The role of cognitive processes in creative problem solving: a computational approach

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The role of cognitive processes in creative problem solving: a computational approach.

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Context: a multi-disciplinary perspective on ill-defined learning activities

Creativity, a phenomenon whereby something new and valuable is formed by a subject in a given context, plays a critical role in specific phases of learning activities. Here, we aim at analyzing creativity in the precise context of ill-defined problem-solving tasks, as it can be experienced during learning activities.

This study aims to contribute to a better understanding of creativity within ill-defined creative problem-solving (CPS) tasks, including complex problem solving, through a multi-disciplinary approach using computational and neuro-cognitive formalisms. This approach allows us to propose a multi-factor theoretical description of such cognitive human activities. Based on this, we aim to operationalize a computational framework of creative processes during CPS learning tasks. We focus on an ill-defined CPS task performed by a unique learner, while even in this case sociocultural perspectives have to be considered to model prior knowledge and situational awareness aspects..

Problem solving as a trajectory generation

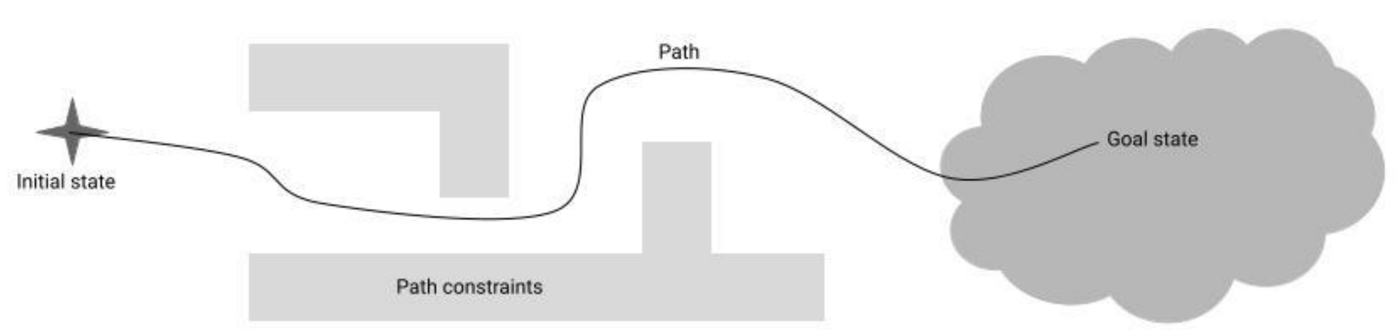
Problem Space

A problem space consists of:
- a set of symbolic structures (the states of the space)
- a set of operators over the space.

