The Restless Neurons: Spontaneous Activity is Fundamental to the Mind

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‘The Restless Neurons: Spontaneous Activity is Fundamental to the Mind’ (an article)

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Abstract

The vast number of neurons in the brain are ceaselessly engaged in spontaneously generated activity in virtue of interactions between those. It is in the background of this intrinsic activity that the brain responds to signals from the environment *and* from endogenous signals received by way of active mental processes. This spontaneous activity persists in the 'resting state' and is modulated by evoked signals resulting from task-induced activity. The two together generate an ongoing process of *self-organization* in the brain whereby dynamic excitation patterns are set up and correlated with one another in neuronal aggregates of diverse population size in an intricately nested hierarchy. These correlated patterns constitute distributed *models* of reality, based on which the brain generates expectations, plans, and predictions relating to the dynamically evolving world that we all are embedded in.

The process of neuronal self-organization provides the basis for the emergence of a structured *mind* exhibiting an exquisite functional complexity. Generally speaking, mental (and, in particular, *psychological*) processes are based on large scale ('macroscopic') neuronal networks, while microscopic and mesoscopic neuronal populations constitute the 'substratum' of the mind, where elementary and tiny bits of experience are represented so as to act as atomic ingredients in the more complex processing of compositely constituted information involved in mental activities.

Processes in the microscopic and mesoscopic neuronal aggregates occur on relatively short spatial and temporal scales while those in macroscopic networks are slower and distributed across brain regions. The large scale networks operate near the 'edge of instability', which means that these networks, taken together, form a system close to *criticality*—this is what makes the mind possessed of its remarkable fluidity.

The neuronal aggregates themselves are in a constant state of flux, with groups of neurons constantly entering and leaving larger aggregates, and with neurons being simultaneously operative in the functioning of more than one aggregates at a time. In the backdrop of this enormous complexity, the operations of the mind constitute a complementary description of the brain-mind complex to those of the neuronal populations—neither of the two is reducible to the other. In other words, the functioning of the mind is not determinable in terms of the activities of the neuronal populations.

The ‘substratum of the mind’, made up of microscopic and mesoscopic populations of neurons, in addition to providing the hinterland in which latent operations supporting all mental processes are enacted, is involved more directly with representations of elementary *concepts*, with distributed *memory* (in a broad sense), and with *heuristics* of an elementary and atomic nature that help us in making vast numbers of ‘decisions’ of a similarly elementary nature.

Contents

1 The restless brain and the restless mind: Introduction

In this article we are going to look at two distinct but complementary aspects of the brain as an assembly of neurons: the one of a *reactive* and the other of a *proactive* entity in respect of its interaction with the world at large—the world that includes, in addition to the external reality, the *internal reality* of the brain-mind complex too. As far as current understanding goes, the stream of ceaseless spontaneous activity within the brain is consistent with the emergence of the mind and the anticipatory response of the latter to the world we all are immersed in.

Thus, in parallel to the reactive and the proactive aspects of the brain, the *mind*—an *emergent* formation based on the former—has its complementary aspects too as it faces a complex reality. The mind not only responds to immediate challenges thrown up to it: it constructs its own world too by means of its interpretations, predictions, and plans—it *anticipates* as it continually faces challenges itself. It harbors deep conflicts within its folds that tend to tear it apart, but it takes all this in its stride and faces the world. Underlying all this is the eternal unrest of the brain itself.

We will begin by way of a very brief note on *complexity* and *emergence*—themes of foundational relevance in this essay—the brain and the mind are complex entities embedded in an infinitely complex world and, what is more, the mind is an emergent property of the brain. We will then go on to have a look at the *spontaneous* (or *intrinsic*) activity of neuronal assemblies in the brain. The latter constitute the foundation from which the mind emerges, though mental processes are not determinable from neuronal ones. As mentioned, we distinguish between two points of view ([35])—one of these describes neuronal activity as a response to signals received from the world; the other, in contrast, looks at the brain as a spontaneously active entity while the activity evoked by the world at large modulates the intrinsic neuronal excitations and ultimately gets merged into those. Of course, the two points of view need not be construed as conflicting ones.

We will get launched from there into further considerations. Our presentation—mostly a simplified review of findings reported in the literature, with a few interpretations added here and there—will be broad-based and, mostly, non-technical.

2 Complexity and emergence

For a general background to this section refer to [24]; see also [25]. Within the extensive literature devoted to the topics of complexity and emergence, I especially recommend [21] and [41].

2.1 Complexity and emergence: a brief overview

Complexity is all around us, but is only poorly understood. This is in the very nature of things, since complex systems are infinitely *interconnected*, and any finite (or finite-like) truncation does essential violence to their ultimate being.

Scientific investigations of systems are focused on *models* of the world—indeed, they can't be otherwise. And that means, complexity has to be chopped off somewhere into a simplified entity so that unequivocal statements can be made (the principle of 'excluded middle') regarding their behavior, whether in deterministic or probabilistic terms. However, complexity expresses itself *at all scales*, and any description or prediction is, by necessity, within some particular scale determined by the *context* within which we look at a system.

In our scientific investigations on a system of interest we look at its *components* and relate the system properties with those of the latter. This presupposes an autonomous identity of the components which, in reality, is a myth when we recognize that each of the 'components' interacts infinitely with all the others in a vastly tangled web—any supposed autonomy is violated at some scale in space and time (and in 'spaces' of other descriptions relevant to the system of interest, such as its *phase space*, or 'state space', see below), perhaps beyond the scale of current interest determined by the context within which we look at it. Indeed, the system itself is a component of a larger web of interacting systems, which is precisely why our scientific theories and predictions always break down beyond some horizon or other. In other words, all our science is of limited scope, which is fine so long as we keep in mind these limitations and prepare ourselves for novelties *at every turn*.

