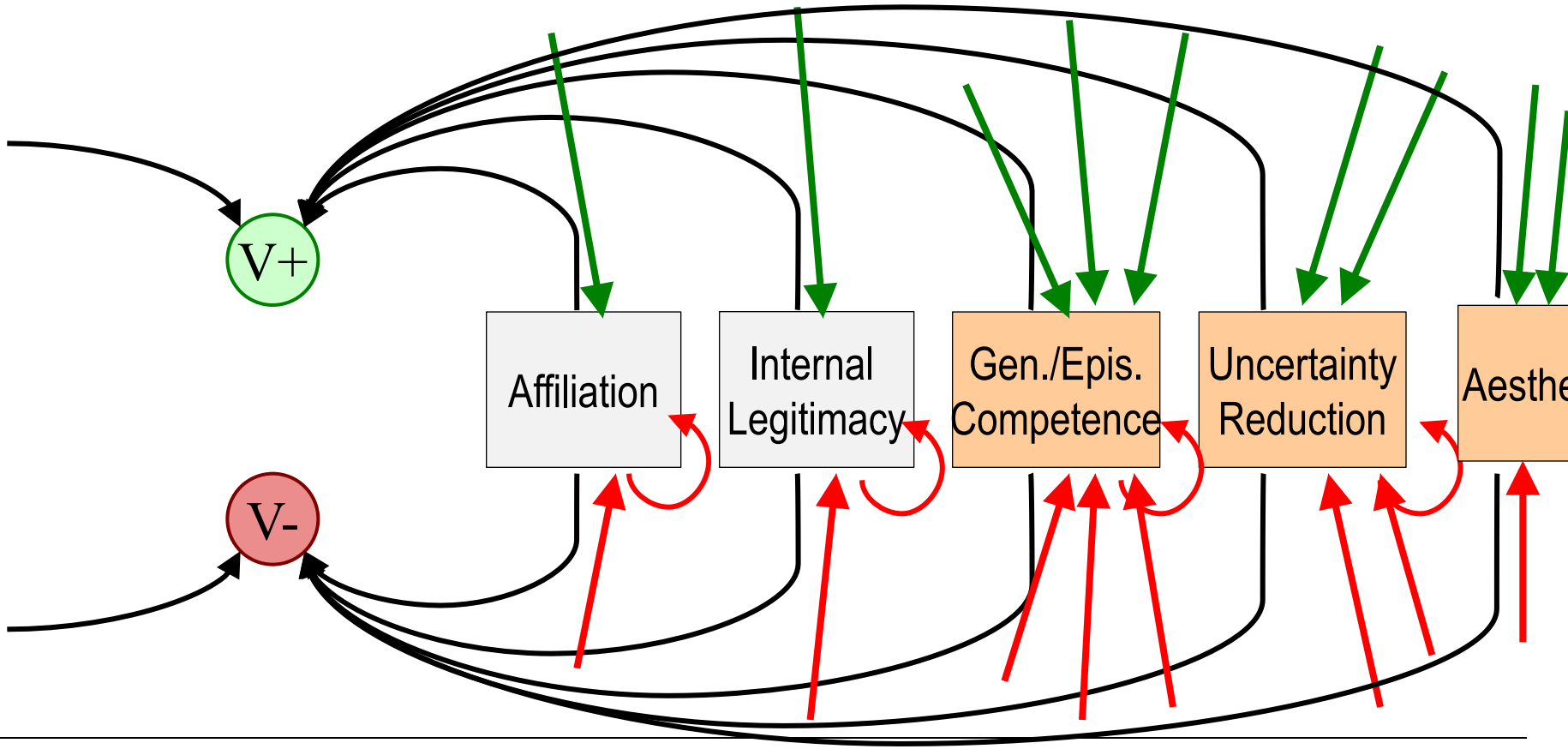
Example: Mapping to FFM (Big Five)

Demand dynamics:



Example: Mapping to FFM (Big Five)

