The MENS model: from neurons up to higher cognitive processes

by

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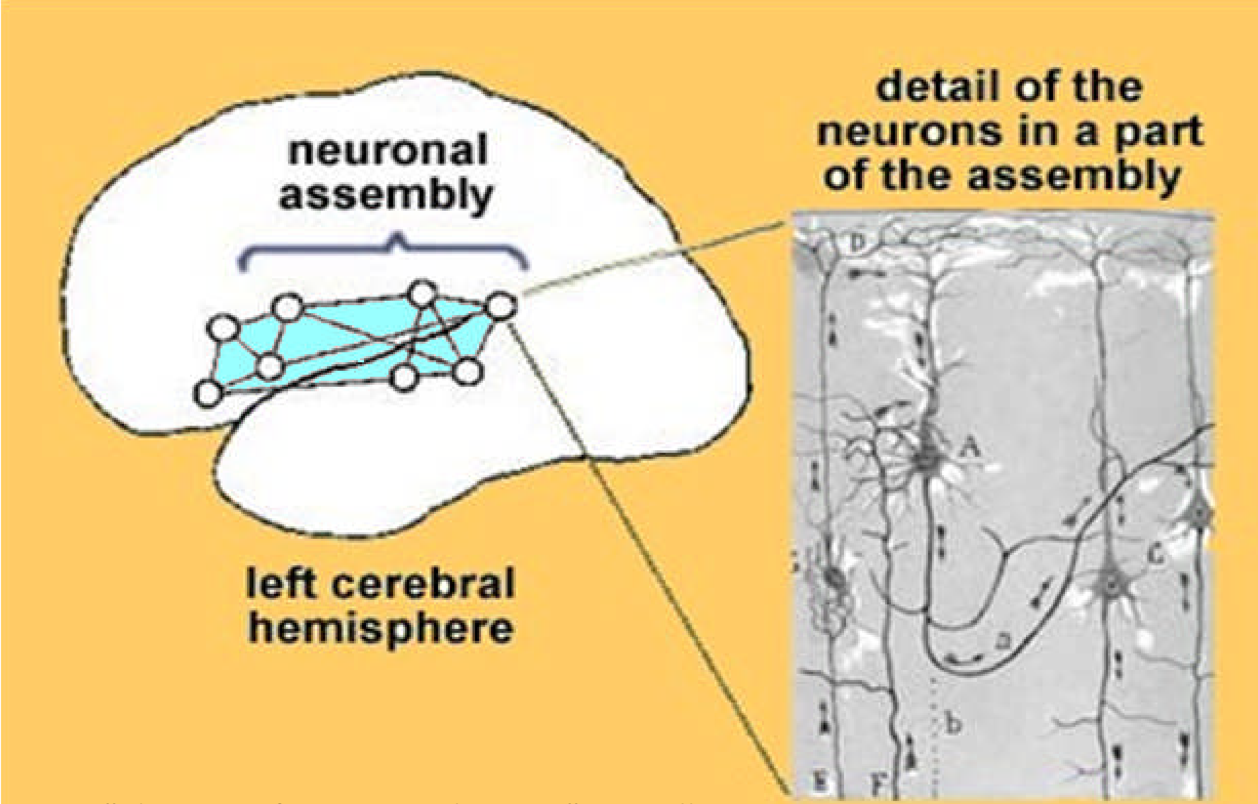
THE ROLE OF NEURONAL ASSEMBLIES



From: "The Brain from top to bottom", McGill

Though various brain areas are heterogeneous both anatomically and functionally, there is a common process in brain dynamics, namely the 'synchronous' activation of more or less complex and distributed *neuronal assemblies*. This process (already noted by Hebb in the fourties), as well as its *degeneracy property* (emphasized by Edelman), is at the basis of our model **MENS** which shows how an 'algebra of mental objects' can be generated through iterative binding of more and more complex such assemblies, leading to the formation of flexible mental objects and cognitive processes of increasing complexity, up to consciousness.

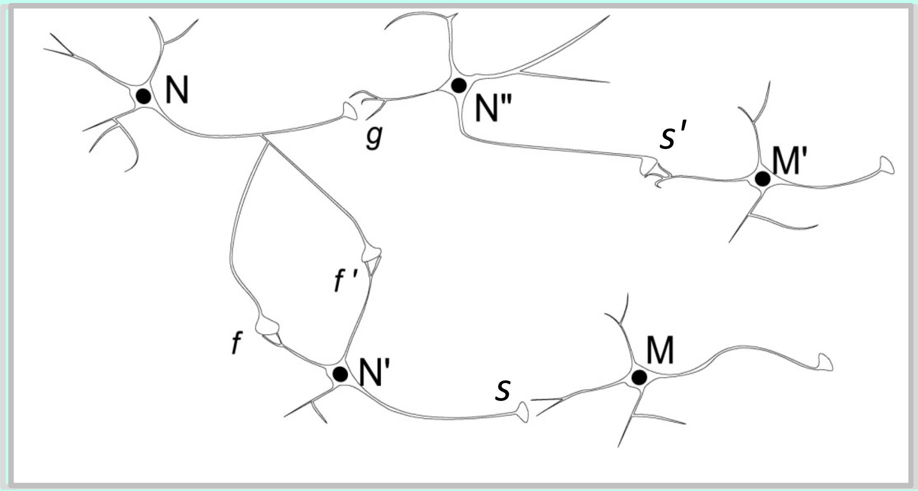
BRAIN, MIND and CATEGORIES

BRAIN	MENTAL OPERATIONS	CATEGORICAL NOTIONS
Neurons Synapses between neurons	Distinguish objects and relate them	(Multi-)Graph
Synaptic paths	Composition of relations. Communication	Category Functor
Synchronous assemblies of neurons	Binding operation (synthesis) Classification	Colimit Projective Limit
Synchronous Hyper- assembly (= assembly^n) of neurons	$\Rightarrow$ Algebra of mental objects	Complexification process
Degeneracy of the neural code	Emerging Properties	Complex links Multiplicity Principle

The neural dynamic relies on the formation of more or less complex synchronous assemblies of neurons, to which the degeneracy property gives some flexibility .

A 'dynamic' category theory (incorporating Time and durations) gives tools for modeling the main neural and mental operations: formation of relations between interacting objects, memory of complex objects binding more elementary ones (colimit, complexification process) and later recognition, classification of objects into invariance classes (projective limit).