These novelties represent the phenomenon of *emergence*—one that is doubted and debated in philosophical and scientific discourse, primarily because it appears to violate our sense of 'continuity' in natural evolution, where continuity essentially means a unique succession of states, providing for predictability of the world at large.

In concrete terms, emergence relates to the *co-ordinates*, or *state variables*, in terms of which the behavior of a system or of its components is described, where these variables are often defined only qualitatively. Suppose for the sake of illustration that a system with K number of components (in some conveniently truncated description), is described in terms of variables, say, $x_1, x_2, \cdots, x_K$ (where these may possibly represent vectors) with each of the components considered in isolation (the 'bare' co-ordinates). Interactions among the components necessitates a modified description in terms of 'dressed' variables, say $x'_1, x'_2, \cdots, x'_K$ where, in the case of weak interactions, there exists a one-to-one correspondence between the two sets of variables. However, for strong interactions, or for interactions over a long time span, this,one-to-one correspondence is broken and the relation between the dressed and the bare variables assumes a complex form—essentially a non-determinable one, especially when K is large. The dressed state variables are then of a *collective* nature (corresponding to a 'renormalized' description), expressing the fact that the behavior of each of the components is now essentially determined by *all* the other components taken together: the interactions have now assumed a *non-local* nature—while each component may interact non-trivially with only a few others in its close proximity (in some defined sense of 'closeness'), their *correlations* are spread over large separations.

Generally speaking, this happens across *instabilities* in the system dynamics when its behavior becomes characterized by some altered space-time scale (in the phase space, see below). In particular, there arises transitions across *critical* states when a number of dominant subsystems ('clusters, see below) are brought close to the edge of instability, and the system as a whole undergoes a transition that is controlled essentially by only one or a few collective variables. The characteristic evolution is then essentially one involving *all scales* that 'helps it choose' some characteristic scale on either side of criticality. This role of collective variables in determining a characteristic scale of the system behavior is typical of *emergence*. More commonly, one encounters simpler instances of emergence where there is a loss of stability along a relatively small number of dimensions in the state space.

> This technically loose description will be made a bit more specific later in this essay. We will, however, aim for a broad comprehension rather than technically rigorous description.

While this description of complexity and emergence is admittedly too brief and vague (strictly speaking, one of only a heuristic and metaphorical nature) it is aimed at giving us an idea as to what these two terms refer to.

The world at large is the *ultimate* in complexity—it includes *all* the complexity there can be. It has an infinite number of dimensions, where the dimensions of a system refer to the independent qualities or aspects of it (its 'state variables') needed for its description. However, at any given point of time, we can access only so many of those—our access expands with time but there always remains an infinite number of dimensions beyond our access. The fragmentary view of the world that we have at any point of time makes up our *phenomenal* reality while the 'real' reality out there continues to remain beyond our grasp. The phenomenal reality is much like a projection from an infinite dimensional space to a subspace of limited number of dimensions—it is rooted in the real (or the *noumenal*, to borrow a term from the Kantian tradition) reality but never allows us to guess back at how that reality is constituted.

The ultimate reality, when truncated to give us our phenomenal world, becomes an essentially transformed entity. The former cannot be described *as it is*, because such a description would have to accommodate *all* space-time scales and would have to transcend the observer-observed divide.

When we speak of a complex system such as the brain as a vast assembly of neurons, we refer to only a part of the ultimate reality, with the crucial but unspoken implication that the system is cut off from an infinitude of interactions that would exert an influence on its evolution at some point of time. Confining our attention to some limited time scale, we predict its behavior—commonly in probabilistic terms, and the predictions are often found to be accurate. However, those same predictions turn out to be inadequate over larger scales of time (and space): for correct predictions over all space-time scales one would have to include the interactions with all other systems in the world. Commonly, we make up for such exclusion by way of specifying the *context* in which the system in question is described. However, the context does the job with only partial success, thereby making our descriptions and predictions valid within some limited horizon that often remains unspecified.

2.2 Complexity emergence and nonlinearity

A hugely fertile metaphor illustrating the idea of complexity and emergence is the one provided by nonlinear dynamical systems, commonly defined in terms of sets of ordinary differential equations (see, for instance, [14]). Concrete results regarding such systems are difficult to arrive at in terms of known mathematical functions, though there does exist a highly developed *qualitative theory*—a geometrical approach—initiated in the first and second quarters of the last century. Differential equations of even relatively low dimensions are found to be useful in illuminating basic ideas relating to complexity and emergence.

The qualitative theory rests on the idea of the *phase space* or 'state space'—a space made up of the 'generalized co-ordinates' or 'state variables' of the system one is interested in.

> Technically, the phase space is appropriate for the description for a *Hamiltonian* dynamical system. However, we will loosely refer to the phase space (or, more generally, the 'state space') for nonlinear dynamical systems in general.

The phase space for a complex system is necessarily one of a large number of dimensions though, as mentioned above, results pertaining to nonlinear dynamical systems of only a few (typically, just three or four) dimensions have great heuristic value. The instantaneous state of the system is represented by a point in the phase space, while its time evolution is represented by a *trajectory* in this space. Of central relevance is the question as to how *stable* the evolution is around a trajectory. This depends on a set of

Lyapunov exponents (or, ‘stability exponents’)—a positive value of one or more of these exponents is indicative of instability: when initiated from a location slightly shifted from a point on the trajectory, the system evolves progressively *away* from the latter (this is referred to as a *sensitive dependence on the initial condition* or, in common parlance, the ‘butterfly effect’—this term, however, is commonly used in the context of dynamical chaos) while a negative value of all the exponents implies that the system moves closer to it after the initial perturbation.