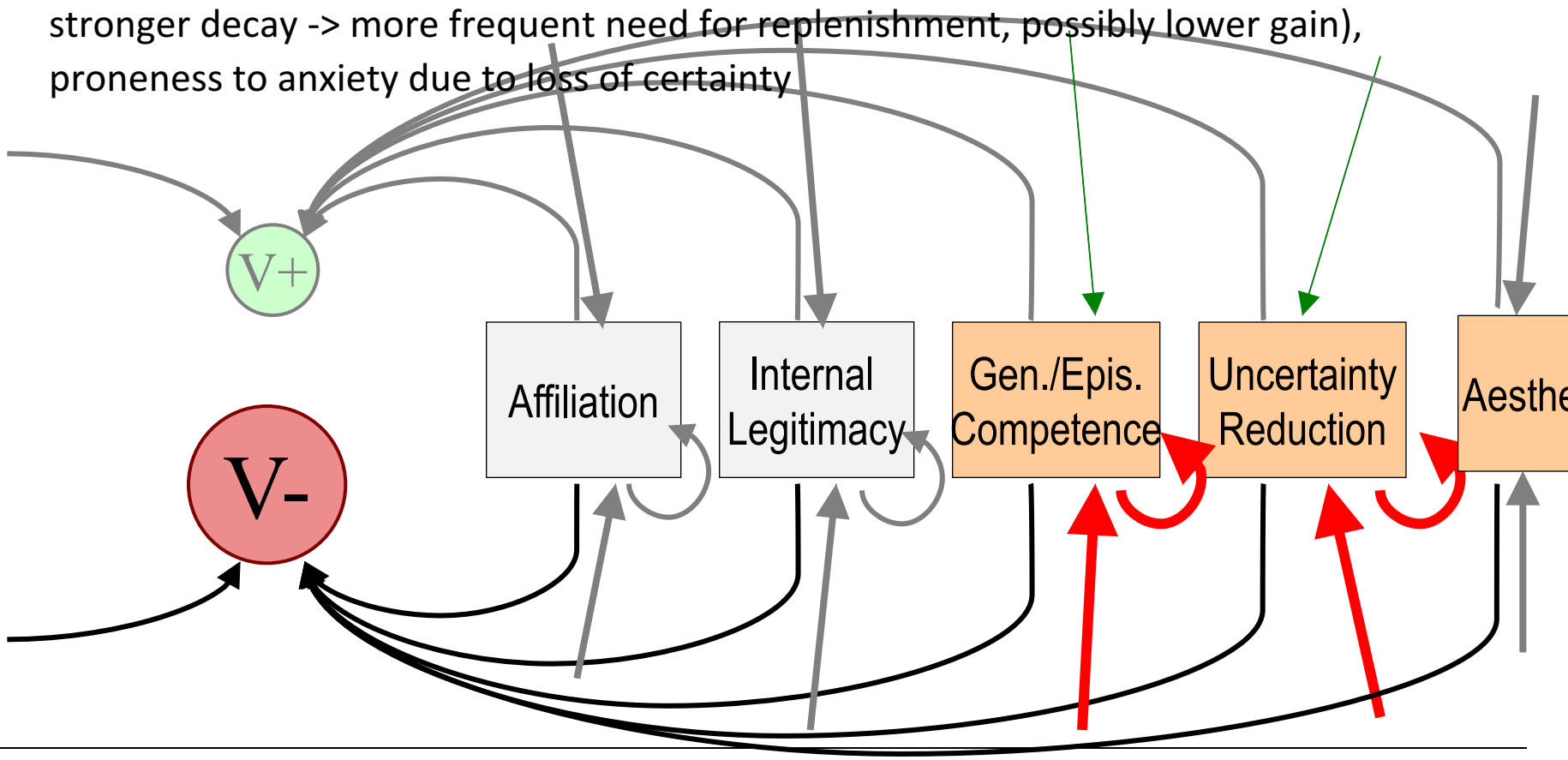
Valence: Pleasure/Pain signals



Example: Mapping to FFM (Big Five)

Neuroticism: stronger experience of negative emotions, lower emotional stability

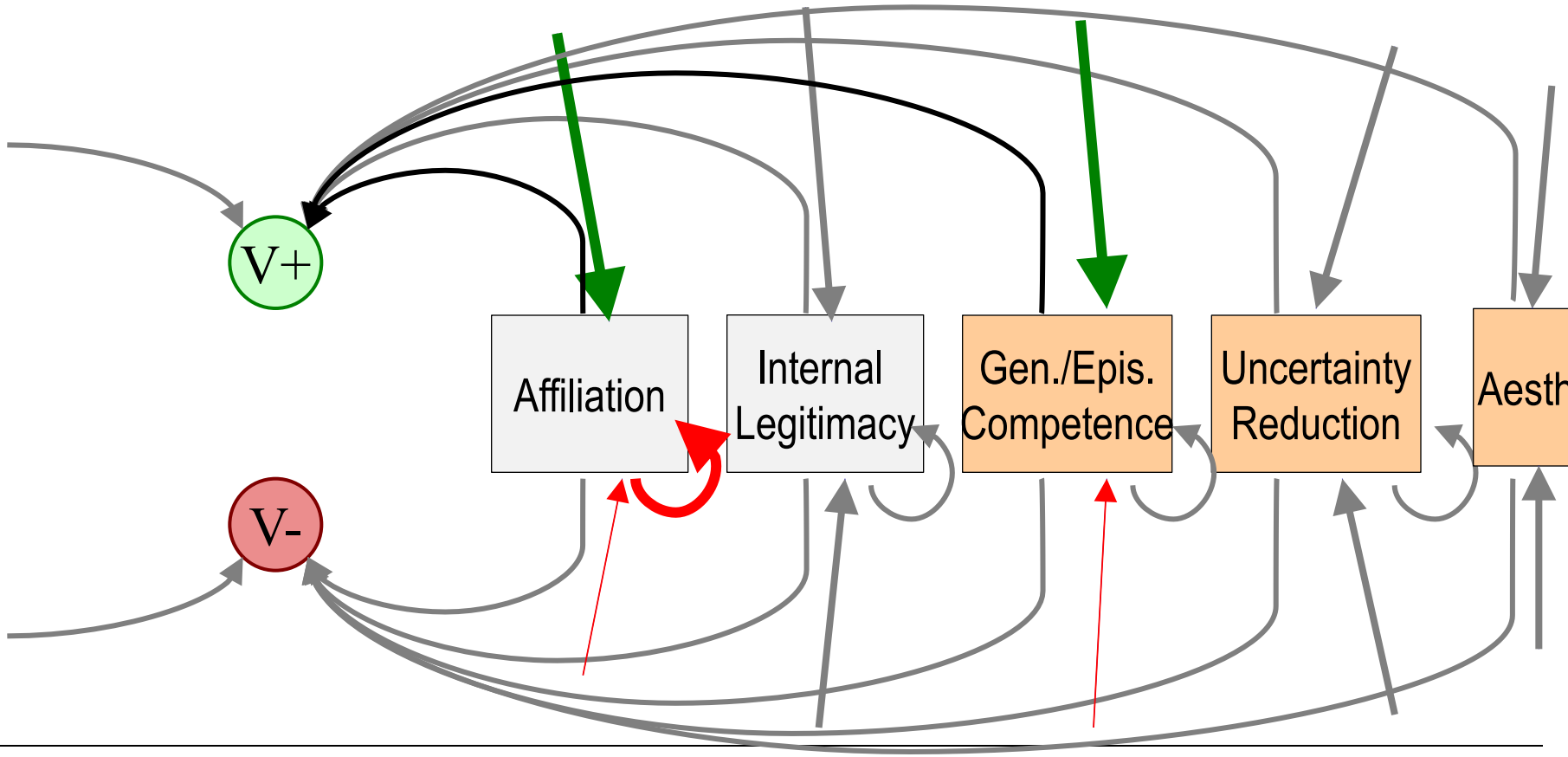
(strong negative reward/stronger loss of competence, certainty;
stronger decay -> more frequent need for replenishment, possibly lower gain),
proneness to anxiety due to loss of certainty