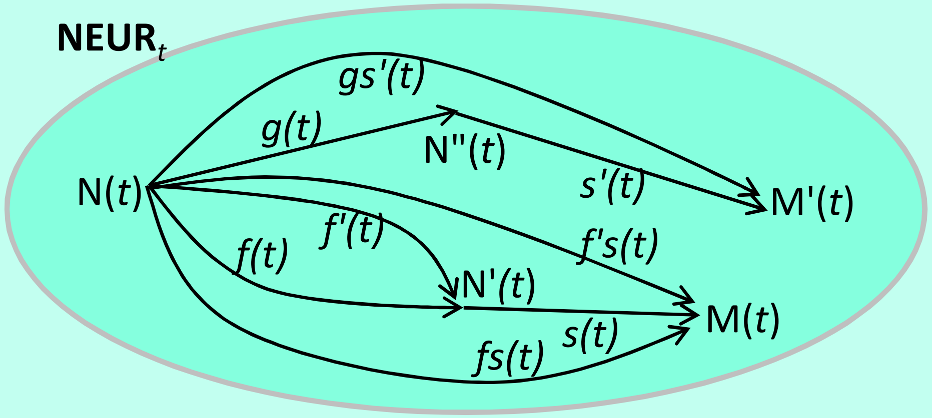
GRAPH AND CATEGORY OF NEURONS



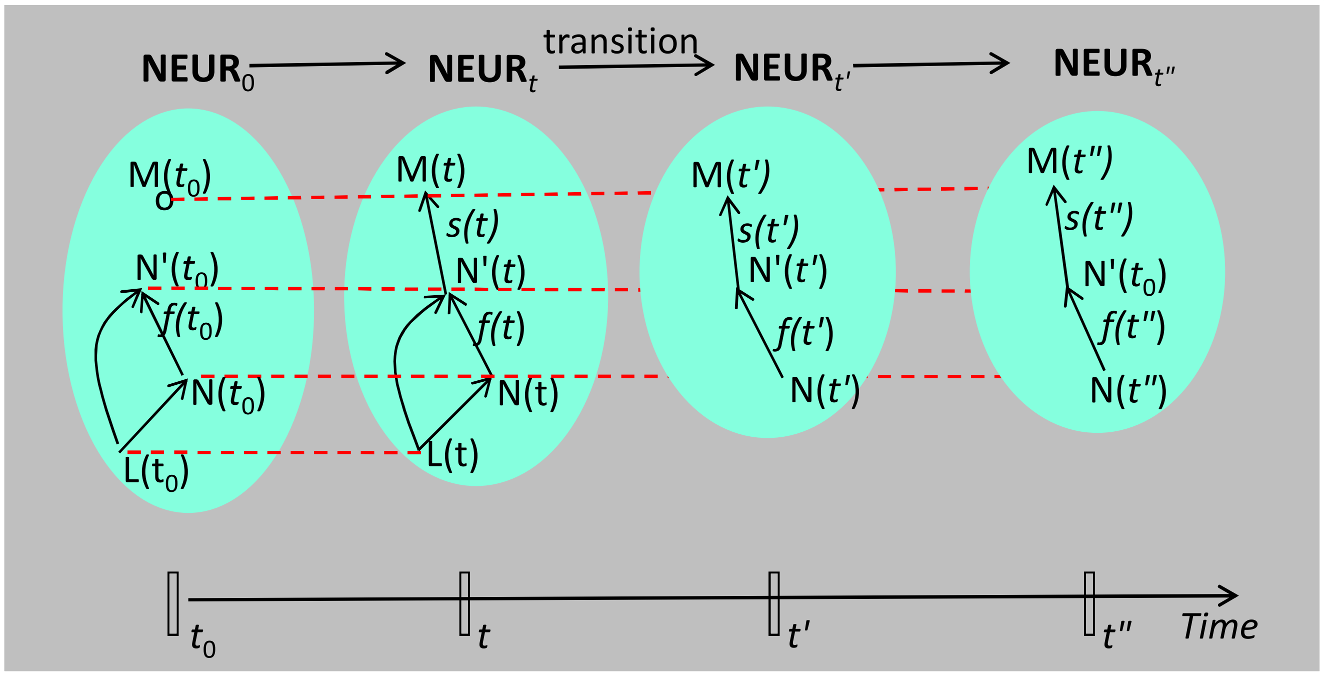
The *graph of neurons* at an instant *t* has for vertices the states N(*t*) of the neurons N existing at *t* (measured by their activity around *t*). *An e*dge from N(*t*) to N'(*t*) is a synapse *f* from N to N'; it is weighted by its *propagation delay* around *t* and by its *strength* (to transmit the activation of N). This strength varies according to *Hebb rule*: it increases if the activations of N and N' are correlated.

The *category of neurons at t*, denoted $\mathbf{NEUR}_t$ is the category of paths of this graph. Its objects are the vertices N(*t)* of the graph, the morphisms (also called *links*) are synaptic paths (= sequence of successive synapses), and the composition is given by the convolution of paths.

(A *category* is a graph on which there is given a composition of successive edges, which is associative and in whch each object has an identity.)



THE EVOLUTIVE SYSTEM OF NEURONS NEUR

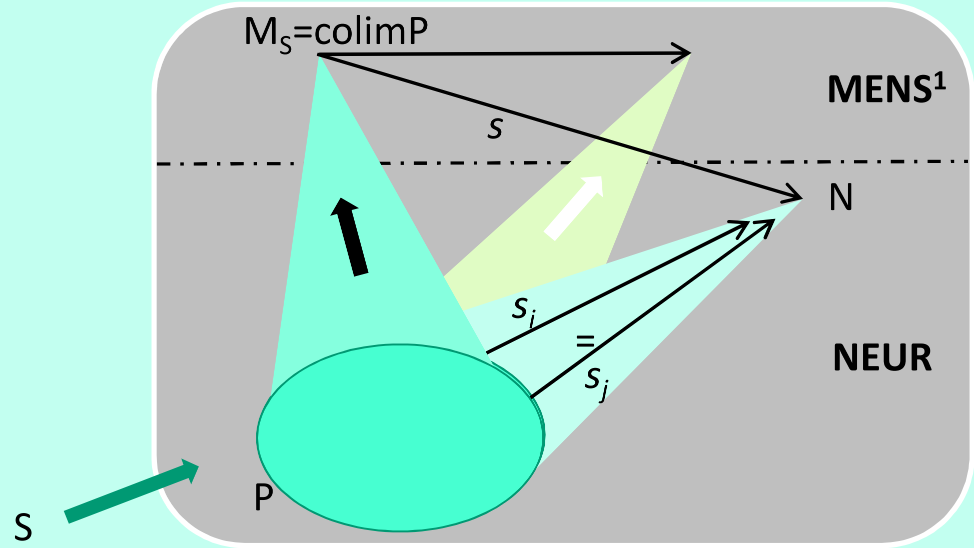


It describes the evolution of the neural system during its life. For each t of the timescale is *Time,* we have the category $\mathbf{NEUR}_t$ of neurons at t.

The *transition* from t to $t' > t$ is a functor from a subcategory of $\mathbf{NEUR}_t$ to $\mathbf{NEUR}_{t'}$ relating the states of the same neurons and links at the two different instants. (A functor is a map respecting the objects and the composition.) There is a transitivity of transitions. A *component of* **NEUR** is a neuron N, looked at as the sequence of its successive states.

MENS is an Evolutive System constructed from **NEUR** by adding more conceptual objects, called *cat(egory)-neurons,* modeling more and more complex mental objects and processes.

