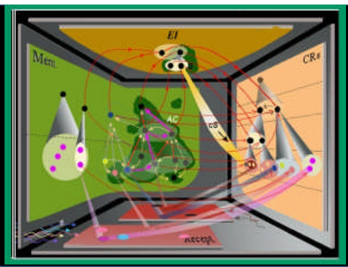

Workshop on Conceptual and Mathematical Foundations of Embodied Intelligence, Leipzig 2013

Some Properties at the Root of Embodied Intelligence

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Introduction

To progress in the study of embodied intelligence, we propose a mathematical biologically-inspired model of cognition, the *Memory Evolutive Systems* (MES) for which we refer to [3]. A MES gives a relational model, based on Category Theory, for an evolutionary multi-scale cognitive system. It conjugates information-processing and a dynamic modulated by a net of internal agents, the *co-regulators*, which operate with the help of a flexible long-term *memory*. The model identifies 3 characteristics of intelligent systems:

(i) The *Multiplicity Principle,* a kind of "flexible redundancy", which is essential for development of an adaptive 'memory', and the emergence over time of cognitive processes of increasing complexity.
(ii) Synchronized interactions between the net of *co-regulators*, with different rhythms and functions, allowing for embodiment and ubiquitous complex-event processing (von Ammon [1]).
(iii) Formation of *an Archetypal Core*, a highly connected central subsystem of the memory acting as an adaptive 'internal model' and a driving force for constructing global landscapes allowing for embodied intelligence.

To introduce the notions, we first describe **MENS** and **NBS**, the MES modeling respectively the neuro-cognitive system, and the whole organism with its biological and cognitive information-processing.

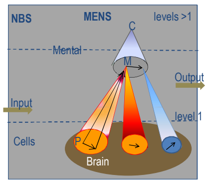
NEUR, MENS and NBS

The neural system is modeled by the *Evolutive System*[6] *of neurons* **NEUR**: For each time *t* the *category*[1] $NEUR_t$ has for objects the neurons N existing at *t* with their activity N_t; and the morphisms model the synaptic paths with their activity, propagation delay and strength around *t*. The change from *t* to *t'* > *t* is measured by the partial functor[2] *transition* which maps N_t on $N_{t'}$ if N still exists at *t'*.

From Hebb (1945) we know that a mental object activates a more or less complex and distributed assembly of neurons operating synchronously, and the *degeneracy of the neural code* (Edelman [2]) implies that such an assembly is not unique. To construct **MENS** we associate to a mental object *M* a conceptual object ('symbol') M, called a *category-neuron* (of level 1), representing the class of all the synchronous assemblies of neurons P which *M* (or M) can activate. And we iterate the process with synchronous assemblies of category-neurons to represent more and more complex mental objects.

Formally by iterated complexifications (cf. later), we extend **NEUR** into the *Hierarchical Evolutive System*[6] **MENS** with **NEUR** as level 0; a component of level *n*+1 is a category-neuron M such that M_t is the colimit of any synchronous assembly of category-neurons P of levels ≤ *n* activated by M at a time *t*..

Embodiment relies on the whole organism and the connections between different parts of the body and brain, e.g. sensory-motor connections. It will be analyzed in a MES, called **NBS** (for *Neuro-Bio-System*) which extends **MENS** by taking for components of level 0 all the cells of the organism (and not only the neurons).



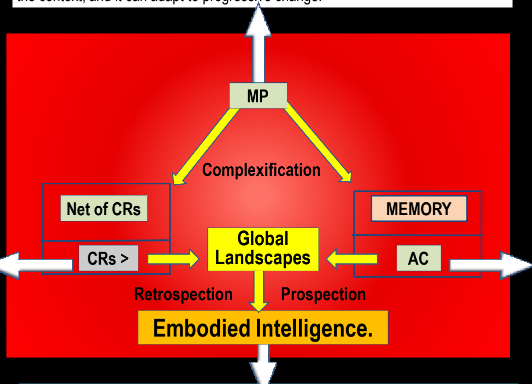
Multiplicity Principle (MP) in MES

A MES **H** is a *Hierarchical Evolutive System*[6]:whose configuration category at a time *t* has for objects the states of the components existing at *t*; the morphisms represent their links, with their *propagation delay* and *strength* around *t*; a link can be active or not at *t*. The components are distributed in a finite number of levels of increasing complexity, so that each object C of level *n*+1 is the colimit[4] of at least one pattern[3] P of interacting lower level components. Roughly, C admits P as a lower level decomposition and P, operating as a whole, and C, by itself, have the same functional role. Then C has a *ramification* obtained by taking a decomposition P of M of lower levels, then the same for each P_i and so on down to level 0. The *complexity order* of M is the smallest length of one of its ramifications.