Another important feature of nonlinear dynamical evolution involves a different kind of stability, namely, stability against perturbation of *parameters* that represent relevant system characteristics. For instance, for fluid flow through a pipe, the defining equation for the flow (in this instance a *partial* differential equation) involves a parameter referred to as the *Reynolds number* that has some fixed value for some particular flow but may have a different value in some other physical situation. It turns out that the nature of the flow undergoes a qualitative change as this parameter is made to increase (by, say, choosing a thinner pipe) through a critical value, somewhere around 2000. Such qualitative transformation in the nature of time evolution of a nonlinear dynamical system, resulting in a change in the geometrical features of trajectories in the phase space, is generically referred to as a *bifurcation*. Speaking in general terms, a bifurcation indicates an instability against a small variation in the *context* in which a system evolves.

From a broad point of view, the sensitive dependence on initial conditions can also be looked upon as a context effect, and the sensitive dependence on parameters referred to above may be clubbed together with it so as to speak inclusively of the phenomenon of the *sensitive dependence on the context*.

The relevance of nonlinear dynamics in respect of complex systems resides in the fact that the multifarious interactions among the components of such a system are generically nonlinear in nature, and the sensitive dependence on the context (across transition values of initial conditions or of characteristic parameters) typically exhibited by it can be seen as instances of *emergence*.

2.3 Complexity and emergence: the network representation

For background to this section, refer to [41].

Complex systems are fruitfully represented as *networks*—this facilitates the simulation of their dynamical evolution. A network is made up of *nodes* and their mutual interactions or correlations appear as *links* between these. The network evolves due to these interactions and, possibly due to external influence as well where, more often than not, such external influence represents interactions with other systems, the latter being, in their own right, nodes in some bigger network. Indeed, a finite network, howsoever large, is a truncated representation of reality, in consequence of which, one needs to include the influence exerted by the *context* (recall that, in a broad sense, the initial condition is also a part of the context) so as to obtain a reasonably accurate and complete description of the dynamical evolution.

The evolution occurs due to the interactions between the nodes and to the context effect too. In the course of such evolution *clusters* of various descriptions make their appearance, where a cluster is an assembly of nodes well connected among themselves, with relatively strong interactions between them, while their interactions with the rest of the network is weak in comparison. Because of the interactions between themselves, the components making up the cluster lose their identity to a considerable extent and the interactions of the cluster as a whole with external systems (other nodes, clusters, and systems outside the network under consideration) are described in terms of a set of *collective co-ordinates* (i.e., 'dressed' variables) that differ from the co-ordinates describing the nodes in isolation from one another.

Generally speaking, the formation of the clusters proceeds in a hierarchical manner—relatively small clusters are formed and then become unstable so as to blend with other clusters, with the process continuing with the formation of bigger and bigger clusters within the network. The dynamical evolution of the latter is then, to a considerable extent, described in terms of the dominant clusters while, all the while, the individual nodes and small clusters continue to evolve in their own way, being described in terms of variables of a less collective nature.

The formation of such large clusters in a complex network can be looked upon as instances of emergence. It is only rarely that a cluster is pulverized into clusters of much smaller size or into individual nodes. Clusters change their constitution or configuration and get reformed by merger or splitting, but on the whole, the network as a whole remains structured into hierarchies of clusters. With such a structure in place, the clusters themselves can be looked upon as individual units interacting among themselves so that, in a certain limited sense, one now has a *network of clusters*.

In the case of large networks, the interactions among nodes and clusters are, in a sense, often correlated only weakly with one another (note that we are now talking about the correlations among the links rather than among the nodes and clusters themselves), so much so that many of the links can be looked upon as *randomly* established. The network is then endowed with the so-called *small world* property. This means that any two clusters may be only weakly linked in so far as the direct interaction is concerned, but are more often than not well correlated through intermediaries.

In following the dynamics of clusters in a network, one can refer, with some justification, to the phase space made up of the collective variables of the clusters and then look at the Lyapunov exponents in this 'emergent' phase space. As one or more of these 'emergent' Lyapunov exponents change sign, there occurs a change in the configuration of clusters—the relevant clusters are then said to be at the 'edge of instability'. If it so happens that a considerable number of clusters are close to the edge of instability then the overall organization of the network into hierarchies of clusters assumes a considerable degree of *fluidity*. Looking at the conglomerate of clusters near the edge of instability, one describes it (the conglomerate, that is) as being close to *criticality*.

The dynamics of clusters is, generally speaking, the resultant of their mutual interactions *and* of interactions with external systems (the 'environment') too—the latter constitutes what we have referred to as the 'context' effect. In the case of a network with a considerable number of clusters close to instability, the context plays a role equally important with that of the mutual interactions among clusters of various descriptions.

Given a network with an initial configuration involving negligibly few clusters, the mutual interactions among the nodes and the fleetingly formed clusters generates a complex evolution dynamics in which the context effect is not of much consequence—the formation of hierarchies of clusters from such an initial configuration is then referred to as the process of *self-organization*. It is this self-organization that may eventually lead to a state of near-instability of a number of dominant clusters in the network (and of near-criticality of the network as a whole) when the assembly of such clusters acquires a fluidity of structure (much as in the ongoing processes of reconfiguration of clouds in the sky) that is easily influenced with equal facility by internal and external influences. The process of a complex network reaching such a configuration is referred to as *self-organized criticality*.