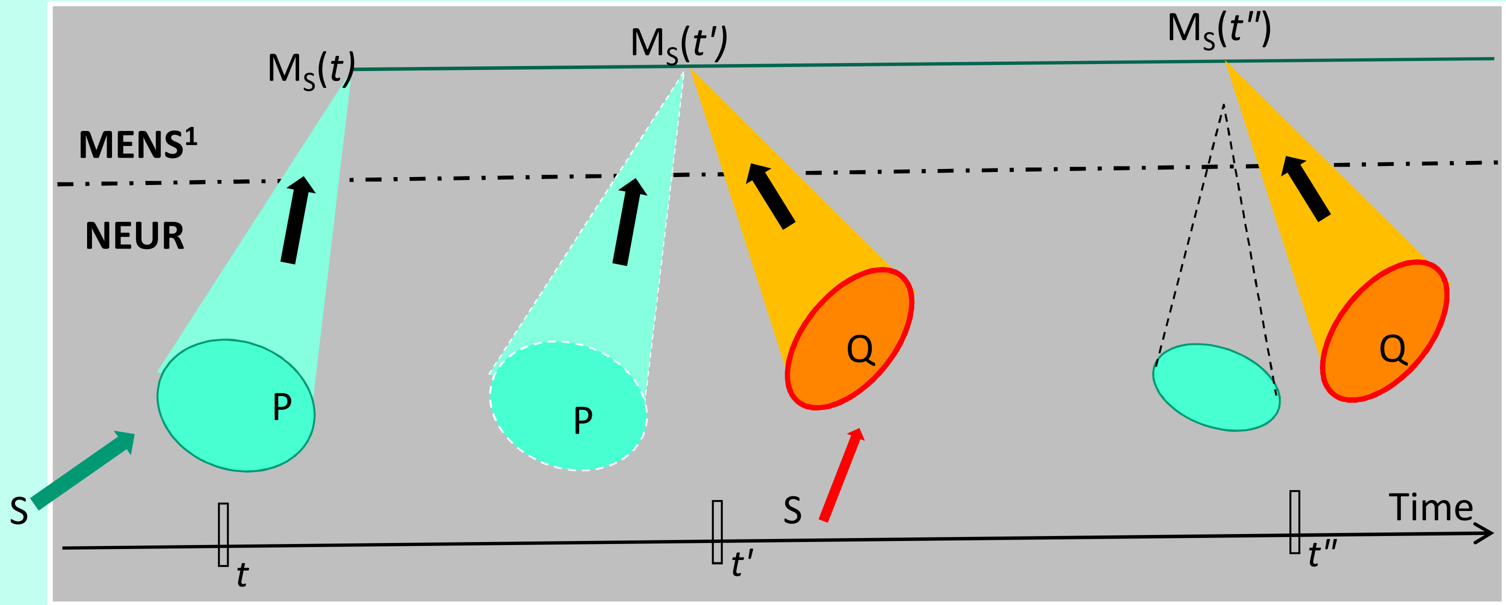
FORMATION OF A MENTAL OBJECT AS A CAT-NEURON



A simple stimulus S (e.g., an external object) at *t* synchronously activates an assembly of neurons, which we model by a *pattern* P in $\mathbf{NEUR}_t$ that is a family of neurons P_i interconnected by some distinguished links (= synaptic paths) *f* through which they transmit their activation to each other. The activation of P is transmitted to a (cat-)neuron N if there is a family of links s_i from P_i to N, correlated by the distinguished links of P, so that they all transmit the activation of P_{ii} to N; at the same time; (s_i) is called a *collective link* from P to N.

If S is repeated or persists, the distinguished links of P are strengthened (via Hebb rule), and P becomes able to act by itself as a synchronous assembly. There is generally no ('grand-mother') neuron representing it in **NEUR**, but the long-term memory of S will be recorded by a cat-neuron (of level 1) M_S in **MENS** 'binding' P, meaning that M_S has the same functional role than P as a whole. Formally M_S becomes the *colimit* of P in **MENS**: the collective links (s_i) from P to any cat-neuron N are in 1-1 correspondence with the links *s* from M_S to N binding them.

DEGENERACY. FLEXIBLE MEMORY

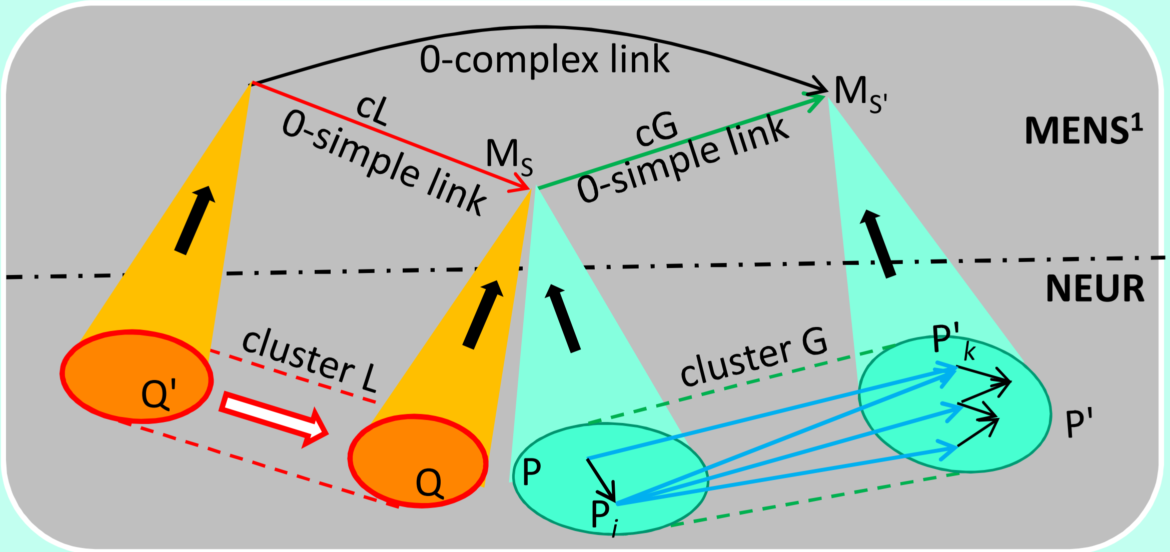


" **More than one combination of neuronal groups can yield a particular output…**"

This is the ***degeneracy*** property (Edelman, 1989, p. 50). In particular a stimulus S can activate more or less different synchronous assemblies of neurons at different times. In **NEUR** the corresponding patterns, though not necessarily interconnected, have the same functional role there is a 1-1 correspondence between their collective links to any N.

In **MENS**, the cat-neuron (of level 1) M_S recording S must represent the invariant common to all these patterns, hence it is the colimit of each of them. Though initially constructed to bind a particular pattern P, later it takes its own identity and can even disassociate from P. Thus it is not a rigid record (as in a computer), but a flexible memory which adapts to changing situations. The multiplicity of its decompositions ensures that S can be recognized under different forms, even new forms not yet met, as long as the change is progressive enough.

THE BINDING PROBLEM. SIMPLE AND COMPLEX LINKS



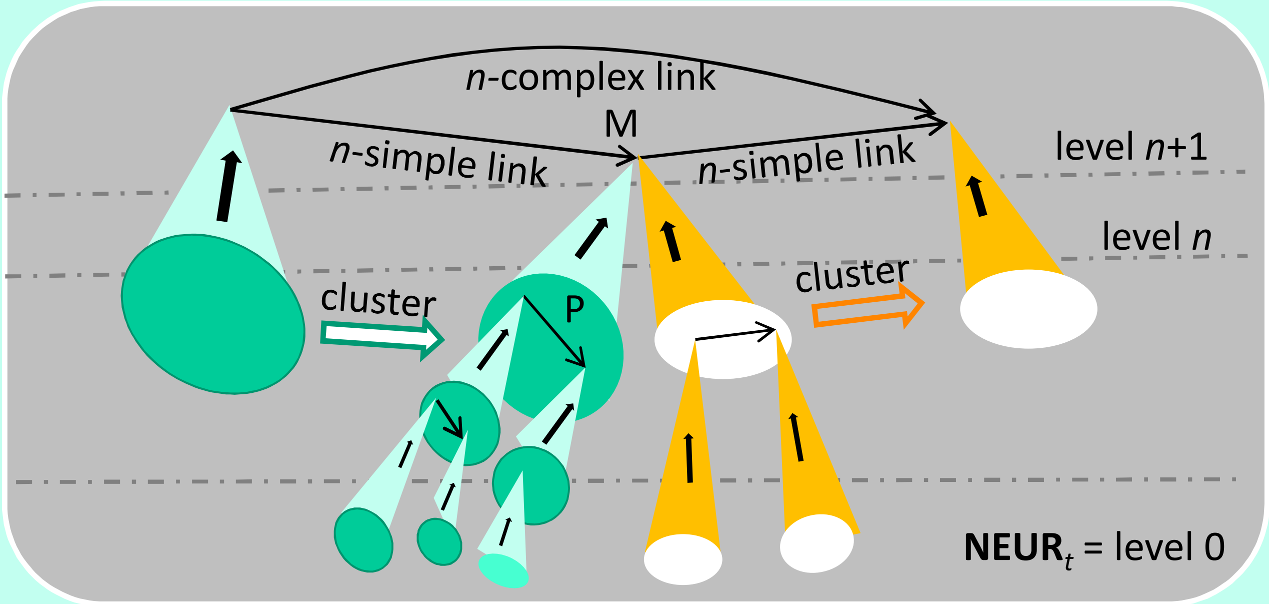
In **MENS** the *Binding Problem* becomes: what are the links between cat-neurons (of level 1).

A pattern P as a whole may activate P' through a *cluster* G from P to P', consisting in links from each P_i to at least one P'_k, these links being well correlated by the distinguished links of P and P' so that they coherently activate the various components of P'. If P and P' are recorded by their colimits M_S and $M_{S'}$ in **MENS,** the cluster G binds into a unique link cG from M_S to $M_{S'}$, called a 0-*simple link.* A composite of 0-simple links binding adjacent clusters is 0-simple.

