Cognitive Ontologies: Mapping structure and function of the brain from a systemic view

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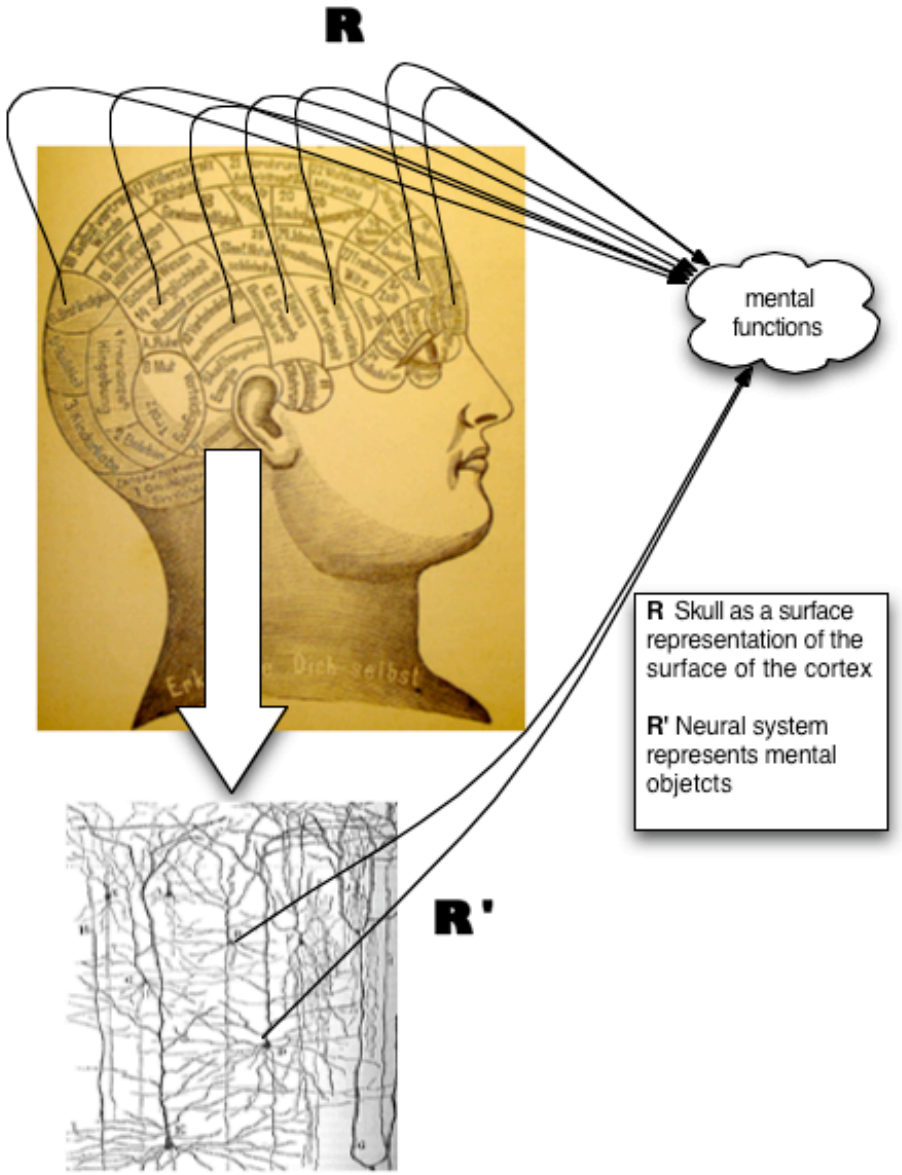
Vindicating Gall



Infering cognition from brain studies

- Let us imagine that the scientific community has built a theory of the brain, of course empirically tested, succesfully enough to be extensively used in the varied spectrum formed by the cognitive sciences.
  - [Direct inference] determine which areas are active given a cognitive process.

    (i.e: "language processing activate the Broca's area" or "Anterior Cingulate Cortex exhibits increasing activity during deception")
  - [Reverse inference] determine from the activation of a brain region, which particular cognitive process is engaged.