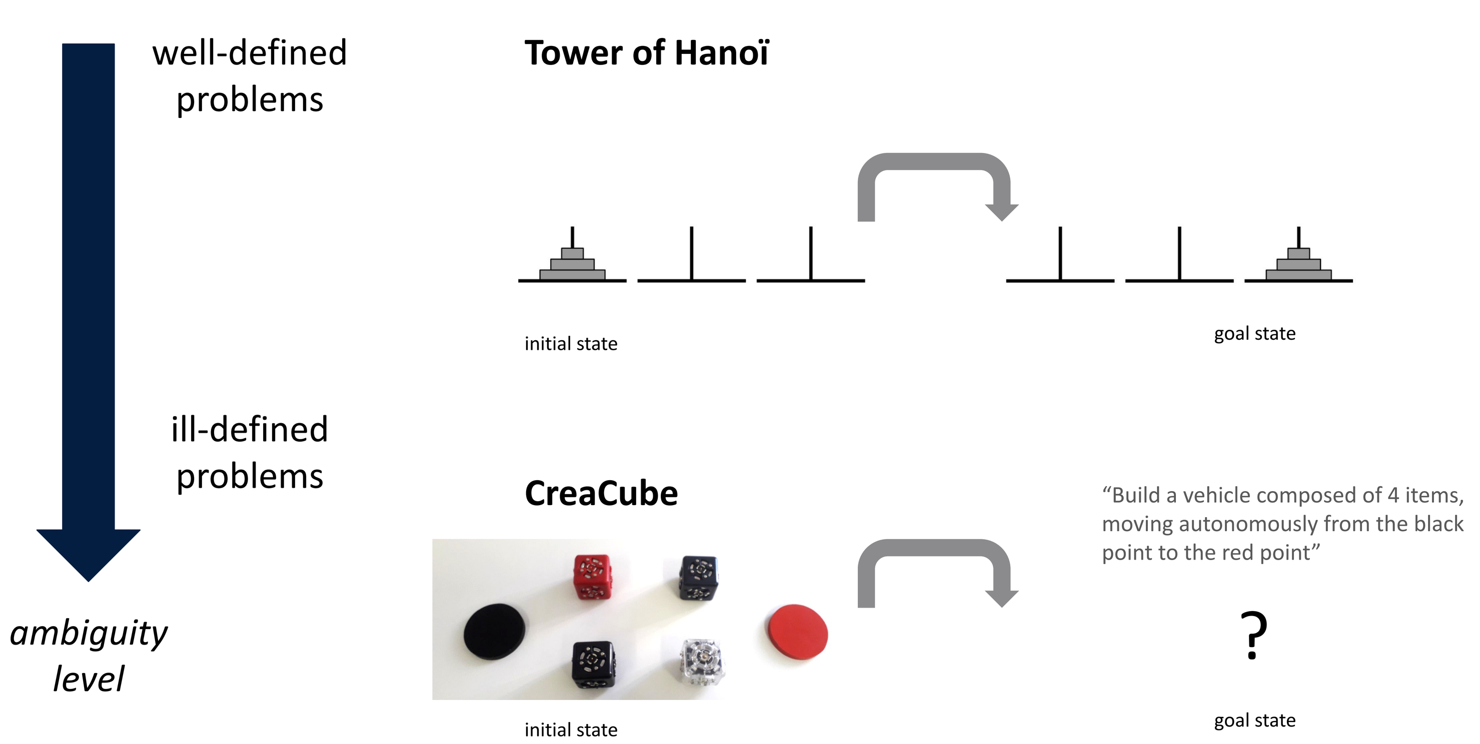
Problem

A problem in a problem space consists of:
- a set of initial states
- a set of goal states
- a set of path constraints.

The problem is to find a path through the space that starts at any initial state, passes only along paths that satisfy the path constraints, and ends at any goal state.

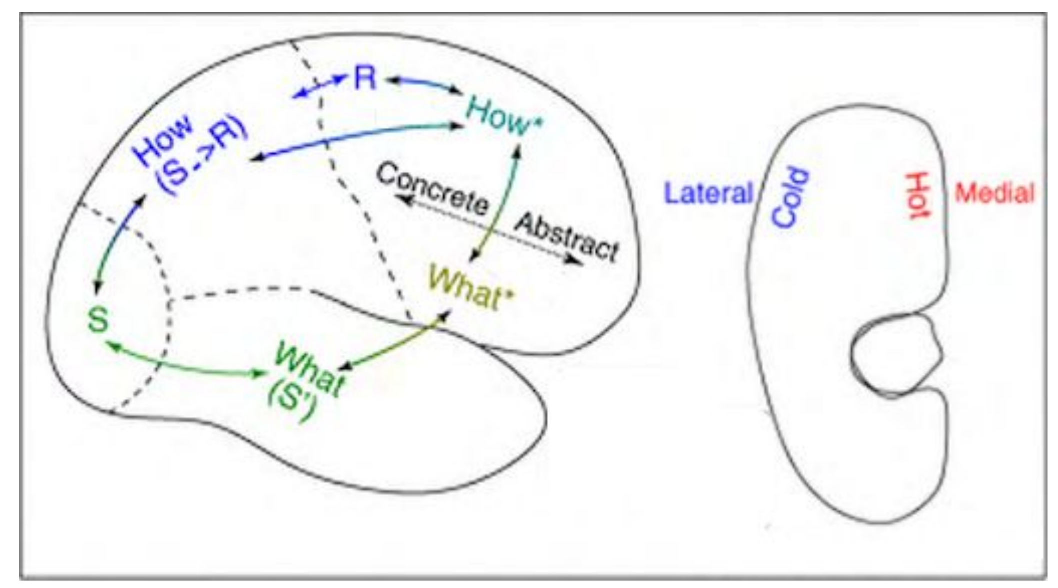


Formalizing problem solving as a trajectory generation problem in an abstract state space. Here, the definition is extended to complex ill-defined problem solving and allows us to propose an operational specification of creativity in this context.