From degeneracy, it follows that M_S can be the colimit of 2 patterns P and Q non connected by a cluster; M_S is then called a *multiform object.* In this case there are also 0-*complex links* cLcG in **MENS c**omposing 0-simple links binding non-adjacent clusters (such as L and G). They *emerge* ar the cat-neuron level (though depending on the 'global' properties of the neural level).

The propagation delays and forces of synapses extend to the 0-simple and 0-complex links, so that Hebb rule and equations known for neural systems can be extended at their level**.**

THE HIERARCHY OF CAT-NEURONS

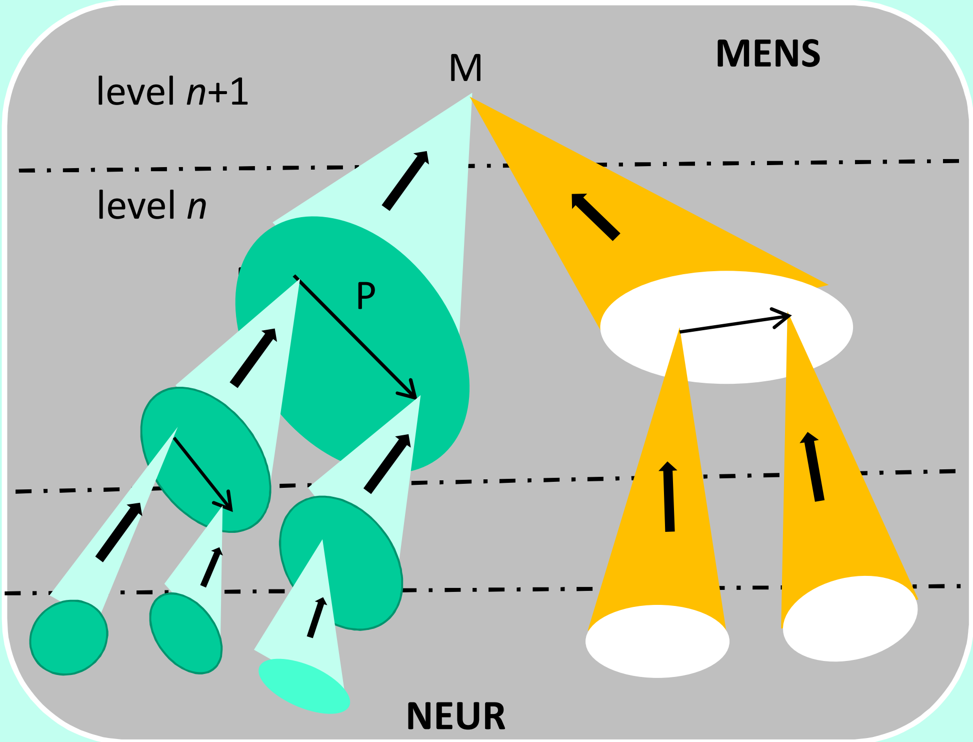


A complex mental object can be constructed by combining simpler ones. For modeling that, we imitate the construction of cat-neurons of level 1, replacing synchronous assemblies of neurons by synchronous assemblies of neurons and cat-neurons of level 1; this defines cat-neurons of level 2 and their 1-simple and 1-complex links. And by iteration of the process, we obtain a hierarchy of cat-neurons of increasing levels.

Thus for each *t*, we obtain the *hierarchical category* **MENS**$_t$ based on **NEUR**$_t$. Its cat-neurons are partitioned into levels, so that each object M of level *n*+1 is the colimit of at least one pattern P with values in the full subcategory whose objects are of level ≤ *n.* The degeneracy extends, so that the links are *n*-simple links and *n*-complex links defined as before.

By construction, a cat-neuron M admits at least one *ramification* down to the neuron level 0, In fact the degeneracy entails that it may have several such ramifications.

UNFOLDING OF A CAT-NEURON. COMPLEXITY ORDER



The activation of a cat-neuron M of level n+1 consists in the unfolding of one of its ramifications down to the neural level: first activation of one of its decompositions P in a synchronous assembly of cat-neurons of lower levels, then a decomposition of each component of P, and so on down to the *physical activation* of synchronous assemblies of neurons. At each step, there is a choice between the various (non necessarily connected) decompositions, so that the activation of M has several freedom degrees leading to *multiple physical realizabilities*.

The ramifications of M have not all the same length. We define the *complexity order* of M is the smallest length of a ramification. It is less or equal to the level of M. Thus the level indicates the number of steps in which M has been constructed, but not always its 'real' complexity, measured by the smallest number of steps for its formation or its activation.

Theorem. *Without the degeneracy property, hence if there was no multiform cat-neuron, all cat-neurons would be of complexity order* 1.

Thus the degeneracy property is necessary for the emergence of mental objects and higher cognitive processes of increasing complexity order.

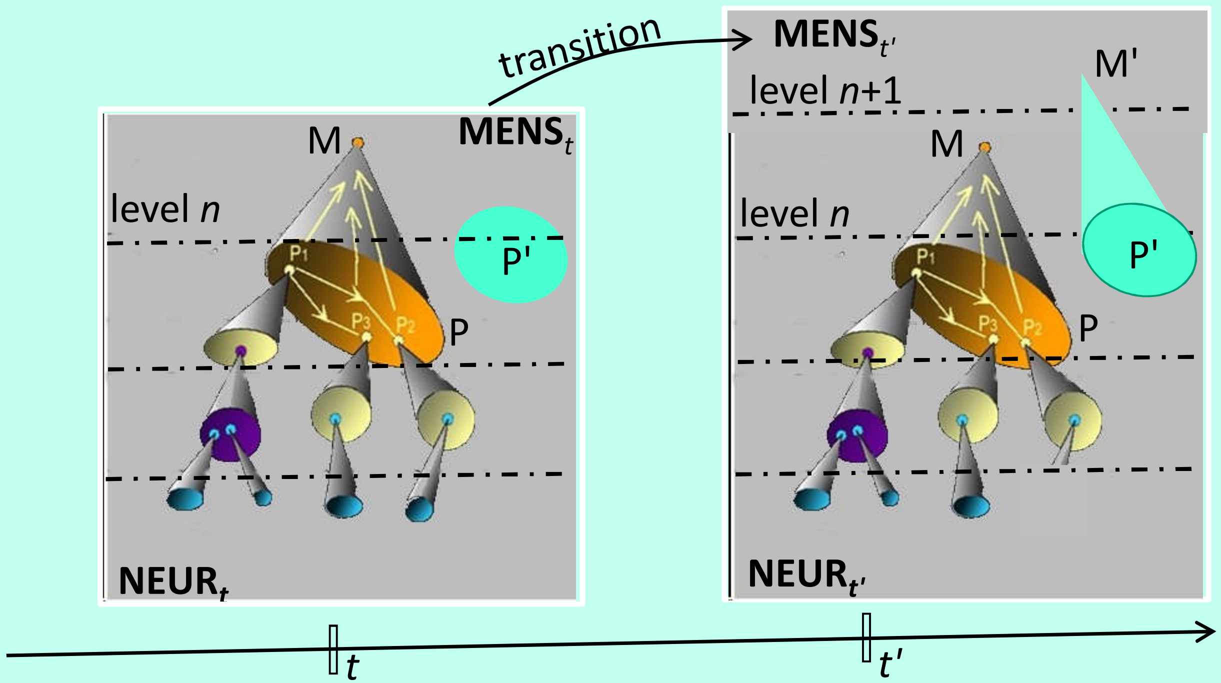
RELATIONS BETWEEN MENS, MIND AND BRAIN

MIND	MENS	BRAIN
Simple Mental Object	(Cat)-neuron level 0 Cat-neuron of level 1	Neuron Class of (equivalent) synchronous neural assemblies
Algebra of mental objects	Cat-neuron of level 2	Class of synchronous assemblies of neural assemblies
	Cat-neuron of level *n*	Class of synchronous neural hyper-assemblies (= assembly^n)
Emerging Properties	Multiform objects Complex links	Degeneracy of the neural code

A mental object recorded as a category-neuron is iteratively constructed as the binding of synchronous assemblies of more and more complex (cat-)neurons; and its activation proceeds by unfolding of a ramification down to the neuron level. Because of the degeneracy poperty it admits several such *physical realizations* with several freedom degrees. **MENS** tus proposes a kind of *emergentist reductionnism* (in M. Bunge's sense).