Infering cognition from brain studies

Schematically

[Hypothesis 1] When task T is presented, brain area A is active

[Hypothesis 2] When cognitive process X is engaged, brain area A is active

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[Inference] Brain activity in area A, demonstrates the engagement of the cognitive process X by the task T

Infering cognition from brain studies

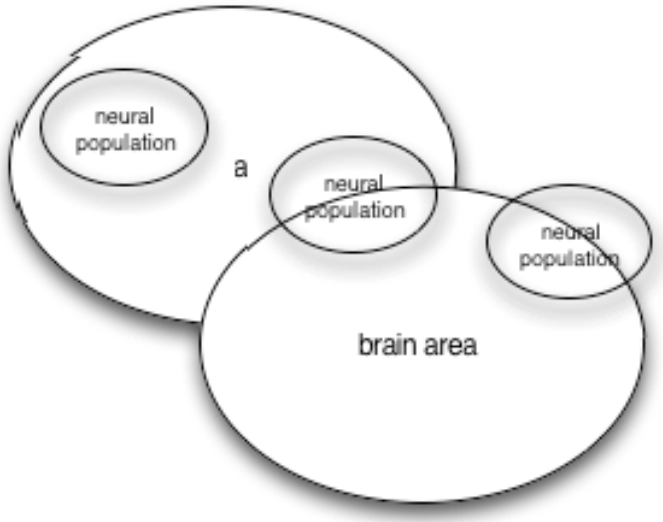
- In fMRI study with rats, for the tasks “pup suckling”(A) and “cocaine administration”(B), demonstrates that there is a higher increment in the ventral stratium for A task than for B. [Ferris05] [Poldrack06]
- The authors conclude that pup suckling(A) is more rewarding(X) than cocaine administration.

This is logical fallacy!

A cognitive process was infered fom activation in a paticular area

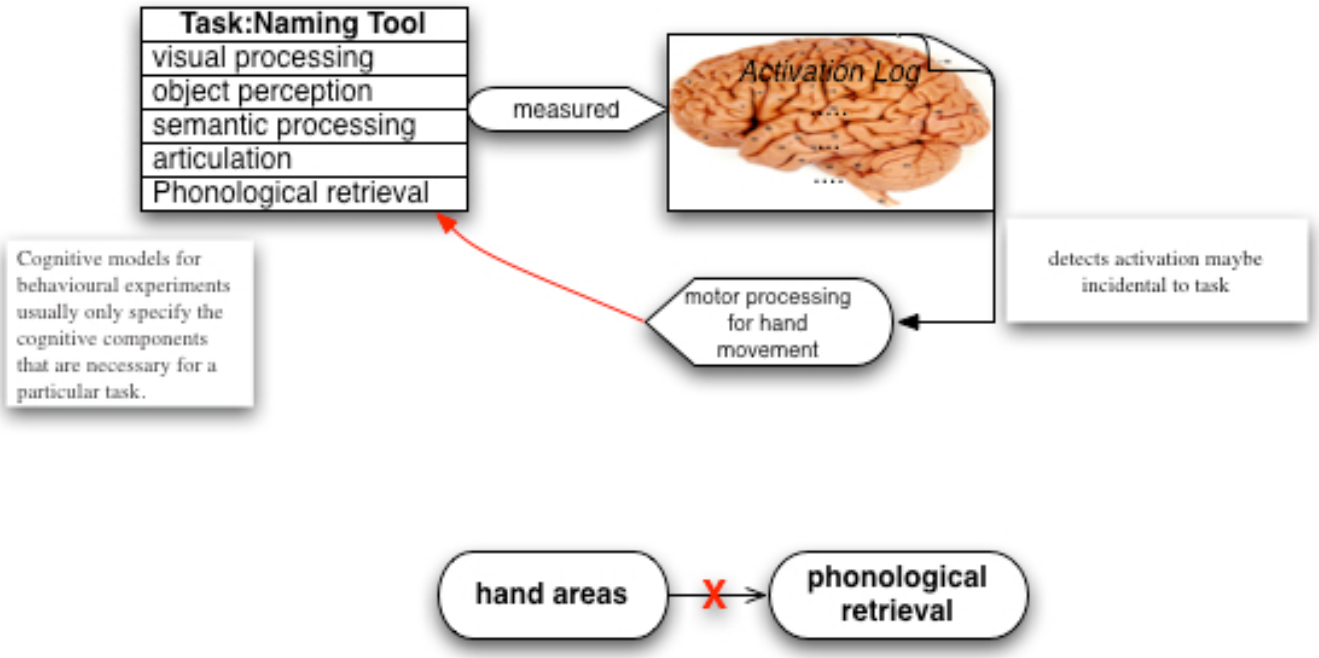
The problem of selectivity

- How can we determine which areas are relevant for a cognitive process?
- Which areas are activated incidentally when a cognitive process is engaged?