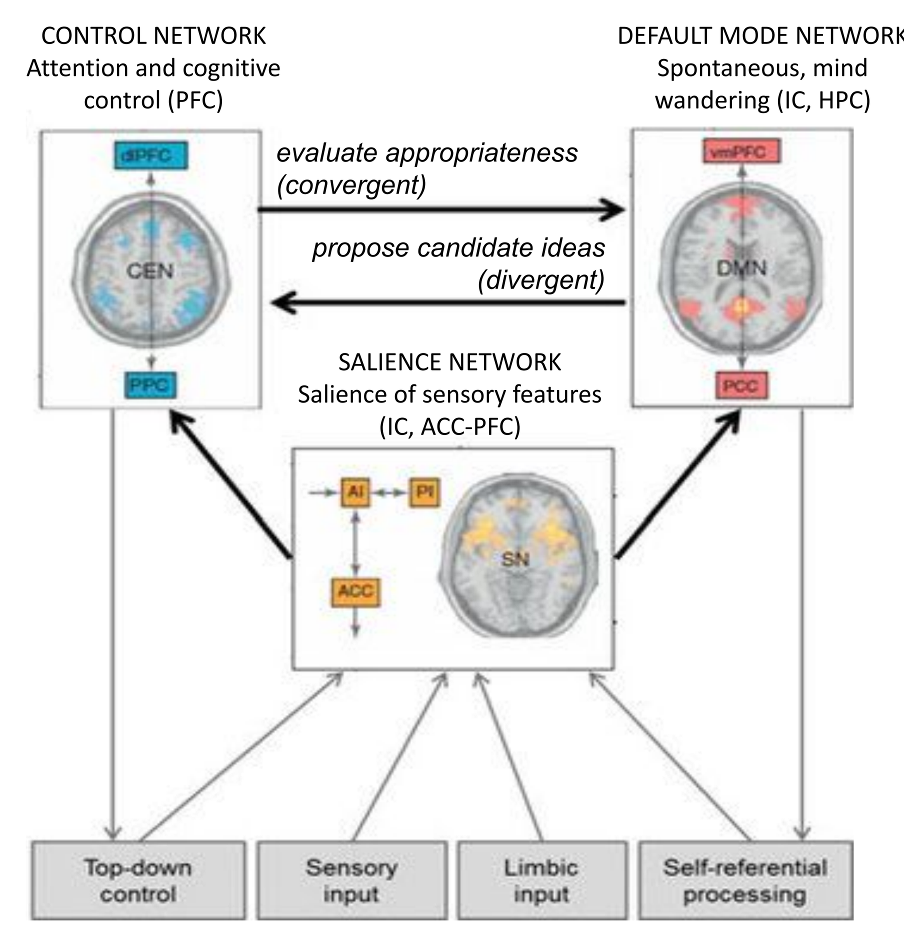


We hypothesize that solving such ill-defined problems requires *creativity*, in a sense of the competency to generate, select and implement ideas that are both
i) **novel** (i.e., original, unexpected) and
ii) **appropriate** (i.e., useful, adequate regarding task constraints),
from the problem posing disambiguation to the problem solving enaction within a specific task and sociocultural context.

Neural basis of creative problem solving



A general view of the broad functional organization discussed here, from (O'Reilly, 2010) adapted to our purpose. The *What* stimulus-driven (S) semantic representation (S') corresponds to the ventral posterior pathway, while the *How* stimulus (S) to response (R) mapping, i.e. perception to action, corresponds to the dorsal posterior pathway.
In the anterior part of the brain, the prefrontal cortex (PFC) organization is multidimensional as detailed in (Alexandre, 2021), with a *What - Why - Where - How* goal-directed organization, a *What* concrete-abstract gradient regarding representation abstraction and a *How* concrete-abstract gradient regarding rule complexity.
A step further, the lateral-medial axis corresponds to cold cognitive calculation versus hot emotional value representation.



3 main neural networks involved in creative processes:

- the Default network corresponds to brain regions active during spontaneous thought and mind wandering. It includes the insular cortex (IC) and the hippocampus (HPC) and a primary function of this network is episodic memory retrieval.
- the Control network includes the prefrontal cortex (PFC) and is activated for the control of attention.
- the Salience network includes the insular cortex (IC), the prefrontal cortex (PFC) and the anterior cingulate cortex (ACC) and monitors the salience of sensory features.