The complex links reflect global properties of the lower levels which are not observable locally at these lower levels. It is the precise mechanism at the root of the emergence of mental objects and processes of increasing complexity.

THE HIERARCHICAL EVOLUTIVE SYSTEM MENS



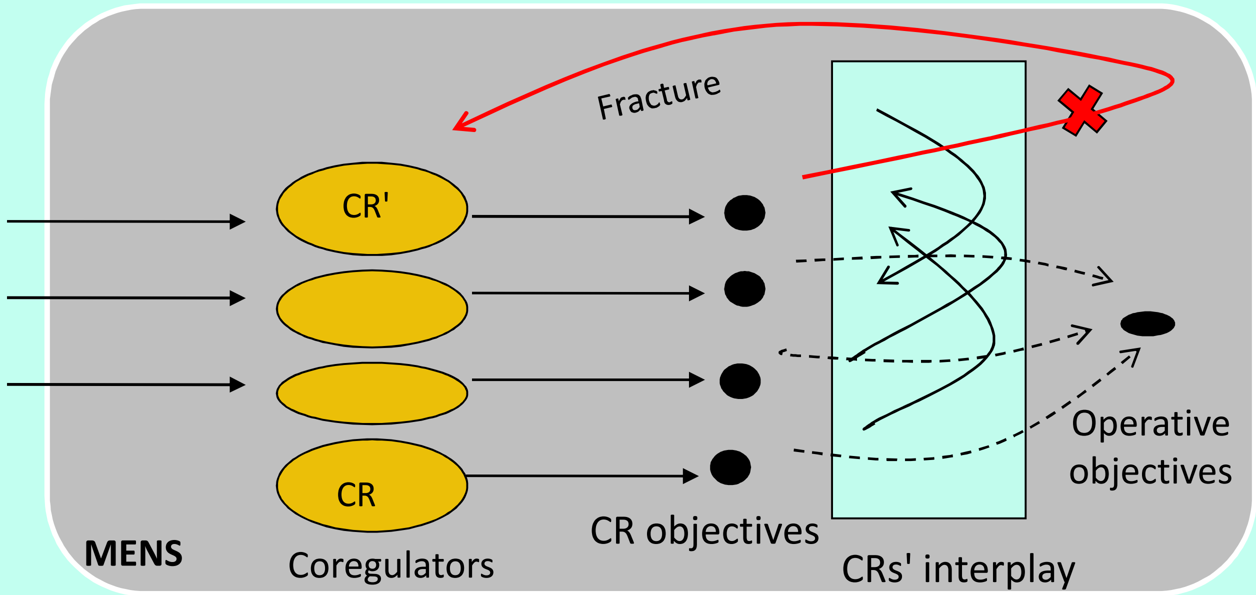
The evolution of the cognitive system depends on its successive sensory, proprioceptive, motor, affective, cognitive… experiences which lead to the formation (or suppression) of mental objects.

To account for this in the ES **MENS**, we model the transition from t to t' by a *complexification* process with objectives of the kinds: formation (or preservation, if it exists) of a cat-neuron binding a given pattern P of cat-neurons; elimination or inhibition of a (cat-)neuron; formation of a cat-neuron 'classifying ' other cat-neurons.

The complexification is explicitly constructed and we prove the emergence over time of cat-neurons (hence of mental objects and processes) of increasing complexity order thanks to the

Theorem. If a category has multiform objects, so does a complexification, and iterated complexifications may lead to the emergence of objects of strictly increasing complexity order.

MENS AS A MEMORY EVOLUTIVE SYSTEM

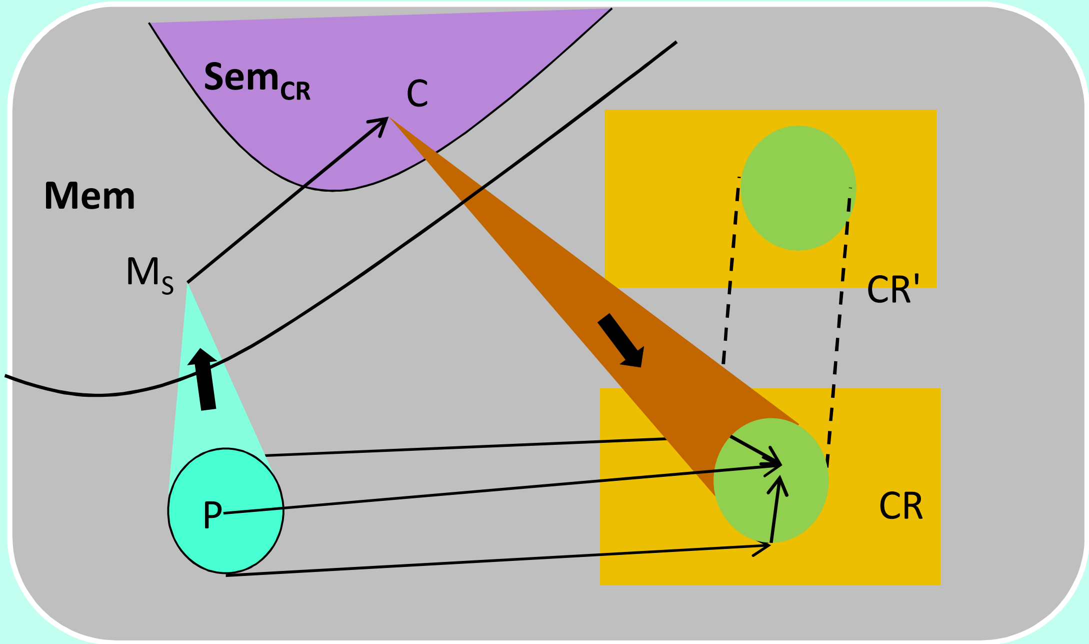


MENS is self-organized: the objectives of the successive complexifications are internally selected by a net of subsystems, the *Coregulators*, based on specialized brain areas, which modulate the dynamics through their competitive interactions. They help developing the subsystem **Mem** of **MENS** which models the mental objects and knowledge of any kind of the system with much plasticity, in a constantly revised manner to account for new situations.

Each CR acts stepwise, at its own rythm and with its specialized objectives. At each step it forms its *landscape* (modeled by a category) with the partial information which activates patterns in it, and selects objectives adapted to respond, using its differential access to **Mem**.

The objectives selected by the various CRs at a given time may not fit together since their perspectives are different. The operative objectives actually carried out on the system come from an equilibration process between them, the *interplay among the CRs*, possibly by-passing the strategies of some CRs (thus causing dysfunction (fracture or dyschrony) to them.