The problem of incidentally

- Brain image studies detects activation that may be incidental to the task
- To claim that an area is involved in task is very different that the area is specific to that task. [Price, Friston05]

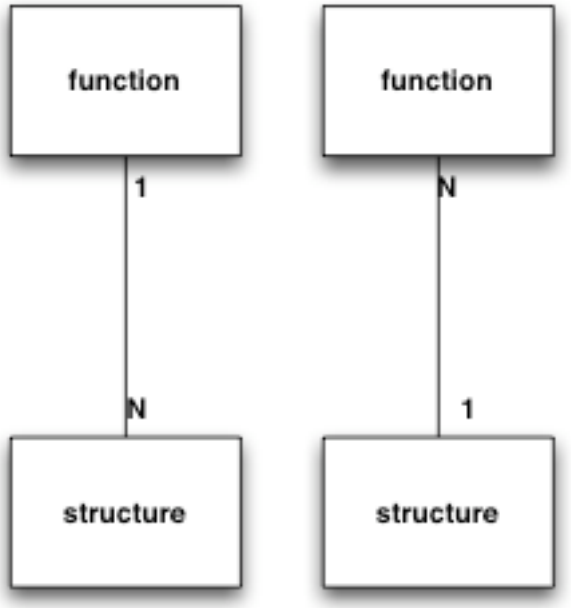


The problem of proliferation

- Since most psychologists focus on “their” cognitive task, different labels to the same brain area are assigned
  - Studies of reading refer LPLFr(left posterior lateral fusiform region) as VWFA (visual word form area)

Cardinality S-F

- Can a brain region have more than one function?
- ….*yes*…maybe *no*?
- BOTH!
- It depends at which level we are measuring the brain responses and to what do we call cognitive function
- Structure-Function relationship can be describe at many different levels
- Level of Granularity: Depending on the level of description required, different areas of the brain can be assigned to different cognitive operations. Technical details of the scanner and parameters like the activation threshold are relevant.



a) Degenerate function-struture relationship

b) Pluripotential function-struture relationship

More problems. . .contradictory results

- The obtention of contradictory conclusions in different experiments.
  - Ventral activities occur in the contrasts between coherent and incoherent motion[Cheng94]

  vs

  - The ventral area is activated only when the coherent motion represents a curved surface rotating in depth [Paradis00]
- it is a logical consequence of the lack of an ontology that maps the functions with their correlated brain structures and vice versa.

Cognitive ontologies

ACT-R theory of cognition is a cognitive architecture which reflects assumptions about human cognition. These assumptions are based on facts derived from psychology experiments.

"rather unexpected convergence of an empirical and theoretical methodology. The empirical methodology involves fMRI, which has become a major research tool in cognitive science. The theoretical methodology involves cognitive architectures, which are formalisms for modeling mental interactions that occur in the performance of certain tasks".

Localism-Modularist optimism:The brain is a system so adaptative and complex that it offers many opportunities for getting what you are seeking.

Are the cognitive modules isolatable entities?

Opinion

Cell

A central circuit of the mind

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The methodologies of cognitive architectures and functional magnetic resonance imaging can mutually inform each other. For example, four modules of the ACT-R (adaptive control of thought – rational) cognitive architecture have been associated with four brain regions that are active in complex tasks. Activity in a lateral inferior prefrontal region reflects retrieval of information in a declarative module; activity in a posterior parietal region reflects changes to problem representations in an imaginal module; activity in the anterior cingulate cortex reflects the updates of control information in a goal module; and activity in the caudate nucleus reflects execution of productions in a procedural module. Differential patterns of activation in such central regions can reveal the time course of different components of complex cognition.