Example: Mapping to FFM (Big Five)

Extraversion: surgency, activity in social relations, expressivity

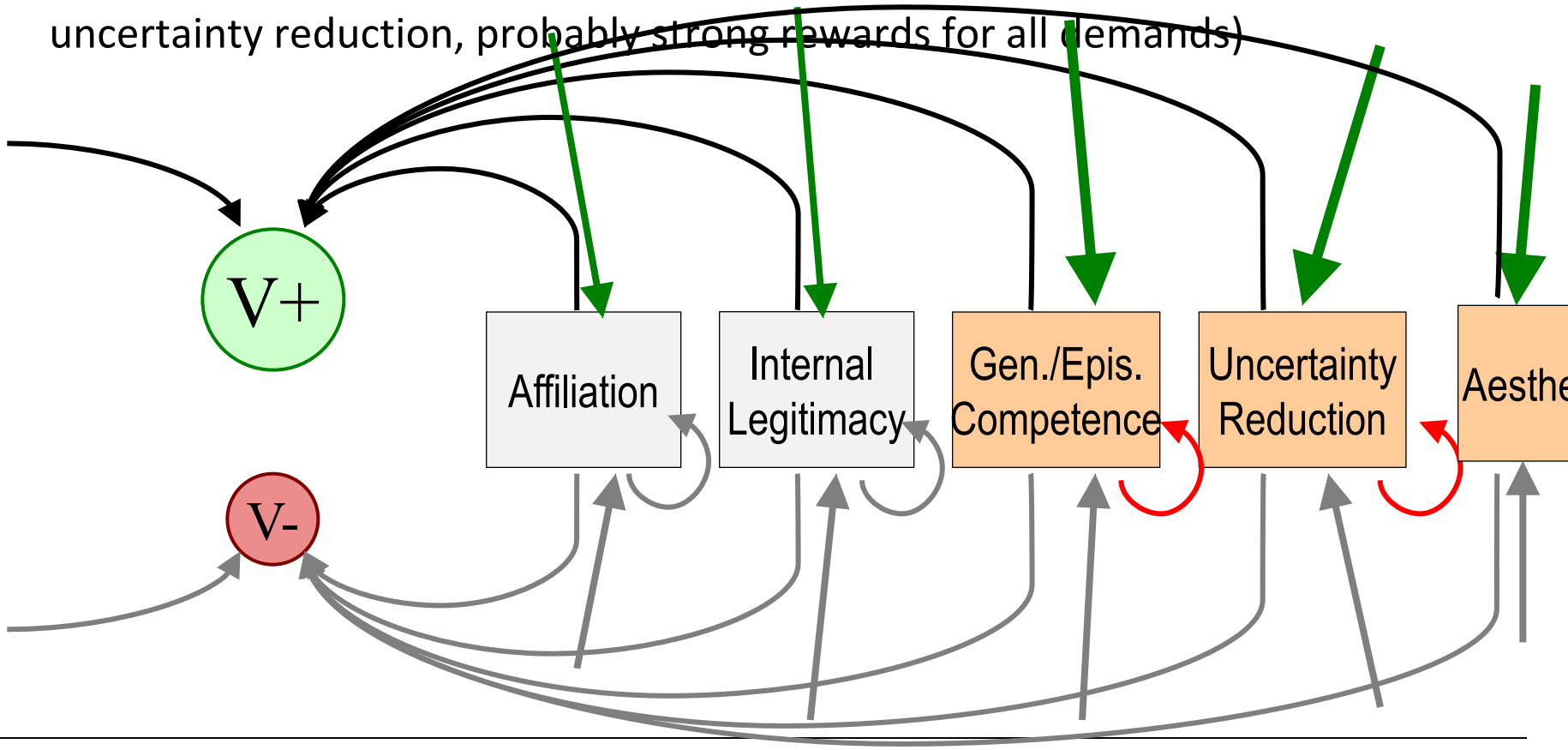
(strong gain for affiliation and competence, high decay of affiliation)



Example: Mapping to FFM (Big Five)

Openness: desire for novelty, intellectual independence, non-conservatism, appreciation for art and new ideas