SEMANTIC MEMORY



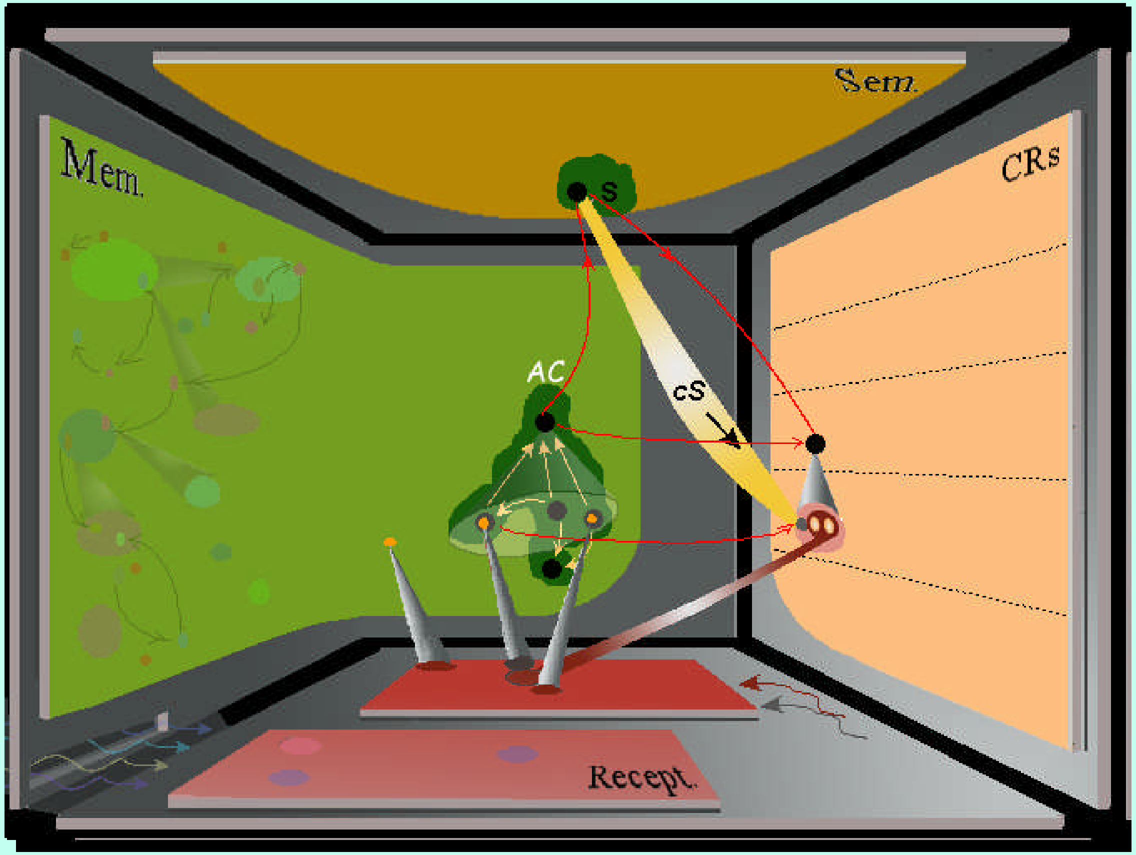
Mem is divided into an empirical, an episodic and a procedural memory. Higher animals can develop a *semantic memory* **Sem** in 3 steps;

1. Given a coregulator CR specialized for some attributes ‘ e.g., color), recognition of the CR-*similarity* of 2 cat-neurons (or of the mental objectts they record) by the (projective) equivalence of their CR-traces, the CR-trace of M_S being the pattern activated in CR by a decomposition P of M.

2. Formation du CR-*concept* correspondant as the *projective limit* C, added to **MENS** through a higher coregulator CR' observing CR. Then C is the reflection of M_S in the subsystem **Sem$_{CR}$** of **Mem,** as well as of all the *instances* of C**.**

3. More abstract concepts are obtained by iteratively adding colimits or projective limits of patterns of CR_i-concepts for various coregulator CR_i.

THE MEMORY AND THE ARCHETYPAL CORE

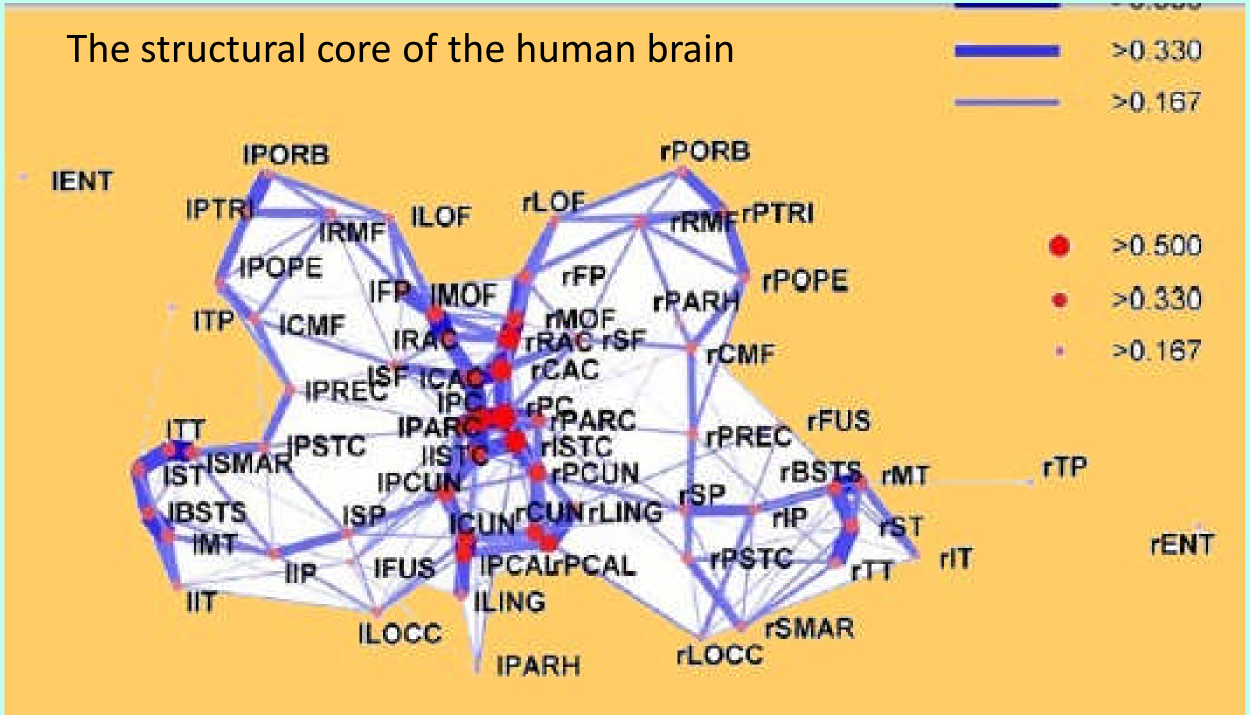


The semantic memory allows the development, from birth on, of a central subsystem of **Mem**, which we have called (1999) the *Archetypal Core.*

AC develops over time to integrate and intertwine recurring sensorial, proprioceptive, motor, emotional, procedural memories and notable experiences. It consists of higher level cat-neurons connected by strong and fast links, which self-maintain its activity for a long time. It acts as a flexible internal model of the self, allowing for the development of higher processes.