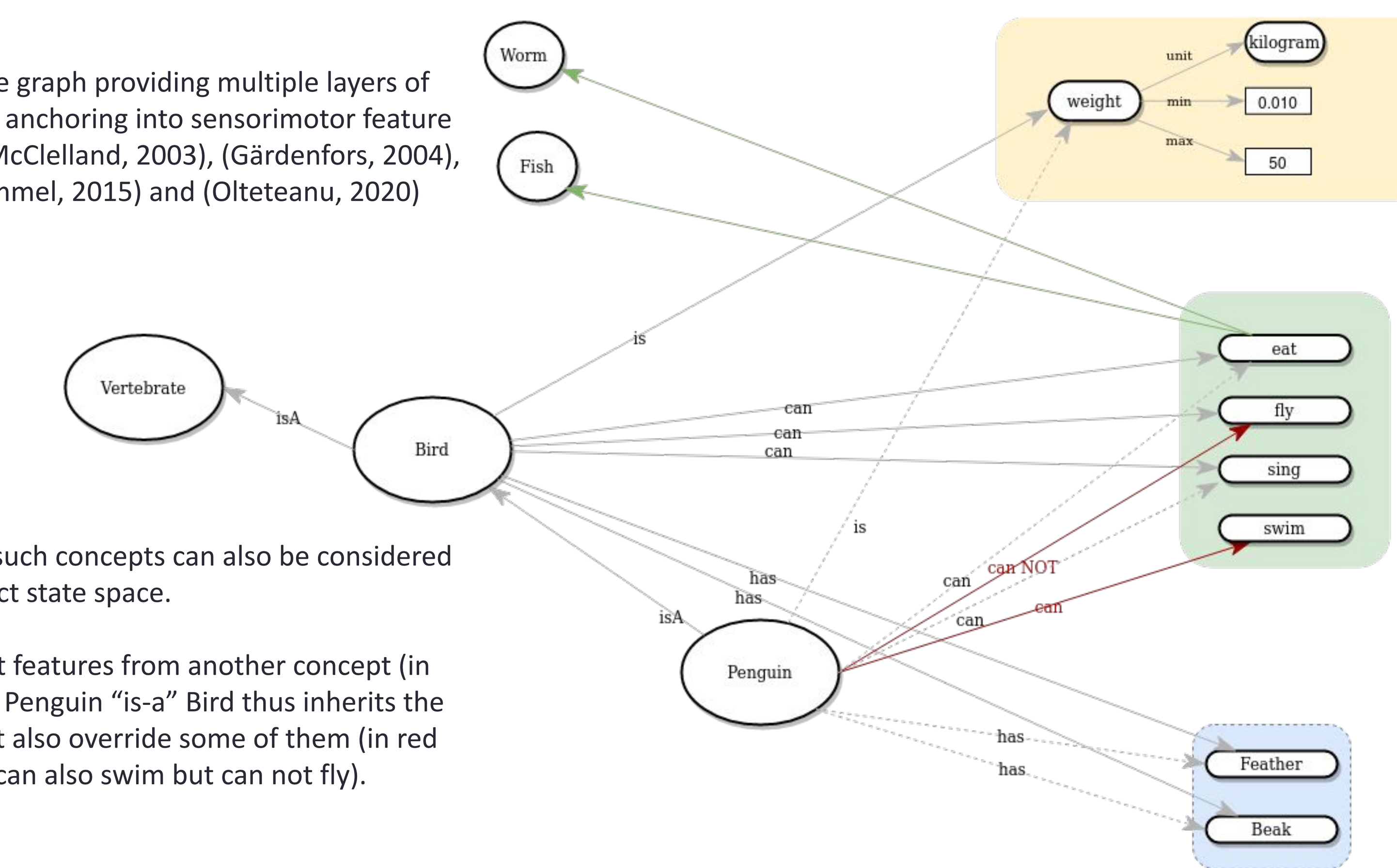
(Beaty et al., 2016) has reported a major association between the default and control networks during creativity, where the default network proposes candidate ideas (divergent phase) and the control network stands for the evaluation of their appropriateness (convergent phase).

Figure adapted from (Lesage, 2016).

A computational framework for knowledge representation

Symbolic concepts anchored on sensorimotor features…

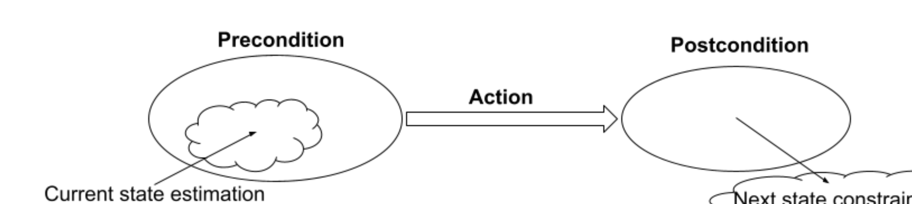
A symbolic knowledge graph providing multiple layers of abstraction as well as anchoring into sensorimotor feature spaces, inspired by (McClelland, 2003), (Gärdenfors, 2004), (Wiggins, 2006), (Hommel, 2015) and (Olteteanu, 2020) among others.