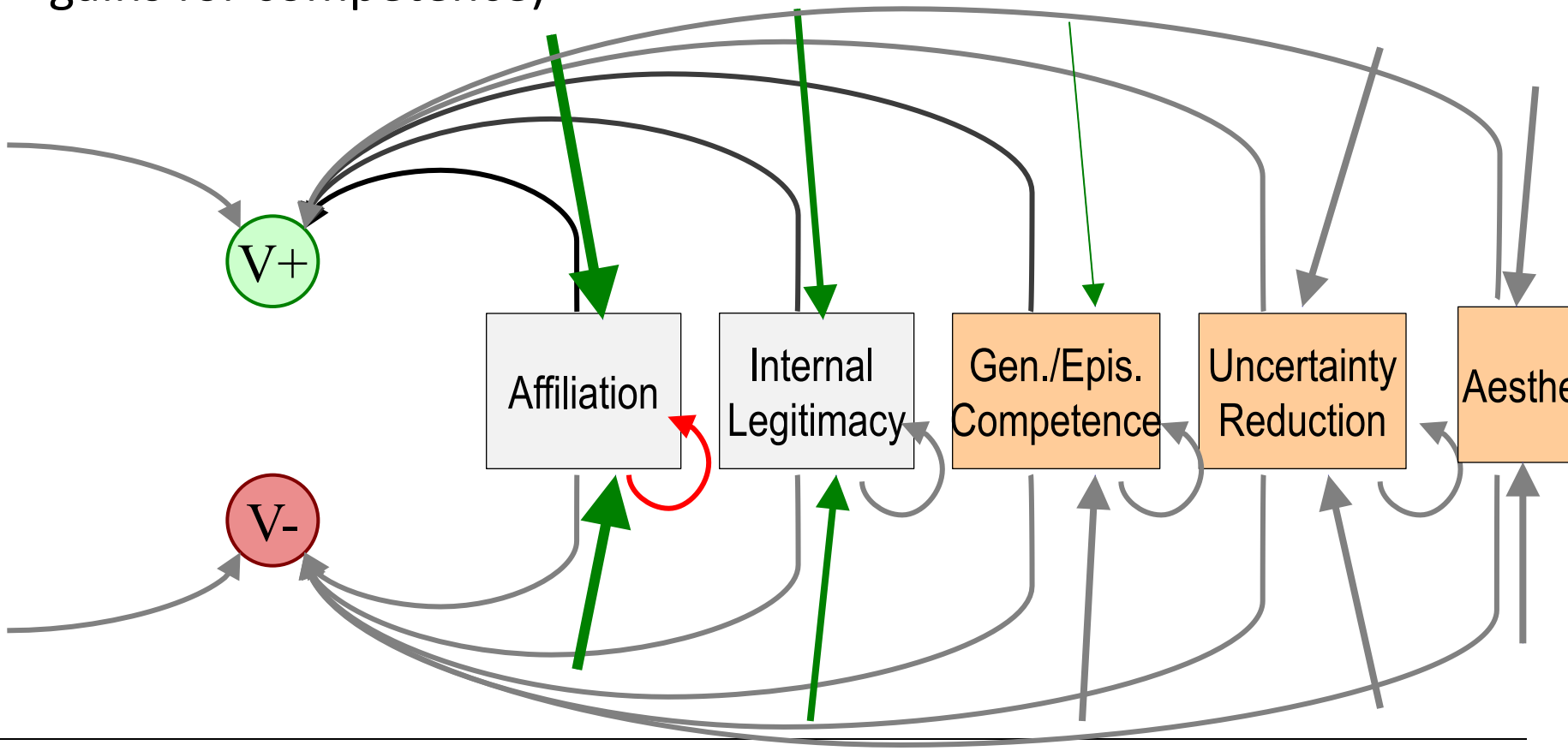
(strong gain for uncertainty reduction, high epistemic competence for uncertainty reduction, probably strong rewards for all demands)



Example: Mapping to FFM (Big Five)

Agreeableness:

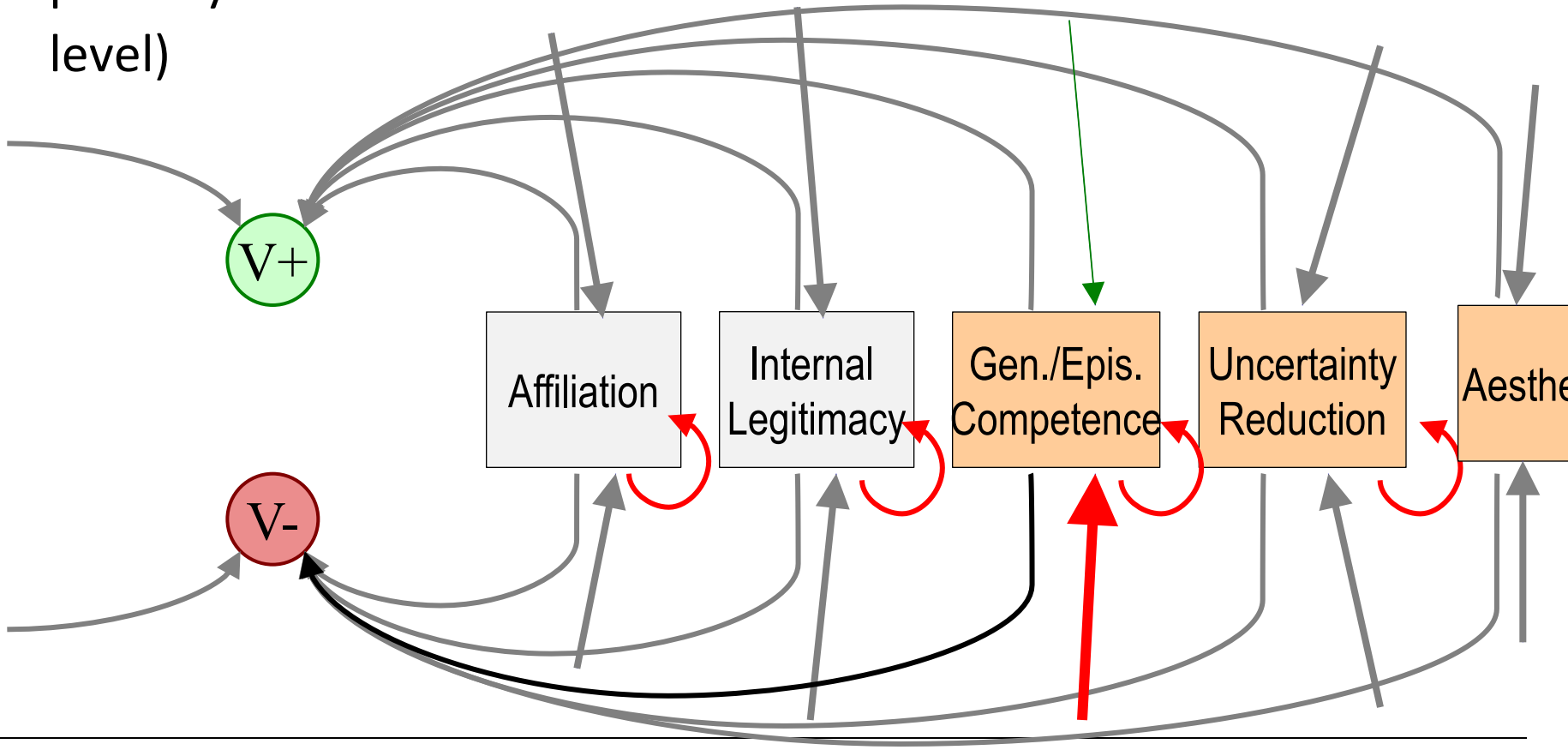
(strong positive and negative reward for affiliation, lower gains for competence)