Introduction

This paper will describe a rather unexpected convergence of an empirical and a theoretical methodology. The empirical methodology involves functional magnetic resonance imaging (fMRI), which has become a major research tool in cognitive science. The theoretical methodology involves cognitive architectures, which are formalisms for modeling the mental interactions that occur in the performance of complex tasks. These two methodologies are rather distant members of the cognitive science field: one has strong ties to traditional neuroscience whereas the other has strong ties to traditional artificial intelligence. However, they can be brought together such that fMRI data provide converging evidence for architectural assumptions, and the architectural assumptions provide explanations for when certain brain regions will show correlations in their activation and when they will not. Our specific case will involve the ACT-R (adaptive control of thought – rational) cognitive architecture and its relationship to several brain regions that are often active in the performance of complex tasks.

ACT-R [1,2] has been used to model people's behaviors in a great variety of tasks including categorization, learning algebra and geometry, driving while talking on a cell phone and air traffic control (see ACT-R [http://act-r.psy.cmu.edu/] for the variety of tasks researchers have modeled). By specifying behavioral models within such a framework, one is forced to make the theory computationally explicit, thus allowing for true evaluation of the theory as well as allowing for predictions in novel circumstances. According to the ACT-R theory, cognition emerges through the interaction of several relatively independent modules. Figure 1 illustrates the modules in a model of solving equations such as $7x + 3 = 38$. In Figure 1, the visual module is extracting information about the equation; the retrieval module is obtaining arithmetic facts relevant to this information; and the imaginal module is changing the representation of the solution to incorporate the retrieved information.

Before our work in brain imaging, ACT-R addressed only behavioral measures, such as the timing of keystrokes or patterns of eye movements. These behavioral data sources failed to test detailed assumptions about which modules were active in the performance of a task. We have recently been engaged in a process of using imaging data to provide converging data on module activity. Figure 2 illustrates the associations we have made between the six modules in Figure 1 and brain regions. Coordination among all of these components occurs through actions of the procedural module, which is mapped to the basal ganglia. Box 1 describes the methodology by which we are able to use the time course of the activity of the modules to make predictions about the blood-oxygen-level-dependent (BOLD) response obtained in fMRI.

The basic information processing circuit

Although perceptual and motor modules can be very important to the performance of a task, this paper focuses on the four central modules and their associated areas, which we have shown to be independent of the modality of input or output [3]:

(i) The module responsible for controlled retrieval from declarative memory is associated with a lateral inferior prefrontal region (Talairach coordinates $x = +/-40$, $y = 21$, $z = 21$) around the inferior frontal sulcus.

(ii) The module responsible for constructing imagined representations is associated with a parietal region centered at $x = +/-23$, $y = -64$, $z = 34$, on the border of the intraparietal sulcus.

(iii) The module associated with setting controlling goals is associated with the anterior cingulate cortex centered at $x = +/-5$, $y = 10$, $z = 38$ in the medial frontal cortex.

(iv) The module associated with procedural execution is associated with the head of the caudate nucleus, part of the basal ganglia, centered at $x = +/-15$, $y = 9$, $z = 2$.

Many researchers have noticed that these regions tend to activate together (e.g. see Refs [4–6]). However, there are systematic differences in the factors that these regions respond to, and these differences can be predicted from the properties of their associated modules. Below, we review evidence about each of these mappings and their regions. Box 2 illustrates an experiment in which specific regional responses were successfully predicted for each