In the case of a complex system at criticality, processes occur within it over *a large spectrum of scales*. Small scale processes continue to occur due to the direct interactions among its components (the nodes in the network representation), while large scale ones involve the clusters as a whole that keep on being reconfigured—the collective coordinates characterizing the clusters are responsible for this since a cluster includes a large number of nodes many of which are 'remote' ones relative to one another in the network.

> One can define a concept of closeness between any two nodes within a network in terms of the number of intervening nodes in a path from one to the other along the shortest succession of links.

If there occur a number of large clusters close to instability within the network, then a likely scenario is that some one cluster or other keeps on crossing the stability border (due to internal and external interactions) all the while, as a result of which processes keep on taking place *at all scales* within the network (relative to the separation measure mentioned above). The probability distribution of diverse processes (or 'events') in the system then assumes a characteristic feature—that of what is referred to as a *fat-tailed* distribution or a *power law* one.

In summary, for a system with numerous large clusters close to instability, processes occur at all scales, characterized by a power-law probability distribution (or one close to it). In all these processes, the small-world architecture of the representative network remains as a characteristic feature, with the clusters getting reconfigured continually.

Much of the above discussion in this section is to be taken as being of heuristic value.

2.4 Complexity and conflicts

The hallmark of complexity is *conflict*, which is ubiquitous in any and every complex system. Considering any particular node or a cluster (in the network representation), whether large or small, it experiences pulls and pushes in diverse directions in the phase space in virtue of the internal interactions within the system, and of the environmental effects too. Because of the large number of variables characterizing the various pulls and pushes, the node or the cluster in question evolves in a delicate state of balance. At certain critical junctures, the balance gets upset by some particular Lyapunov exponent becoming positive, which then becomes the dominant aspect of the conflict and a new state of balance is realized.

Considering the case of the brain, the various neuronal networks experience these pulls and pushes in virtue of the diverse nature of their interconnections and of the complex environmental effects, as a result of which there occurs frequent changes in the configuration of the networks (refer to sec. 6.5 later in this essay), when the pulls and pushes, never in complete synchrony, operate in a new setting. In the midst of this background of conflicts and contrary influences, there arises synchronous and ordered patterns of behavior too, where the emergence of these ordered aspects is made possible by a balance between conflicting influences that remains in force for a relatively long duration, since such synchronous patterns turn out to have a stabilizing role for the system at large. The various large scale brain waves or rhythms may be cited as a case in point (see sec. 4.7).

Finally, in the case of human social communities, the conflicts on individual members of a community or on various groups within it often take the form of conflicts of *interest*, based on conflicting preferences, ambitions, intents, and so on. Generally speaking, however, the term ‘conflict’ is to be taken in a value-neutral sense, viz., the one of contrariness.

3 The spontaneously active brain: introduction

3.1 What is spontaneous brain activity

While the idea of a spontaneously active brain has been raised by scientists and philosophers since early days, it acquired new relevance from around 1995, when there came definite indications that ubiquitous and seemingly random activities in the brain, traditionally thought to represent meaningless noise generated in the neuronal mass, was actually coherently organized across brain regions and were thus likely to carry significance in brain functioning. This innately generated and spatially distributed disturbance, which persists in sleep and even unconscious states as in wakeful conditions, is referred to as intrinsic or spontaneous brain activity.

> Hans Berger, who initiated the application of EEG in humans, noted the ongoing spontaneous electrical activity in the brain as one of the prominent features in it, though that observation was not to be pursued further for more than sixty years.
>
> A vast discourse on numerous aspects of spontaneously generated signals in the brain and the far-flung significance of such intrinsic unrest has erupted in the literature since the discovery of slow neuronal activity, characterized by a complex spatiotemporal organization, in functional magnetic resonance (fMRI) studies.
>
> Antonio Damasio speaks of the ‘map’-making activity of the brain as a most fundamental one ([10], chapter 3), which includes the brain ‘mapping itself’. As we will see later in this essay, the intrinsic neuronal activity in the brain fundamentally involves the setting up of far-flung correlations among dynamical excitation patterns bearing the imprint of multifarious evoked signals received by it. We adopt the position that it is this ceaseless process of setting up of correlations that underlies the ‘mapping’ referred to by Damasio. Among the intrinsically generated excitation patterns in neuronal assemblies are ones (arguably a vast majority) that result from internal activities of the brain—corresponding to processes in the mind—activities that can be described as the brain ‘mapping itself’. In the context of brain activity, the distinction between *intrinsic* and *internal* is of considerable relevance, briefly explained later in this section (sec. 3.3).

The intrinsic activity consists of complex and ever-changing excitation patterns in neuronal assemblies and is notably characterized by spatiotemporal coherence across brain regions. In a sense, it can be looked upon as self-generated activity based on intricate interconnections among the neurons in the brain, where spontaneous excitations are developed in neuronal aggregates of *all* scales in respect of population size of neurons. Indeed, even a single neuron can sustain self-generated oscillatory excitations if held under appropriate conditions (a well-known example of such oscillatory dynamics is referred to as a ‘burst’), based on which an interconnected neuronal assembly routinely generates self-excited oscillations because of feedback paths provided, of course, that appropriate ionic concentrations and neurotransmitters are available, along with the supply of nutrients and of energy to activate the ionic pumps.

1. A single neuron can be far more complex than what was considered to be the case in early days, when it was commonly understood to be an ‘integrate-and-fire’ type device. A neuron can have intricate structure involving ion channels of diverse descriptions, controlled by the trans-membrane voltage and an array of neurotransmitters and neuromodulators ([42], [6]).