Example: Mapping to FFM (Big Five)

Conscientousness, Rigidity:

(high loss in competence, high selection threshold, possibly low effect of demands on arousal and resolution level)



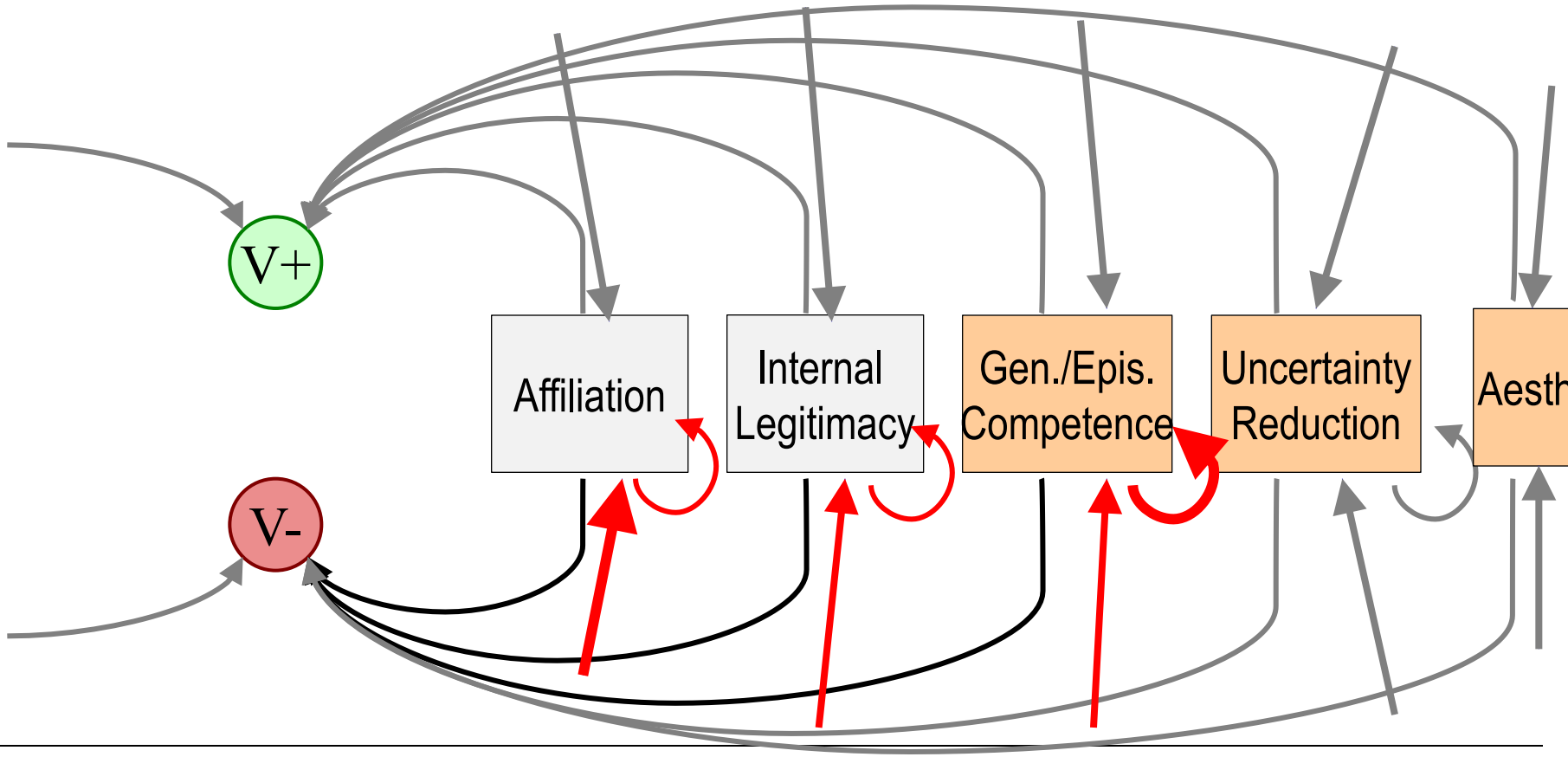
Example: Mapping to FFM (Big Five)

- Why not one free variable per FFM dimension?

FFM does not tell the complete story

Shyness != Introversion

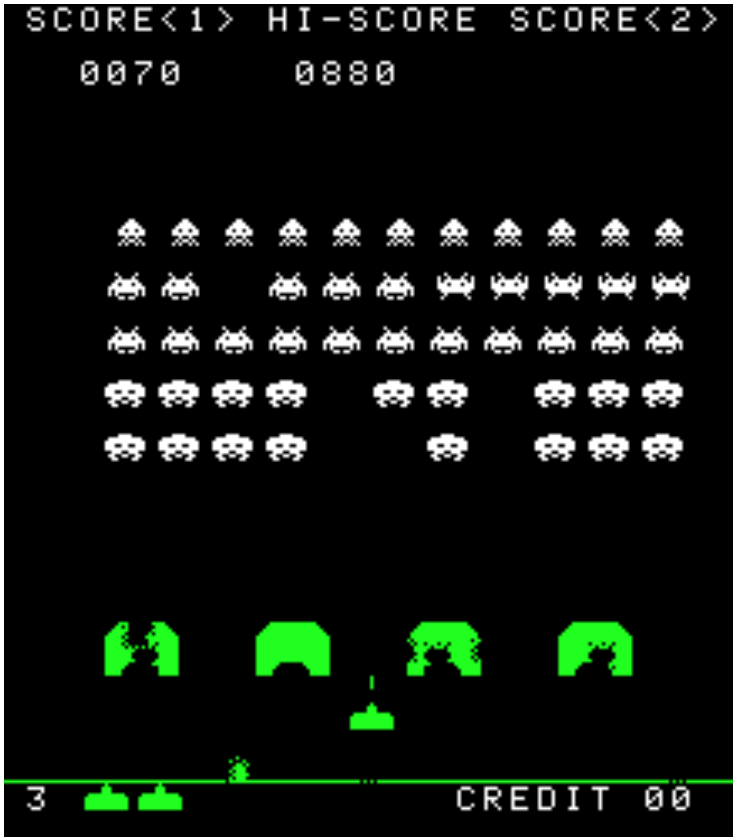
(high loss of affiliation, low competence)



How can we evaluate a model of motivation?