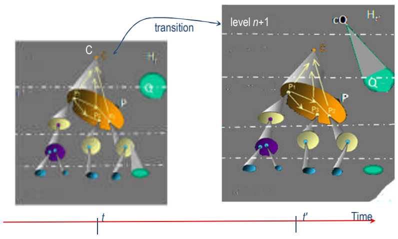
The degeneracy of the neural code used to construct **MENS** is generalized in a MES by a kind of 'flexible redundancy, called the *Multiplicity Principle* (MP):

Multiplicity Principle*:* There are *multiform* components M which are the colimit of at least 2 patterns of lower levels which are not well connected by a cluster of links between their components. Then M can operate through any of its decompositions and switch between them.

MP gives flexibility to the MES in particular to develop a flexible adaptive *memory*: a component can be recalled through different of its decompositions depending on the context, and it can adapt to progressive change.



Complexification. Emergence



In a MES the transition from *t* to *t'* results from changes of the following types: 'adding' external elements, 'suppressing' or 'decomposing' some components, adding a colimit to some given patterns. This is modeled by the *complexification process*: given a *procedure* Pr on H_t with objectives of the above kinds, the *complexification* of H_t for Pr is the category $H_{t'}$ in which these objectives are optimally satisfied. It is computable and has been explicitly constructed [3].

Emergence Theorem. ***MP is necessary for the existence of components of complexity order > 1. It is preserved by complexification and it allows for the emergence of components of increasing orders through iterated complexifications.***

Co-Regulators' dynamic. Synchronicity Laws

A MES is self-organized by a net of functional subsystems, called *co-regulators* which operate as parallel processing agents with different discrete timescales; some are in direct relation with the environment (e.g. sensors and effectors), others only act internally (e.g. evaluators in relation with the wellbeing). Their competing interactions modulate the dynamic and help develop a subsystem **Mem** acting as a robust but flexible memory.

In **MENS** co-regulators are based on small or large specialized brain modules, in **NBS** on different organs.

Local dynamic. Each co-regulator CR acts stepwise according to its own discrete timescale. At each step, the information received by CR (perception) is processed in the *landscape*[7] of CR at *t* An adapted procedure (action) Pr is selected on it, and the corresponding commands sent to effectors; that starts a dynamical process carried on during the step (modeled by differential equations implicating the propagation delays and strengths of the links). The result is evaluated at the beginning *t'* of the next step; if the objectives are not attained, we have a *fracture* for CR.

Global dynamic. The commands to effectors sent by the different co-regulators at *t* may be conflicting. Thus their local behaviors must be coordinated by interplay among them, made flexible by the possibility of switches between ramifications of complex effectors. This interplay may cause fractures to some co-regulators. An important cause of fractures is the non-respect of the structural temporal constraints of each co-regulator CR imposed by the **synchronicity laws**:

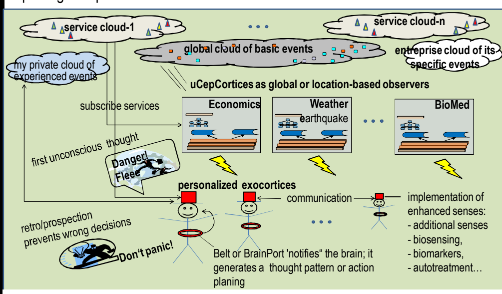
$s(t) >> d(t) >> p(t)$ for each *t* (>> means of a greater magnitude order)
where:: $d(t)$ = period of CR, $p(t)$ = average propagation delay of links in L_t ,
$s(t)$ = least stability span of components.

If these laws are not respected for one or several co-regulators, fractures can backfire through levels, forcing a cascade of re-synchronisations (by change of their period) to co-regulators of increasing levels to avoid systemic disease or even death.