   Even the Hodgkin-Huxley model that initiated the era of modeling the single neuron, and relatively simple neuronal circuits, admit of complex behavior because of the intrinsic nonlinearity of dynamics ([17]).

2. Intrinsic activity in the brain has been found to involve fluctuations in ion concentration dynamics relating to opening and closing of ionic channels of individual neurons and in glial activity influencing populations of neurons. Model simulations indicate that the observed spontaneous activity in fMRI and EEG recordings is likely to be made up of very *slow* variations in ion concentration, ion-pump activation, firing rates of neurons, and in what is referred to as the local field potential ([23]).

   However, going by the general features of time evolution of complex systems, where a hierarchy of space-time scales is the rule rather than the exception, the intrinsic activity is likely to involve not only the ultra-slow fluctuations of physically relevant parameters across relatively large spatial extensions in the brain, but more rapid fluctuations as well in much more localized brain regions, where only small numbers of neurons generate the activity. It is a plausible conjecture the overall functioning of the brain and the mind is integrally related to spatiotemporal fluctuations in multiple scales.

3.2 Two views of brain activity

The distinction between ‘noise’ and ‘signal’ in experimental data is often quite arbitrary, reflecting the purpose or aim of an investigation, and what is considered as noise is often elevated to the status of data as the scope and depth of the investigation get augmented ([42]). Precisely this is what happened in the case of intrinsic neuronal activity, as it was gradually realized that it possibly relates to ‘information processing in the brain for interpreting, responding to and predicting environmental demands’ ([35]). A large body of literature now indicates that the spontaneous activity of the brain characterizes the way it ‘responds’ to the world it is immersed in—signals received from the world modulates the intrinsic activity and augments the ‘information’ already encoded within the previously generated patterns, and equips the brain with an updated model of experienced reality. This remarkably adaptive process continues, making us survive and flourish in an uncertain and complex world.

In other words, at any given moment, the spontaneously active brain *already contains a model* of its environment ([4]; in this context, see [2]), generated from its past interactions with the latter, so as to interpret information received from the world at subsequent points of time and to prepare for acting back on the world. In this, the brain appears as a remarkably adaptive and purposeful device, imparting an equally remarkable purpose to the mind that emerges from its ceaseless and complex intrinsically generated dynamics.

In contrast, another view of the brain ‘pioneered by the work of Sir Charles Sherrington, posits that the brain is primarily reflexive, driven by the momentary demands of the environment’ ([35]). In this view, every new experience results in a fresh representation that *gets added as a newly generated pattern* along with similar patterns generated in the past. However, while being seemingly contradicted by the other, more recent, view of a spontaneously active brain, this view of a reflexive brain has been successful in our understanding of brain functioning and the two views are, in reality, much like the two sides of the same coin. Both relate to the way incoming information from the world interacts with the information already existing in the form of neuronal excitations, though envisaging the origin of the excitations and their interaction with subsequently arriving signals in distinct terms.

The view of a spontaneously active brain gains support from the fact that the energy consumed in evoked activity is much less than that in what is apparently the resting state of the brain ([35]), when intrinsic excitations continue to be generated in multifarious neuronal assemblies. Of course, the major reservation against a predominantly reflexive brain model comes from the fact that the latter requires a notable decrease in brain activity in between evoked task-engagements, which is certainly contrary to observations.

3.3 The ‘intrinsic’ and the ‘internal’

As regards evoked activity in the brain one has to make, in principle, a subtle distinction between what we refer to as ‘intrinsically’ and ‘internally’ generated neuronal excitations. Fundamentally speaking, intrinsic activity is produced at all scales in the brain, starting from single neurons, through assemblies of relatively small population size, to large neuronal populations. Among the excitations in large aggregates are ones that correspond to activities of the *mind*. As the mind responds to demands imposed upon it by the world, there occurs two types of mental activity—one evoked by signals of external origin, and the other by endogenous and internalized mental processes. In other words, evoked activity may be due to signals from the outer world, or to signals originating in some particular neuronal aggregates of large population size (the ‘source’) that generate activities in some *others* (the ‘target’; at times, the source and the target may partly overlap)—this latter type are, at times, associated with unconscious mental processes (see sec. 5.2).

> *As I sit in solitude, listening to music, I suddenly recall that my son’s end-of-the-year engineering exam is only a couple of weeks away, and my mind gets focused on planning how I can help him his preparation for the exam.* This is an instance of an internally evoked mental process that sends signals to various regions of the brain, when the latter get imprinted on intrinsically generated signals in various neuronal aggregates.

Intrinsic excitations, even when pertaining to large neural assemblies, do not commonly correspond to activities of the mind, because the spatiotemporal organization ([42]) of the former is based on fluctuations of an approximately *scale-free* nature as regards population size of the assemblies—among all possible excitations, the ones pertaining to relatively large aggregates are detected in the fMRI (specifically, the fMRI BOLD) signals and are characterized by spatiotemporal coherence to some extent. All the while, the intrinsically generated signals in the brain are possessed of coherence and organization at all scales—the ones involving small aggregates have low coherence while those based on large assemblies possess coherence of a higher degree. Internal mental activity, on the other hand, is primarily based on *collective* excitations of large neural assemblies. In terms of *dimensionality* of the underlying dynamics in a putative *phase space*, the latter can provisionally be identified as one of a *lower* dimension compared to the former which is, in a manner of speaking, a mixture involving a large spectrum of dimensions (all these statements are of a metaphorical nature; the metaphor of dynamical systems, as applied to the dynamics of neuronal populations, is a loose one when considered in the context of the brain as a whole or of large neuronal aggregates, but is nevertheless of considerable heuristic value).