- Games!

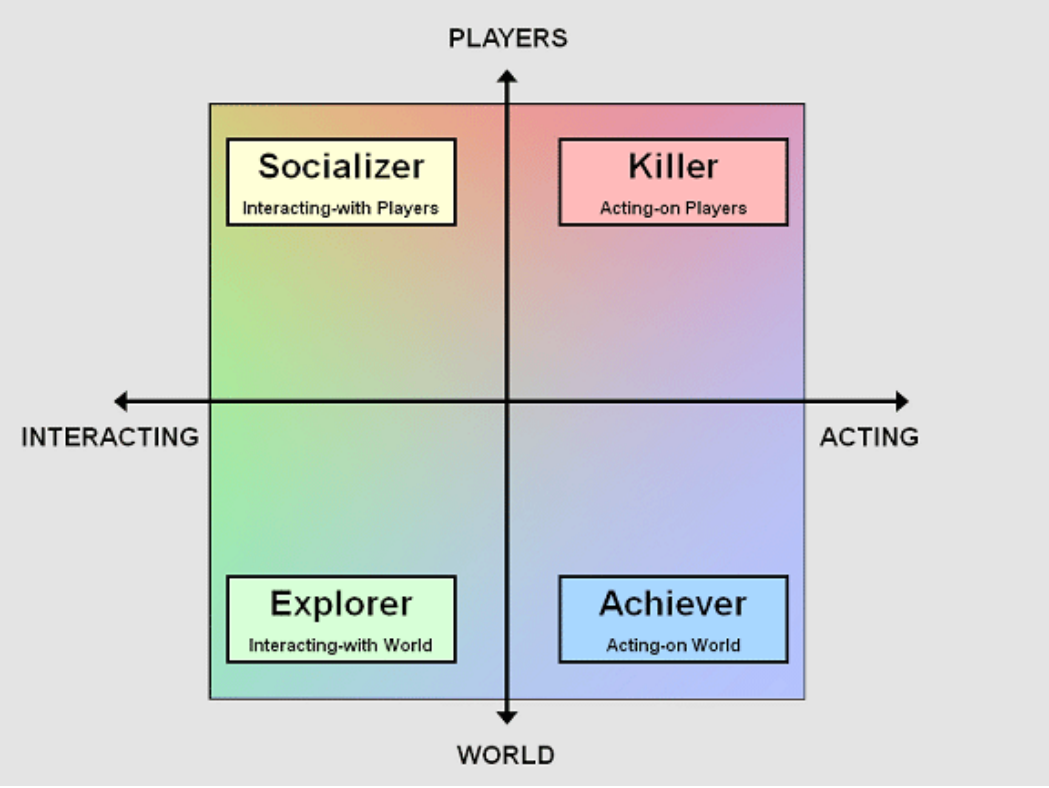
Space Invaders (1978, Tomohiro Nishikado)



World of Warcraft (Rob Pardo, Jeff Kaplan et al. 2004)

Player personality types

Richard Bartle (1996): “Hearts, Clubs, Diamonds, Spades: Players Who suit MUDs”

