# Anchoring Knowledge in Interaction: Towards a harmonic subsymbolic/symbolic framework and architecture of computational cognition

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# Honor to whom honor is due...

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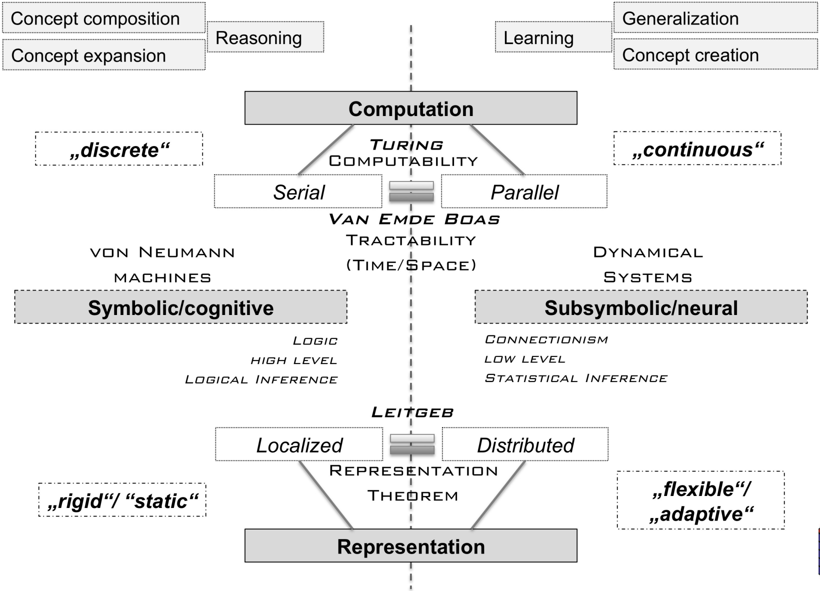
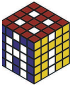
# Prelude: The Status Quo in Neural-Symbolic Integration



# Overview of the Talk

1. A Harmonic Analogy: Coupled Layers of Knowledge from Embodied Interaction to Symbols (and Back Again)
2. The Core Ideas and Objectives
3. Steps Towards an Implementation: A Sketch of an Architecture
4. Going Far Beyond Multi-Level Data Fusion

# A Harmonic Analogy

Natural agents seem to rely on...

- ...enormous richness of representations (multimodal, grounded, embodied, situated).
- ...many layers of representation at different abstraction levels.
- ...dynamic re-organization of knowledge.
- ...dynamic changes or alignments of representation (e.g., in agent-agent interactions).
- ...online and bidirectional learning in real-time.
- ...flexible adaptations to changes in the environment, the task(s), the “social setting” (presence of other agents), etc.

# A Harmonic Analogy

Conceptually similar situation in music:

- Different levels: Physical level (audio data), MIDI level, chord progression level, harmonic level, melodic level, rhythmic level, score level, structural level of a piece, (semantic) meta-level, etc.
- Transfer/interaction between levels:
  - Sometimes obvious mappings: MIDI to score to harmonic structure.
  - Sometimes partial or incomplete mappings: Harmonic structure to score, rhythmic to physical level.
  - Sometimes fuzzy or tentative mappings: Melody to harmony (in an idiom), physical to structural level of a piece.
  - Sometimes there are no mappings: MIDI to semantic/meta level, melodic to structural to harmonic level.

$\Rightarrow$ Piece of music as multi-layered, multi-representational entity with certain connections and constraints between layers (relations, mappings, etc.).

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# A Harmonic Analogy

**The music/knowledge analogy:**

- Changing one layer in a piece of music influences (in an obvious, partial, or fuzzy way) many (but not all) other levels.
- Multi-representational analysis can be used to learn or detect mappings between layers, novelties and correlations, to systematically unfold specific properties, or to find invariant properties.
- Envision an agent system also operating on different levels of representations:
  - Neural layer learning on the perception/motor level.
  - Anchoring layer learning elementary (semi-)symbolic representations of objects.
  - Reactive layer taking over in critical situations.
  - Deep learning layer learning on more abstract levels.
  - Symbolic layer for reasoning and planning.
  - (Higher) Symbolic layer providing core ontology.
- Some layers have obvious, some have partial, some have fuzzy, some have no mappings/relations between themselves.