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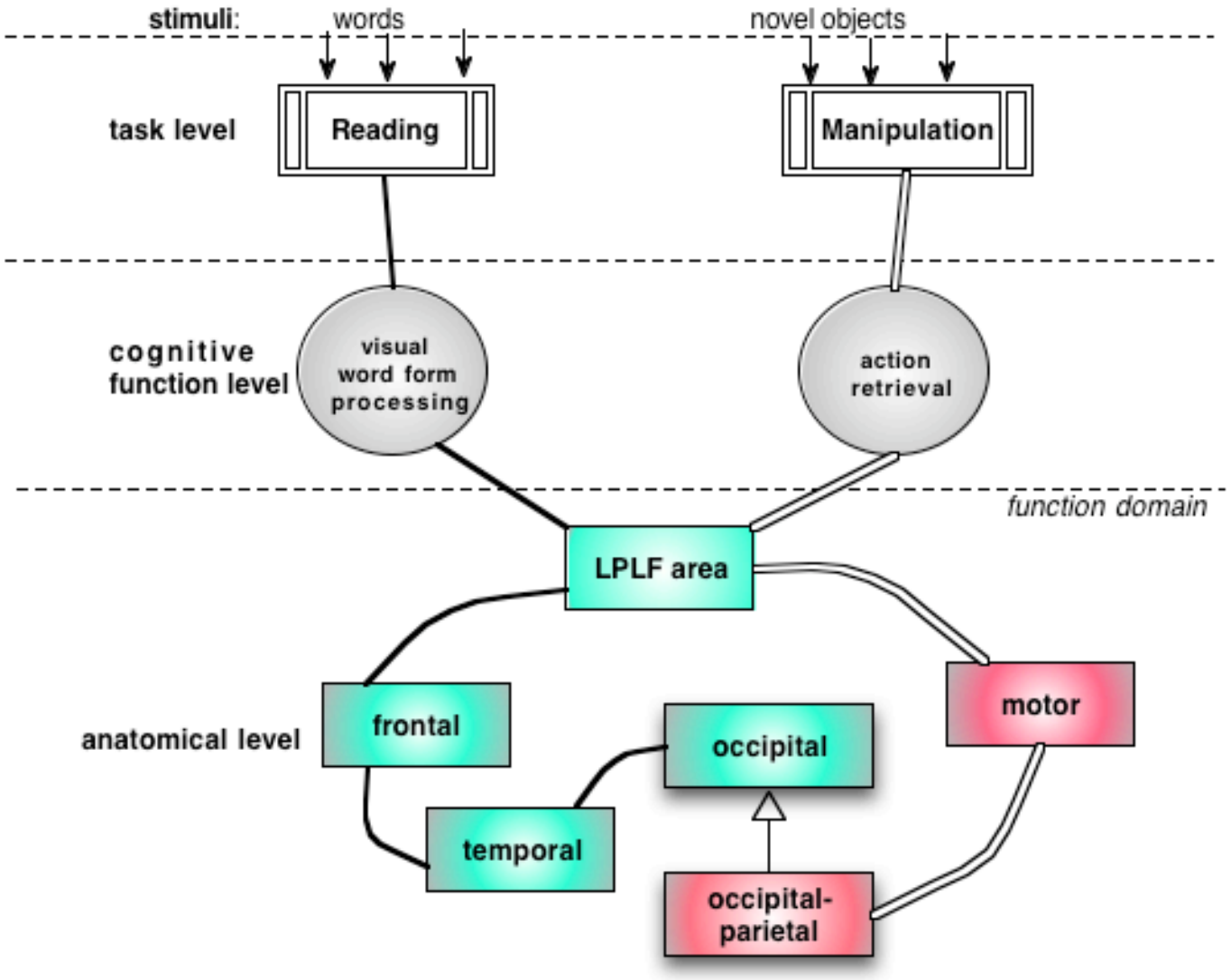
The cognitive ontology building process