Instructive background to this section can be obtained in [7], chapter 8.

4 Spontaneous activity: further considerations

4.1 Neuronal aggregates: schematic

The neuronal assembly of the brain as a whole includes large sub-assemblies or functional *networks*, where a network consists of smaller bunches of neurons—the latter are localized structures, while the various bunches constituting a network are more often than not distributed widely across the brain. What is more, the networks are commonly not of a fixed constitution and, while evolving in composition and location, are often overlapping in their functional identities. This, in brief, is a plausible *macroscopic* description of the brain.

It is the macroscopic description that is often of direct interest—for instance, psychology and psychopathology is commonly concerned with large networks and brain modules. However, underlying the functioning of these large networks are relatively small neuronal aggregates that may be termed ‘mesoscopic’ (see, for instance, [30], [43]) and, at a still finer scale, single neurons or small groups of neurons (the ‘microscopic’)—all these extend their hidden influence throughout the entire brain. For instance, a vast number of elementary concepts, such as ‘red’, ‘round’, ‘hand’, and ‘food’ are lodged in our mind—it is a plausible conjecture that most of such concepts of an atomic nature are represented not in the macroscopic neuronal assemblies, but in smaller mesoscopic ones, where the neuronal excitation patterns in these mesoscopic aggregates are functionally correlated with one another so as to result in more complex patterns representing composite concepts, lodged in larrger networks in the brain.

Among the brain networks of multifarious functional relevance are the ones that are formed in what is referred to as the 'resting' state of the brain, when the latter is not engaged in focused or evoked activity of any sort—not even internally evoked ones.

> However, the mind is seldom free of fleeting and idle thoughts, nor are the neurons ever at peace, free of internal mental processes.

These are termed the 'resting state networks' (RSN's, [34]), whose ceaseless activity makes its presence felt in fMRI signals in subjects under diverse circumstances.

The microscopic, the mesoscopic, and the macroscopic—these get organized by means of the spontaneous activity into a hierarchy (see sec. 7.1 later in this essay), one that is in constant dynamic evolution. What is more, they are intricately nested into and entangled with one another—often the same neuronal group functions as one belonging simultaneously to more than one levels of the hierarchy.

4.2 Intrinsic and evoked activity

Evoked activity relates to a mental state where the mind is engaged in some task that may be an externally or an internally generated one. A task may often require an engagement with external entities, though it needs an active participation of the mind too. No less frequent are tasks originating in the mind, with little direct involvement of external agents or entities (*planning about my son's career, negotiating through possible financial difficulties*).

In any such task-evoked activity, neuronal networks are excited, generating characteristic signals (among which fMRI signals constitute an instance) in brain regions related to the demands placed by the task. However, the evoked response is crucially dependent on the ongoing intrinsically generated excitations that continue to exist across brain regions, the relation between the two being, by all indications, a subtle one. In any case, it is not easy to segregate the evoked and the intrinsic signals ([42]) and whatever success has been achieved in this regard has cost much effort and ingenuity.

Generally speaking, there is a similarity in the excitation patterns of intrinsic and evoked signals (which is why they are difficult to segregate; [42]). The two, indeed, are organically related. If evoked signals are, in a broad sense, indicative of multifarious interactions between the brain-mind complex and the world (the external *and* the internal worlds taken together), the intrinsic signals result from processes in which the brain *prepares itself* so as to adapt to the world by way of making those interactions 'meaningful'. As we will come to see below, 'meaning' resides primarily in *correlations* between excitation patterns resulting from the interactions with the world, corresponding to which concepts, ideas, and experiences get correlated in the *mind* (an emergent entity), making the latter a remarkably adapted device in forming expectations, intents, plans, and predictions, thereby generating our *behavior* in the world.

Evoked and intrinsic neuronal processes are, in a manner of speaking, somewhat like addressing an audience by way of presenting a paper in an academic seminar, and the prior preparation of the presentation—the preparation and the presentation have analogous and inter-related features. Interestingly, the analogy relating to intrinsic and evoked processes goes further—corresponding to the fact that the preparation process almost comes to a halt during the presentation, intrinsic and evoked excitations bear, to some degree, an *inverse* relation to each other ([13]). In other words, evoked activity often suppresses the excitations in the resting state networks ([20]) to a considerable extent. As we will see later, this provides a clue to the relation between *unconscious* and *conscious* processes in the mind (see sec. 5.2 below, where we present a more nuanced view of the relation between intrinsic and evoked neuronal activity).

4.3 Correlation and meaning

Ceaselessly evolving excitation patterns generated in the spontaneous activity of the brain provide a ready-made matrix on which evoked signals get imprinted so as to result in an altered matrix of patterns on which the subsequently emerging evoked patterns get imprinted in their turn. This view of spontaneous activity is distinct from the one where each evoked pattern is thought to generate a fresh pattern on some small or large neuronal aggregate (in this context, refer to [6], chapter 8). This is explained more clearly by imagining the neuronal assembly in the brain of a newborn baby to be made up of smaller neuronal aggregates in which intrinsically excited patterns have been generated without any evoked pattern having been imprinted upon those. These intrinsic patterns, distributed throughout the brain, carry no ‘meaning’ with reference to a newly generated evoked excitation now to be imprinted on the existing intrinsic pattern in some network or other (again,large or small). In this case, only a small alteration in the extant pattern suffices to give a unique identity to the pattern resulting from the evoked action. This is to be compared with an alternative scenario where the evoked action gives rise to a pattern that generates a fresh imprint in a previously inactive neuronal assembly and that imprint identifies the evoked action for future reference, where ‘future reference’ means the process of correlation with the vast number of other patterns so imprinted and marked.