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# A Harmonic Analogy

**A “pre-established harmony”:**

- Triggering abstract plan to move from A to B should result in corresponding motor action, classifying (on the neural level) a perceptual input as chair should activate the concept “chair” in the ontology, etc.
- Basic links might be hard-coded,...
- ...learning a new concept on the subsymbolic level should nonetheless result in a new concept entry in the ontology.

$\Rightarrow$ Interaction between the different layers in terms of information and conceptualizations.

$\Rightarrow$ Simulated or actual system operating on interacting levels in multi-representational manner should allow for mechanisms/interactions similar to music case.

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# The Core Ideas and Objectives

- Developing, theoretically and practically, a conceptual framework and corresponding architecture that model an agent's knowledge, thinking, and acting as interrelated parts of a unified cognitive capacity.
- Knowledge as...
  - ...multi-layered phenomenon appearing at different levels of abstraction.
  - ...promoting interaction between levels.
  - ...influenced by interaction between agent and environment (potentially including other agents).
- Radically new paradigm in...
  - ...interaction styles: Action-centered, embodied, multi-modal.
  - ...knowledge repositories: Different levels and forms of knowledge representation, e.g., multi-modal, hybrid.
  - ...user modeling and communication through learning and adaptation.

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# The Core Ideas and Objectives

**Scientific aims:**

- Embodiment level:
  - **Learning of elementary forms of multi-modal representation from agent interaction with environment.**
  - Emphasize the importance of sensorimotor interactions as part of knowledge formation.
  - Systematic assessment of basic learning signatures in the presence of different sensorimotor experiences.
  - Recommendations for the development of cognitively-inspired formal frameworks for embodied computation.
  - Together with approaches from computational neuroscience and network-level cognitive modeling create cognitively-inspired foundations and low-level input representations for subsequent stages.

# The Core Ideas and Objectives

**Scientific aims:**

- Anchoring level:
  - Representations resulting from embodiment level may be noisy, uncertain, vague, differ in representation languages between agents, subject to changes in the environment, etc.
  - Remedy: **Expand anchoring framework in robotics to grounding not only objects, but also certain general observable properties appearing in the environment.**
  - Top-down and bottom-up anchoring during learning.
  - Dynamic introduction of new symbols for new objects and categories by repair and concept invention mechanisms.
  - Denotations of a symbol used in communication must be consistent across communicating agents.
  - Enable the establishment of analogical links across agents.

# The Core Ideas and Objectives

**Scientific aims:**

- Neural level:
  - Embodiment view provides interaction-based neural representation of knowledge not represented at conceptual level.
  - Remedy: **Specify lifting procedure producing descriptions, i.e., lifting grounded situations and agent's action patterns to more abstract (symbolic) representations.**
  - Combine neural learning with temporal knowledge representation using variations of RBM models.
  - Validate hypotheses through symbolic description of trained networks while robustly dealing with uncertainty/errors through Bayesian inference model.
  - Use conceptual spaces (Gärdenfors) to link symbolic and sub-symbolic data.
  - Additionally combine this with analogy-making and corresponding transfer mechanisms between representation systems.

# The Core Ideas and Objectives

**Scientific aims:**

- Knowledge level:
  - Lifted multi-modal representations can be error-prone, different agents possibly use distinct/incompatible languages, etc.
  - Remedy: **Develop domain-independent dynamic re-organization of knowledge based on ontology repair mechanisms, analogy, concept invention, and knowledge transfer.**
  - Enable adaptation of agent to new situations, alignment between representations across agents, reformation of knowledge entries, and generation of new knowledge.