Embodied Intelligence in MES, e.g. in NBIS

The same processes can be described in any MES in which the level 0 has a structural core analog to that in the brain, leading to an archetypal core through complexifications. Embodied Intelligence can develop in such an artificial system.

In particular, the European project uCepCortex (cf. Figure below, adapted from Rainer von Ammon's slides) proposes a model **NBIS** for a *Neuro-Bio-ICT-System* obtained by connecting **NBS** to a computer-like processing system acting as an "Exocortex", to enhance human capacities by integrating, self-structuring and exploiting multiple sources of information.



The basic idea of the uCepCortex project as a Cognitive System

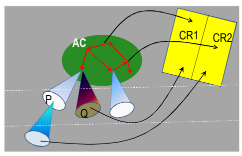
Archetypal Core AC

Higher cognitive processes such as intelligence depend on the development over time of the ***Archetypal Core* AC.**

The neural system contains a topologically central and highly connected subsystem, called the *structural core* (Hagmann & *al.* [4]). In **MENS** (and in **NBS**), it generates through successive complexifications, a subsystem **AC** of the memory, called the *Archetypal Core*, which has higher order components integrating significant memories of different modalities, with several ramifications (thanks to MP). They act as hubs in **Mem** and are connected by a number of strong and fast links which form information loops self-maintaining their activation for a long time.

AC operates as a permanent though flexible *internal model* that plays a main role in self-referential processing and cognition, in particular allowing for the development of embodied intelligence as follows:

Activation of part of **AC** diffuses through self-maintained archetypal loops, and then propagates to lower levels through decompositions and switches between them. Thus a large domain of the system is activated and its activation maintained for some time. All this activation allows for more communication between different parts of the MES, and in particular increases the information received by higher level co-regulators directly linked to **AC**. It leads to the formation of a *global landscape* GL uniting and extending spatially and temporally the landscapes of these co-regulators (cp. GL to the "Global Workspace" of different authors).



A GL gives a unified perspective on the system, where higher level information can be 'consciously' processed, while 'automatically' keeping traces of the operations of lower level co-regulators. Thus intelligent behaviors can develop in successive overlapping GLs through a sequence of intermingled processes as follows:

(i) A *retrospection process* proceeds by abduction to recollect information back in time and coming from lower levels, such as sensory inputs with emotional overtones (thanks to its reinforcement in GL). Processing this information allows for embodiment and "sensemaking" of the present.

(ii) A *prospection* process is then developed in a longer term GL, to select procedures allowing for intelligent behaviors, action or long term strategies.

Recall of basic notions on categories and on Memory Evolutive Systems

For more information, cf. [5] and [3].

1. A *category* is a directed (multi-)graph H equipped with an internal (partial) composition which maps a path (*f, g*) from A to B on an arrow *fg* from A to B; it is associative and each object has an identity; a vertex is called *object,* and an edge *morphism* (or 'link').
2. A *functor* F from H to a category H' maps an object A of H to an object FA of H', a link *f*: A ⟶ B on a link F(f): FA ⟶ FB, and preserves the composition.
3. A *pattern* (or diagram) P in a category consists in a family of objects $(P_i)_i$ and distinguished links between them. A *collective link* (or inductive *cone*) from P to C is a family $(s_i: P_i \rightarrow C)_i$ of links well correlated by the distinguished links of P.
4. P admits a *colimit* cP if there is a collective link from P to cP through which any other collective link from P to an object C factors uniquely.
5. H is *hierarchical* if the class of its objects is partitioned into a finite number of *complexity levels*, so that an object M of level *n*+1 is the colimit of at least one pattern P with each P_i of level < *n*+1.
6. An *Evolutive System* (ES) **H** is a family $(H_t)_t$ of categories and partial 'transition' functors between them satisfying a transitivity condition; a component of the system is a maximal family of objects of the H_t related by transitions. **H** is a *Hierarchical Evolutive System* (HES) if the categories H_t are hierarchical and the transitions respect the level.
7. In a MES, the *landscape* of a coregulator CR at time *t* is the category L_t whose objects are the clusters of links from a component to CR which are active during the step beginning at *t*.

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