> As emphasized in [6], the brain of a newborn is no *tabula rasa* but is already a spontaneously active one where intrinsically generated excitation patterns are engaged in the process of self-organization of the neuronal assembly in the brain. Evoked activity modifies this matrix of self-generated patterns so as to launch the ongoing process of generation of *meaning*, based on all the other modified patterns in this evolving matrix.
>
> How do evoked signals get ‘imprinted’ on intrinsically generated excitation patterns? This is a deep and tricky question. As Buzsaki suggests in [7], chapter 10, this does not involve a simple superposition of the two. A likely mechanism (among others, perhaps, see [27]) is based on the process of *phase resetting* (see, for instance, [44]) of ongoing brain oscillations. This is essentially the reason why evoked response and intrinsic activity appear to have very similar characteristics.

Here it may help to consider a metaphor of a dictionary being generated by building up a catalog of unique identifiers meant to indicate concepts coming in succession and then correlating them with one another. A remarkably efficient way of doing this is to first build up an initial catalog of a large number of arbitrarily generated meaningless ‘words’ and assigning each newly arriving concept as a marker to some particular word in that initial catalog. This is vastly more convenient than creating a new word identifying the concept in question according to some rule of correspondence. As the concepts get identified in terms of the existing meaningless words, these can then be made to acquire *meaning* by establishing *correlations* among them. It is the correlations that are of fundamental relevance in generating meaning. For instance, the meaning of a word in the English dictionary is explained by means of other words or phrases correlated with it (thus ‘round’ is correlated with ‘shaped like a sphere’, or ‘the shape of a ball’).

4.4 How are correlations established?

How exactly are ‘correlations’ established among the excitation patterns in diverse neuronal populations? Most likely, *by association*, where the detection of *similarities*, plays a seminal role. However, this is only seemingly an attempt at answering the question, though perhaps an indicative one. Excitation patterns may be associated with one another along various lines, such as the one of associating two patterns that are produced by events occurring at neighboring locations in time and space or have some other aspects in common (*a dearly loved one present at two distinct events* as a result of which, the two corresponding patterns and the related neuronal populations have strongly similar features). The setting up of correlations also requires that the relevant neuronal populations be made to communicate either directly or through intermediate chains of neurons.

It is highly unlikely that the brain performs sophisticated computations except through elementary steps—just as a computer works on the basis of elementary operations (‘gates’) so does the brain perform its ‘computations’—only the elementary operations in the two cases are likely to be radically different. Thus, computations in the brain (e.g., in decision making, planning and predicting, and also in reasoning and logical inference) are likely to be widely different from the ones we know or can think of (e.g., Bayesian inference)—the latter are ‘as if’ analogs of the former. This, indeed, is the fundamental problem of *scientific realism*.

> In our attempts to uncover the mechanisms underlying the ‘real nature’ of a complex system, do our efforts approach progressively toward a ‘truth’ independent of the context in which we look at it, where the context includes our repertoire of concepts and our viewpoint generated in the past? Or do we, at critical junctures in our investigations, get a glimpse at novel aspects of the system, upsetting to a large extent our past concepts and generating *emergent* ideas and theories where our point of view acquires a new *dimension*? These are questions fundamental to our view of Nature as a whole, and of complex aspects of it. This paper is based on the supposition that, while there is certainly a sense in speaking of a progression of our ideas regarding a complex system (relating to the acquisition of a succession of new dimensions in our views of it), successive revisions in our ideas and theories are still *incommensurate* with one another ([24], [25]).

We will come back to the question of the mechanism of setting up of correlations among neuronal excitation patterns in sec. 4.7 below, where we look at what is referred to as the *brain waves*.

4.5 The global signal

The *global signal* (GS) is the average of the intrinsic excitation levels over the entire extent of the brain, which was considered to be irrelevant noise in brain imaging studies even a decade or two ago. However, it is now acknowledged to be of basic relevance in brain functioning, being a significant indicator of the phenomenon of spontaneous activity itself. It does include several types of 'noise' irrelevant to neuronal excitation *per se* but, at the same time, it reveals much that is relevant to the functionality of neuronal networks too. For instances, it has been found to be correlated with vigilance and arousal. The global signal variation among individuals appears to be correlated with 'positive and negative life outcomes and psychological function' ([42]).

> The global signal appears to have contrary significance in respect of intrinsic brain activity. For instance, the removal of the global signal as useless noise brings to a clear focus the inverse correlation between the activity levels of certain pairs of brain networks ([13]). In other words, the said inverse correlation may have its causal roots in a broader biological setting.

The global signal is seen to be correlated in a characteristic manner with local excitation levels in various brain regions—a feature of the former referred to as GS-topography. The following summary in [1] gives an indication of how relevant the global-local correlation is:

> 'It was observed that the GS topography has an intrinsic structure characterized by higher GS correlation in sensory cortices and lower GS correlation in higher-order cortices. The GS topography could be modulated by individual factors, attention-demanding tasks, and conscious states. Furthermore, abnormal GS topography has been uncovered in patients with schizophrenia,

> major depressive disorder, bipolar disorder, and epilepsy. These findings provide a novel insight into understanding how the GS and local brain signals co-activate to organize information in the human brain under various brain states.'