THE NEURAL BASIS OF THE ARCHETYPAL CORE

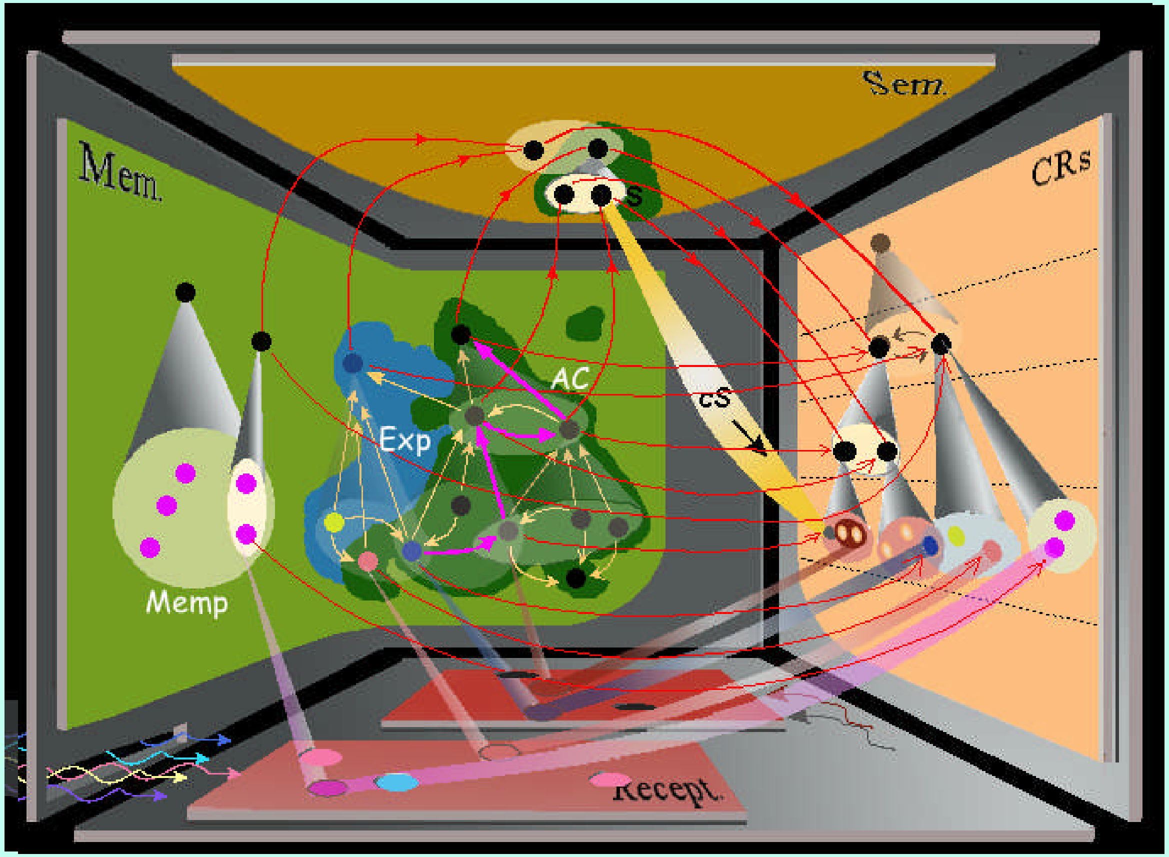
The structural core of the human brain



In 2008, Hagmann & al. have found an integrative part of the brain, they call its *structural core,* with the properties required for generating the **AC** (meaning that the cat-neurons in **AC** have ramifications coming down to this core). They write (PLoS Biology, VoL 6, Issue 7):

> " **Our data provide evidence for the existence of a structural core in human cerebral cortex. This complex of densely connected regions in posterior medial cortex is both spatially and topologically central within the brain. Its anatomical correspondence with regions of high metabolic activity and with some elements of the human default network suggests that the core may be an important structural basis for shaping large-scale brain dynamics**. "

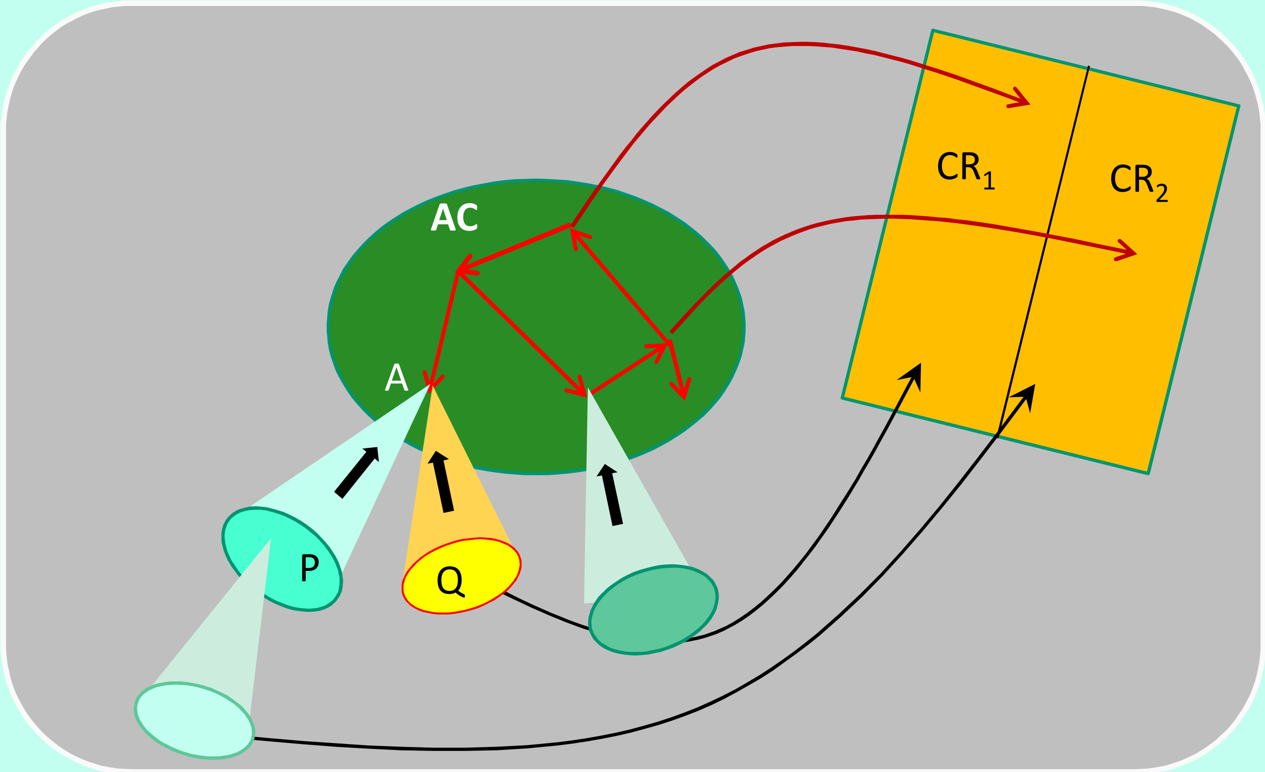
ARCHETYPAL LOOPS



To each archetypal cat-neuron A is associated a bundle, called a *fan*, of strong complex links from A to other cat-neurons in **AC**, with the following property: *archetypal loops* formed of successive links belonging to fans propagate very quickly the activation of A back to itself, thus maintaining it.

The activation propagated by fans resonates to lower levels via the unfolding of ramifications and shifts between instances of concepts, thus activating a large domain of **MENS.**