# The Core Ideas and Objectives

**Overall account:**

- Grounding knowledge in cognitively plausible multimodal interaction paradigms.
- Llifting grounded situations into more abstract representations.
- Reasoning by analogy and concept blending at more abstract levels.
- Repair and re-organization of initial and generated abstract representations.

# The Core Ideas and Objectives

**Five thrusts:**

1. Cognitive Foundations of Knowledge.
2. Anchoring Knowledge in Perception, Action, and Interaction.
3. Lifting Knowledge from the Subsymbolic to the Symbolic Level.
4. Analogy/Blending.
5. Concept Formation/Reformation.

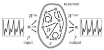
# The Core Ideas and Objectives

**Conceptual commitments:**

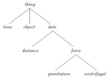
- *How does knowledge develop from the concrete interaction sequences to the abstract representation level?*
  The crucial aspect is the lifting of grounded situations to more abstract representations.
- *How can experience be modeled?*
  Experience can be explained by deep learning.
- *How is deeper understanding of a complex concept made possible?*
  Theory repair makes precisely this possible.
- *To which extent do social aspects play a role?*
  Analogical transfer of knowledge between agents is a central aspect concerning efficient and flexible learning and understanding.

# Steps Towards an Implementation

Conceptors and similar approaches are used for abstraction levels based on interaction

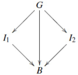



Objects can be anchored in a hierarchy of concepts




Hierarchical anchoring is the basis for lifting procedures moving knowledge from subsymbolic representations to symbolic ones

Two input theories $I_1$ and $I_2$ result in a generalized theory G and blend space B




Analogy and concept blending results in a new theory $T_2$ containing a new (potentially inconsistent) concept C

$T_1 \rightarrow T_2[C]$

**Cognitive Foundations of Knowledge**

↕

**Anchoring Knowledge in Perception, Action, and Interaction**

↓

**Lifting Knowledge from the Sub-symbolic to the Symbolic Level**

↓

**Analogy / Blending**

↕

**Concept Formation / Reformation**

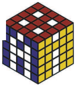
The technical perspective of anchoring imposes constraints on perception, action, and interaction for cognitive agents

$G \rightarrow G'$
$B \rightarrow B'$

$T_2[C] \rightarrow T_2'[C']$

The resolved concept C' and the resolved theory $T_2'$ [C'] might be fed back to update the generalized theory G and the blend B

The inconsistent concept C is resolved by reformation into a concept C' resulting in a new theory $T_2'$ [C']



# Going Far Beyond Multi-Level Data Fusion

**Data fusion:** "*data fusion techniques combine data from multiple sensors and related information from associated databases to achieve improved accuracy and more specific inferences than could be achieved by the use of a single sensor alone.*"

**Difference in ambition:**

- Development of a cognitively-inspired combination of low-level sensing with high-level reasoning in attempt of anchoring (symbolic) knowledge in (subsymbolic) perception and (inter)action in continuous feedback loop.
- Significant step towards (re-)creation of foundation for cognitive capacities and forms of reasoning in next generation AI systems.
- Major progress towards development of computational test bench and agent model for theories from cognitive science.

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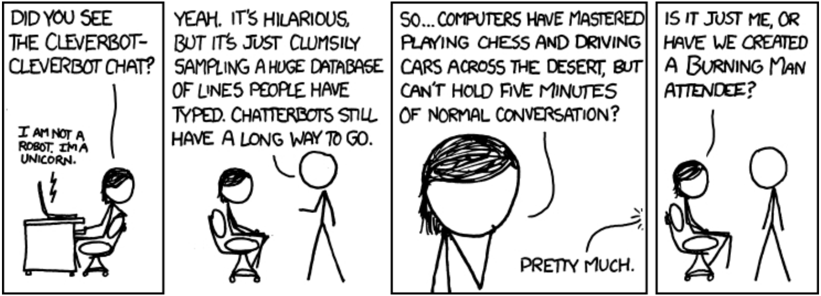
# (Definitely Not) The End



(XKCD #948)

**Questions, comments, criticism, ideas,...?**

Get in touch:

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