The key point is that such concepts can also be considered as points in an abstract state space.

A concept may inherit features from another concept (in dotted lines, e.g., the Penguin "is-a" Bird thus inherits the features of a Bird) but also override some of them (in red lines, e.g., a Penguin can also swim but can not fly).

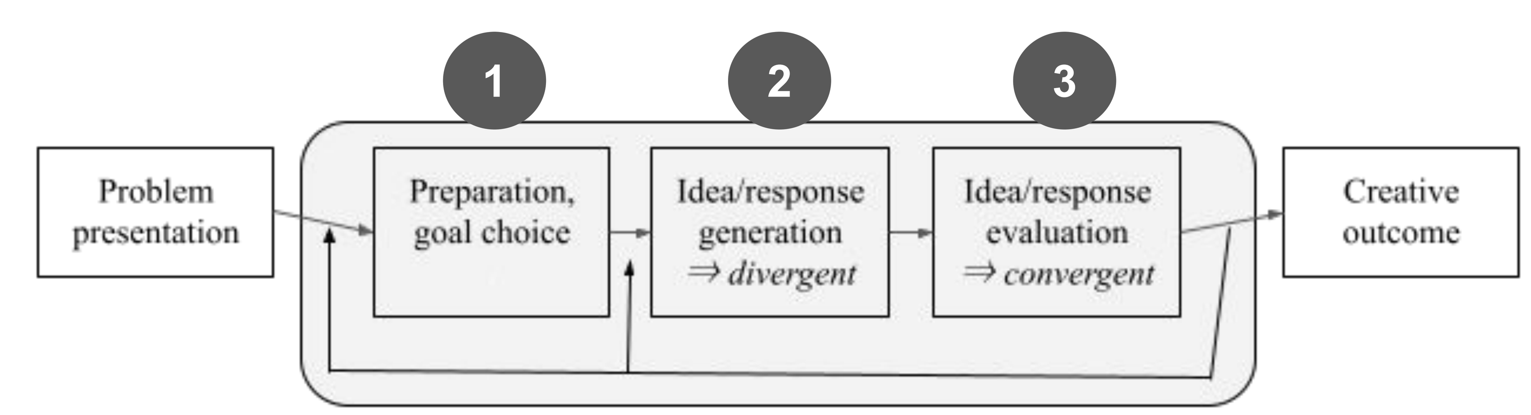
… allowing to define behavioral rules at a meta-level

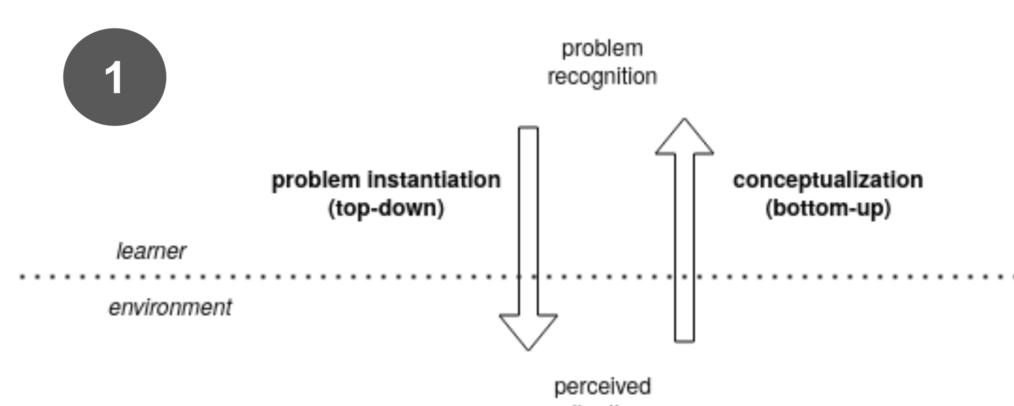


The notion of behavioral rule in order to formalize an action in a problem-solving task. A precondition is to be satisfied for the rule to be applicable. The precondition is defined as a region of the state space, the current state space estimation as another region and the rule is applicable if the latter is included in the former. The result of the action corresponds to a postcondition, defined as a region of the state space, and the next state space is included in this region.