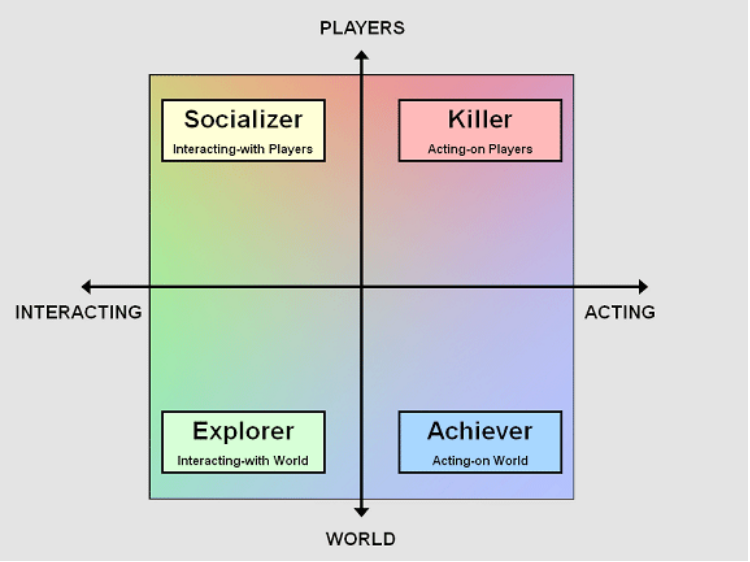


Motivation and personality

- Personality properties can be modeled as motivational variability

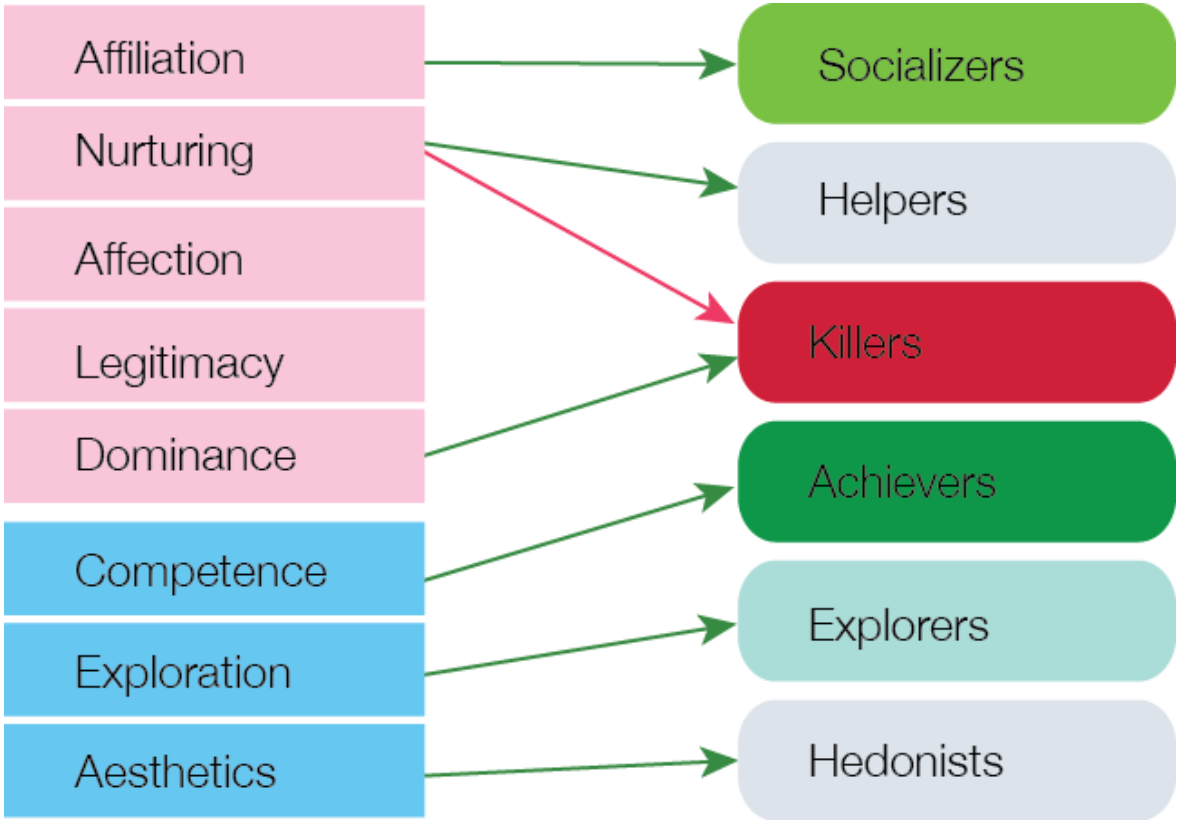
Affiliation

Uncertainty reduction



Competence

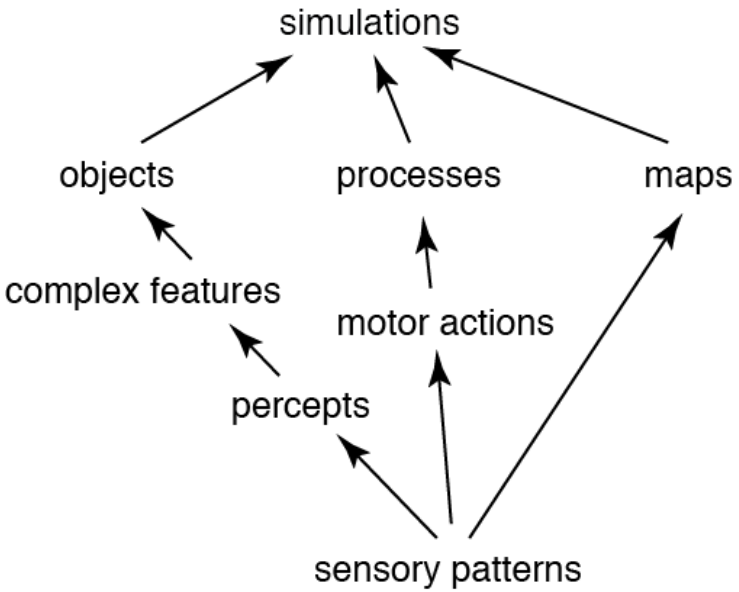
Needs and player types (with S. Tekovsky)