INTENTIONAL CRs AND THEIR GLOBAL LANDSCAPE

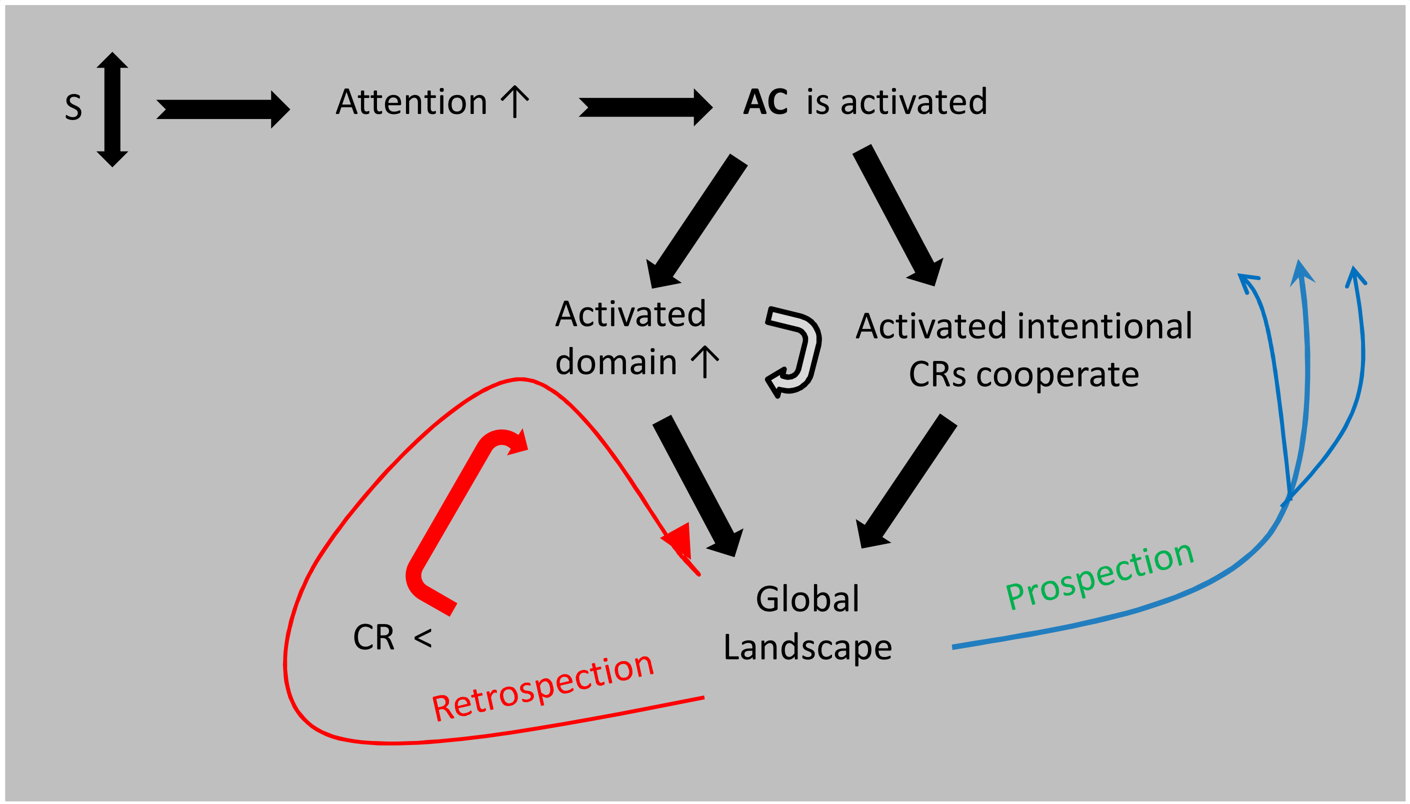


We call *intentional CR* a higher CR, based on associative brain areas, which is directly linked to some archetypal cat-neurons, such as CR_1 and CR_2.

An increase of activation of some cat-neurons in **AC** triggers, through archetypal loops, a self-maintained recollection of a large domain of **AC**, which propagates first to a decomposition P of some cat-neuron A, then, via a complex switch, to another nion-connected decomposition Q of A and to a decomposition of components of P.

This activation is transmitted back to intentional CRs, allowing the formation of a *global landscape* **GL** uniting and extending their landscapes.

CONSCIOUS PROCESSES

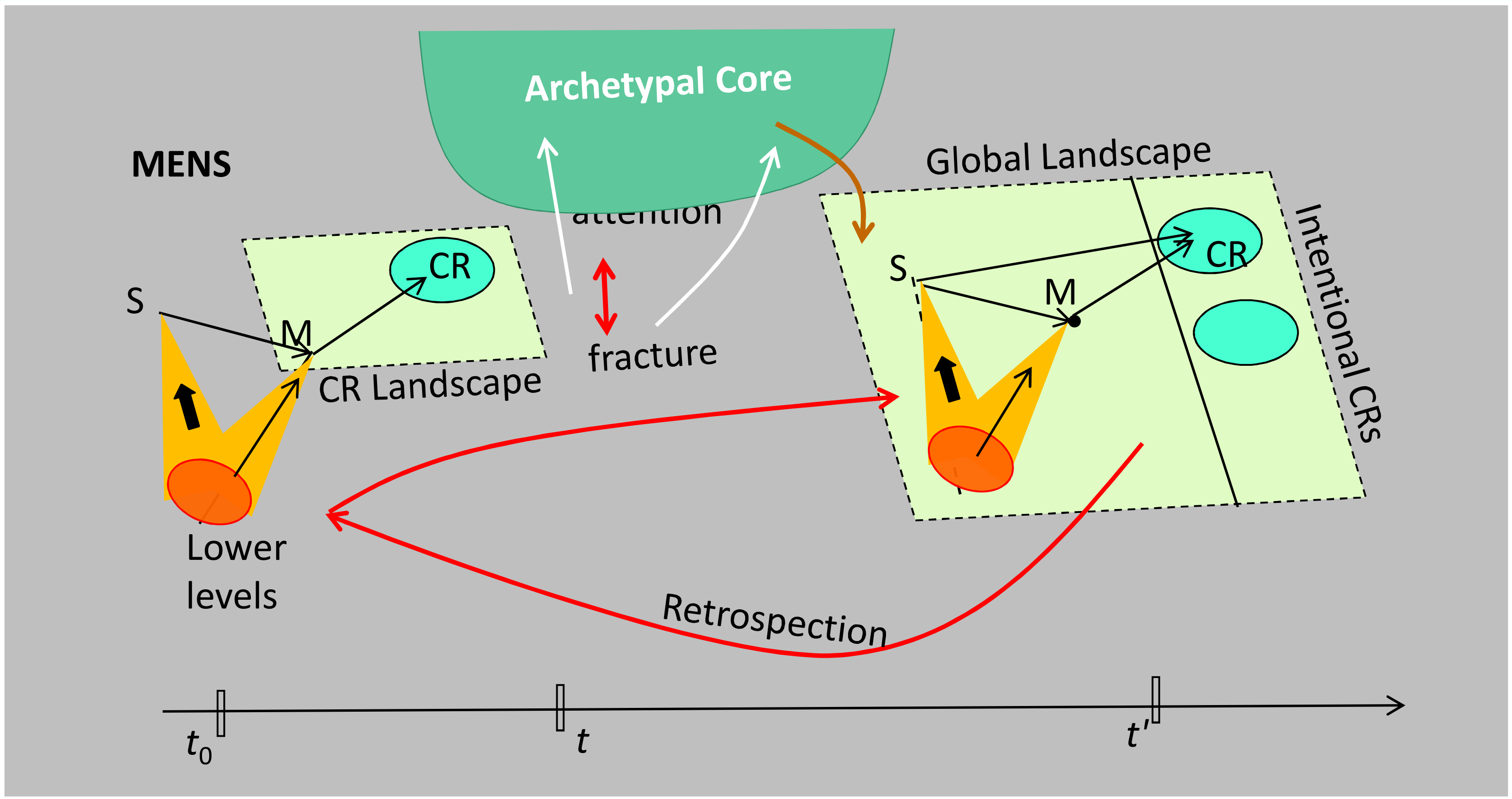


A non-expected event S increases the attention, that leads to an activation of a large part of **AC**.

This activation spreads and extends the activated domain, in particular activating intentional CRs which cooperate to construct a global landscape **GL** in which they start a *retrospection process* (in several steps) for recollecting the recent past and analyzing the event.

Then a *prospection* process can be developed in the longer term **GL**, still using the motor role of **AC**, to iteratively construct virtual landscapes in which sequences of strategies are tried with evaluation of their risk of dysfunction, and an adequate one is selected.

RETROSPECTION



S activates M at t_0 and causes a fracture to an intentional coregulator CR by appearing in its landscape at t. In response a surge of attention propagates through the archetypal core and leads to the formation of a global landscape.

The retrospection process proceeds by abduction to recall various possibly faded components of M (through the unfolding of ramifications of M) of which the activation is renewed via **AC**. This activates their binding S, so that S and the link from S to M become observable in the global landscape.

CONCLUSION

MIND	MENS	BRAIN
Simple Mental Object	(Cat)-neuron level 0 Cat-neuron of level 1	Neuron Class of (equivalent) synchronous neural assemblies
Algebra of mental objects	Cat-neuron of level *n*	Class of synchronous neural hyper-assemblies (= assembly^{n})
Emerging Properties	Multiform objects Complex links	Degeneracy of the neural code
Self	Archetypal Core	Structural core of the brain (Hagman et aL)
Conscious processes	Global Landscape Retro- and prospection	Structural core of the brain Consciousness loop (Edelman)

MENS proposes a theory of mind, in which a hierarchy of mental objects and processes emerges from the functioning of the brain, through the iterative binding of neuronal assemblies. We show that *the degeneracy property is the characteristic which makes this emergence possible*, and explain how it allows the development of a flexible memory, with a central part, the Archetypal Core . AC is at the basis of the self and of the formation of higher cognitive up to consciousness, seen as the integration of past and future. It is mainly qualitative, though some quantification should be possible using the propagation delays and forces of links in **MENS.**

FOR MORE INFORMATION

Memory Evolutive Systems: Hierarchy, Emergence, Cognition, Elsevier, 2007.

MENS, a mathematical model for cognitive systems, *JMT* 0-2, 2009.

The following internet sites contain a large number of our papers:

http://pagesperso-orange.fr/ehres

http://pagesperso-orange.fr/vbm-ehr

THANKS