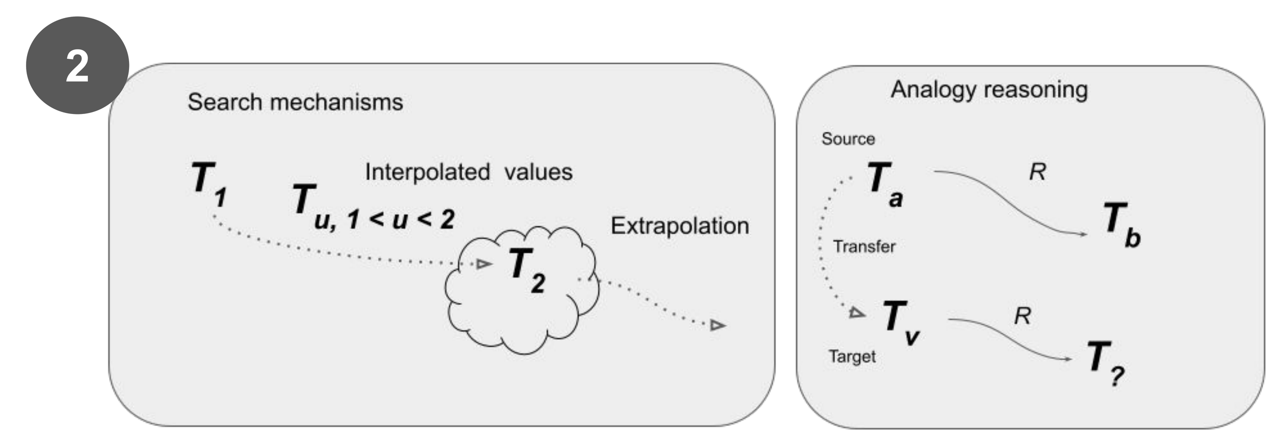
Creative problem solving, step by step

General schema of creative problem-solving steps, adapted to our approach, from the componential model proposed by (Amabile 1996). The central part corresponds to the creative process itself.

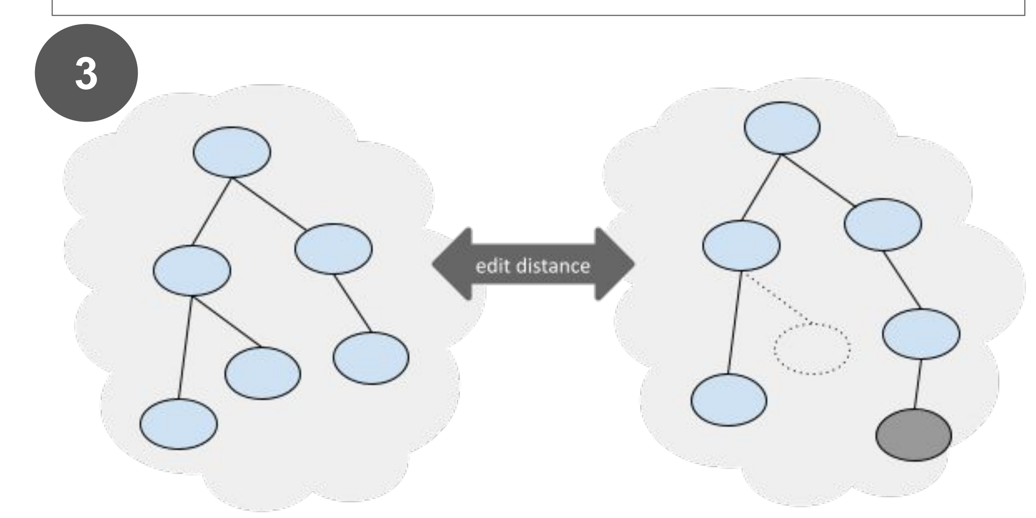




The preparation phase requires an interaction between the environment and the learner in creative ill-defined complex problem solving. We formalize this interaction in terms of bottom-up conceptualization, i.e., building an internal representation of the external situation to raise the problem issue, and top-down instantiation of the problem, i.e., setting a goal for the next step.



A geometric illustration of two idea generation mechanisms, allowed by the previous symbolic knowledge representation.
Left: Exploratory search in the sense of (Ritchie, 2012; G. A. Wiggins, 2006).
Right: Reasoning by analogy.



The distance between the current state and the goal state can be estimated using an edit distance between two semi-ordered hierarchical tuples (geodesic structure).

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