An algorithm for the cognitive ontology building process

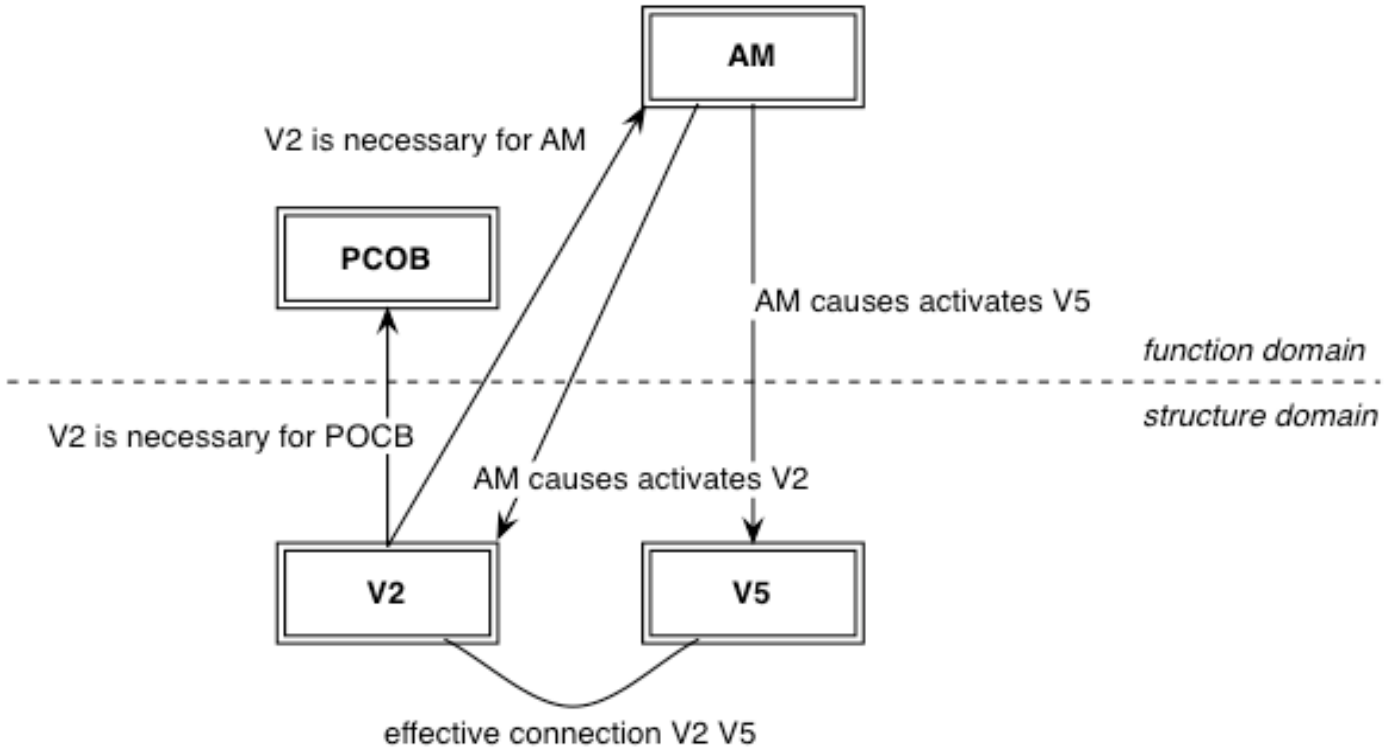


Figure 4: V2 area is necessary for both processing the contour of objects from the background (PCOB) and attending to motion in a visual stimulus (AM). Attending to motion AM, causes activation of areas V2 and V5, thus it increases the effective connectivity of areas V2 and V5

An algorithm for the cognitive ontology building process

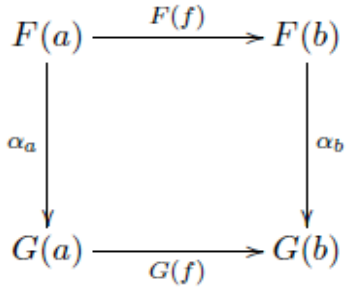
- It is assumed that direct inferences are necessary. This means that for a normal healthy person's brain, if the cognitive function F activates the area A, it always does it $F \longrightarrow A \Longleftrightarrow F \longrightarrow \Box A$
- We do not start from scratch, we know which areas are activated given a set of cognitive processes. So, we have initially ontology from fMRI studies of brain

1. $L_0 = \{(F_1, A_1)...(F_m, A_n)\}$ // initial list of *causes activation* relations
2. while ((∃ in L some F⟶A tupla ≠ 1:1) or (added new functional label in L))
{
3. for (index=1; i++; index < n) {
4. If ($A_i \longrightarrow F_i, F_j$) { Revise the label for F_i, F_j. A new lable F_k is needed }
5. If ($A_{1..i} \longrightarrow F_i$ and $A_k \longrightarrow F_i$ for k<i) {
6. $A_{1..i,k} \longrightarrow F_i$. Thus, A_k has a *necessary for* link with $A_{1..i}$ }
}
}

As a consequence of the iterative process implemented by the algorithm, the relationship between the functions and structures in the ontology converge.
The mapping function structure at the end will be 1:1.

Conclusions

- It is essential to be in possession of a cognitive ontology that instantiates the structure-function mapping of the brain
- Reverse inference is powerful but dangerous, it awaits for the development of detailed scalable cognitive ontologies
- Explore Formal Tools against insistence in ordinary language
  - Isomorphism: when the cateogories are I. can be formalized as objects of a category and make statements with CATEGORICAL RIGOUR
- Knowledge advances not by copying reality but by schematising it
- Intuitive vs Formal is another fallacy



Thanks!

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