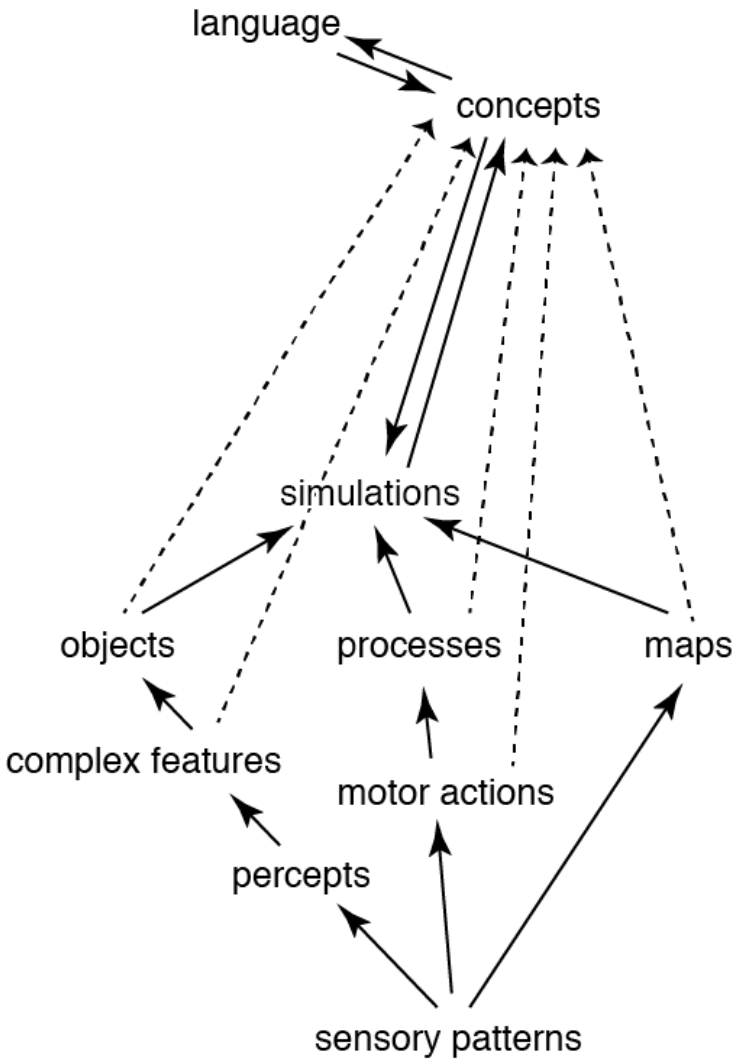
Emotion and the Self

Neocortex as a modeling system

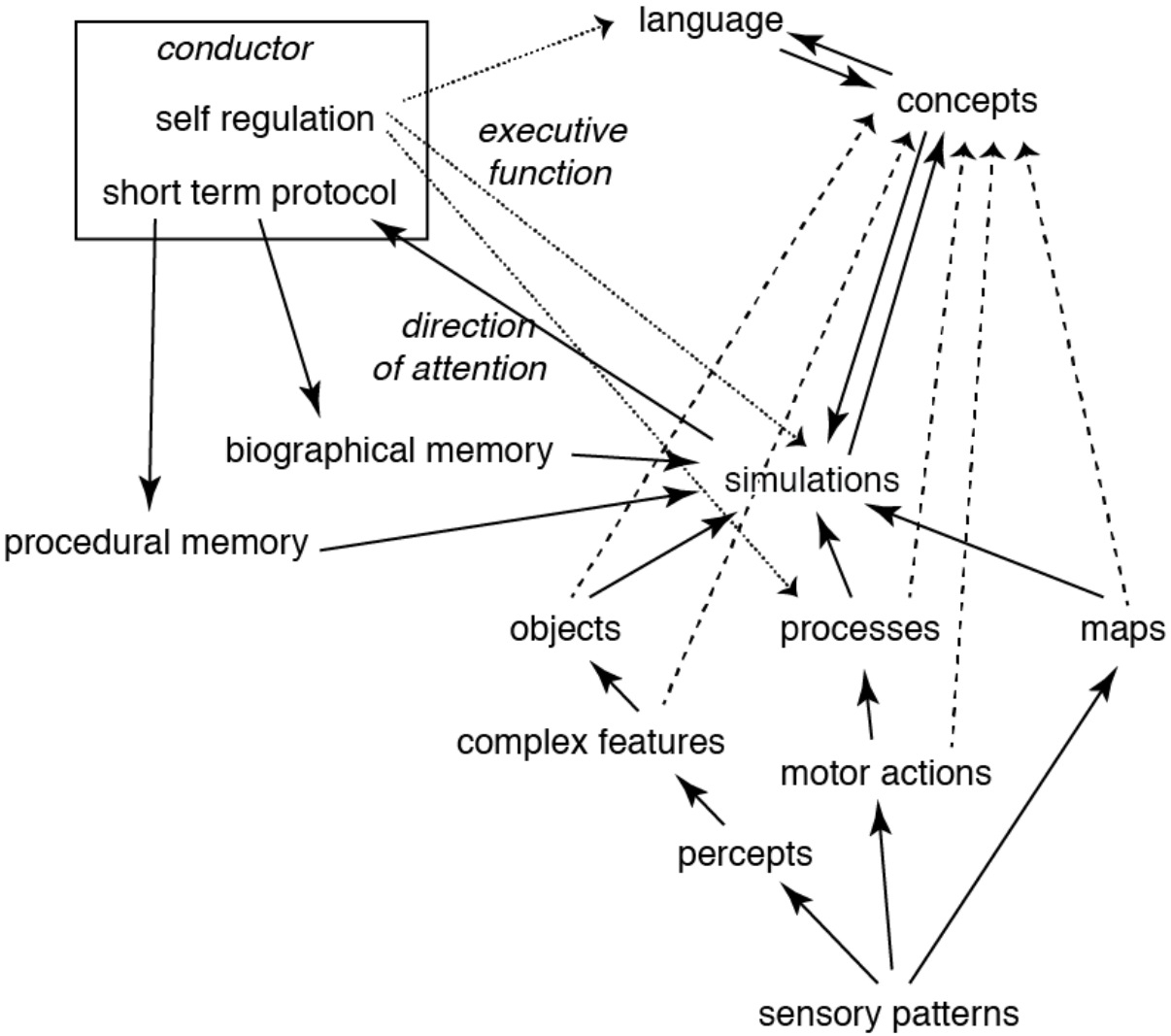
- cortical modeling is a predictive model
  of sensory patterns,
  as a dynamic simulation of world and agent



Neocortex as a modeling system



Neocortex as a modeling system



Neocortex as a modeling system

- Primary model: environment and agent
- Secondary model: interaction of agent with environment
- Tertiary model: functioning of secondary modeling

→Self

- Consciousness as a model of attention

Integration of emotion and motivation

- Control and self regulation depends on learned functional representations in cortical structure
- Attentional biases

- Attention is mechanism for directed learning
- Experiential access via attentional protocol

- Structure of self determines experience of emotion

Social emotions

- Object of emotion requires representation and motivational relevance
- Social urges: affiliation, romantic affect, libido, dominance are transactional
- Love: non-transactional emotion

- Love requires shared purpose, via legitimacy

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Thank you!

Interesting questions:

- Is recursive function approximation plus motivational system sufficient for general intelligence?
- Could we functionally recreate human-like minds with our model?
- How does a motivated/emotional system evolve when it can modify itself?