4.6 The default mode network (DMN)

The *default mode network* (DMN) is of great relevance in the context of spontaneous brain activity and, *at the same time*, in our mental life.

In a manner of speaking, it constitutes the top level in a hierarchy of neuronal networks arising from the intrinsic brain activity that results in a process of self-organization involving the emergence of these networks—ones that have mental and psychological relevance ([35], [37]). The DMN was first noted in 2001 in positron emission tomography (PET) measurements of regional blood flow and oxygen consumption, when it was found that certain brain areas observed to decrease their activity during attention-demanding goal-directed tasks, were activated in the resting state and were indicative of a heretofore-unrecognized organization within the brain's intrinsic or ongoing activity. It is principally made up of discrete, bilateral and symmetrical cortical areas, in the medial and lateral parietal, medial prefrontal, and medial and lateral temporal cortices ([36]).

1. This significant and rather surprising discovery was preceded by an earlier observation by Shulman to the effect that certain cortical areas exhibited reduced activity during the performance of non-self-referential, goal-directed tasks when compared with a control state of quiet repose ([36]).
2. It may be mentioned, however, that self-referential tasks may also be goal-directed. For instance, when I am actively analyzing possible lapses in my mode of thinking and behavior in the society of others, my mind is certainly engaged in goal-directed activity since it is making use of a number of higher order cognitive capacities. It is only when the mind is passively and idly in a resting state that the self 'wanders' through an extended mental terrain, being then in a state of repose.
3. It is worth emphasizing that the fMRI, PET, and EEG studies of the intrinsic brain activity all involve ultra-slow fluctuations in the collective excitation levels of neuronal populations across large-scale brain networks. The DMN and all the other resting state networks (the former seems to be of fundamental relevance as one among the RSN's identified in brain recordings) are characterized by this space-time window of brain activity. These large scale networks are mostly responsible for our complex and eventful mental life. However, the entire range of our mental activities is likely to involve hitherto unrecognized faster excitation processes involving small neuronal populations as well.

4. The DMN and all the other RSN's are characterized by a significant spatial *coherence* in the intrinsic brain activity—this, indeed, was responsible for the identification of intrinsic activity in the first place.

The recording and study of intrinsic activity in the large scale networks, including the DMN, has been referred to as the 'top-down' view in [37]. Complementing this (but without significant overlap thus far) is the 'bottom-up' view of intrinsic activity that starts at the cellular level (refer back to sec. 3.1). The two views, both relating to the ongoing spontaneous brain activity refer to distinct space-time scales in the evolution of a complex system.

> The intrinsic activity in the hierarchically organized neuronal assemblies involves 'top-down' and 'bottom-up' dynamics, analogous to top-down and bottom up mental and psychological processes. In particular, top-down processes include ones that generate *models* of the world (see sec. 6.4 below)—these models lead to the formation of our psychologically generated expectations, anticipations, and plans (in this context, see [33]).

The accumulated literature on the DMN, in particular, provides a bridge between the understanding of the brain as *an assembly of neurons* (supported by numerous physiological systems of diverse descriptions) and an insight into the mechanisms regulating our *mental life*. Put differently, the DMN is a large scale neuronal network that has been the focus of attention generated from the point of view of intrinsic neuronal activity while, at the same time, being recognized as a hub of central relevance in respect of our mental and psychological processes.

> For the purpose of this essay, we interpret the term 'mental' in the sense of being an inclusive one while 'psychological' is understood to refer specifically to those aspects of the mental that are associated with the *self* (refer to sec. 5.3).

The basic anatomical components of the DMN and associated functional aspects are succinctly presented in [36]. In particular, it highlights the important role of the ventromedial prefrontal cortex (VMPFC) as a sensory-visceromotor link concerned with social behavior, mood control, and motivational drive, all of which are important components of an individual's personality. The emotional state of the subject has been found to have a direct effect on the activity level in the VMPFC component of the DMN. As another instance, the dorsal medial prefrontal cortex (DMPFC) is associated with self-referential judgments (e.g., sense of pleasant or unpleasant feeling on encountering an object or an event). In summary, DMN instantiates processes that support emotional processing, self-referential mental activity , and the recollection of prior experiences. These functional elements of the default mode network can be differentially affected during task performance by the nature of the task (e.g., presence or absence of an emotional component or an element of self-reference). However, regardless of the details of a particular task, the default mode network always begins from a baseline of high activity, with small changes in this activity made to accommodate the requirements of a particular task. The available evidence indicates that the functions of the default mode network are never turned off but, rather, selectively enhanced or attenuated.

The DMN is commonly associated with 'spontaneous cognition', i.e., processes in the mind relating to a relaxed state of quiet repose, namely daydreaming, mind wandering, or stimulus-independent thoughts. Furthermore, spontaneous cognition routinely involves thoughts about one's personal past and future (however, see [36]).

A quite extensive literature exists on various aspects of the involvement of the DMN in mental and psychological processes, where these are often related to results from neuro-imaging studies. A few instances are to be found in [22], [39], [11], [46].

4.7 Spontaneous activity: the brain waves

For background to the content of this section, refer to [6], [7], [44], [43], [27], [8], [31].

As mentioned several times in this essay, the ongoing process of interactions of diverse types among the components of a complex system such as the neuronal assembly in the brain, along with environmental influences on it, leads to a process of *self-organization*. Referring to the network representation, hierarchies of clusters are formed on progressively larger scales, whose interactions depend on sets of collective variables, and a large chunk of the behavior pattern of the system (especially the relatively slow evolution) gets determined by the continual change in configuration of the clusters—in the brain, the large scale (or 'macroscopic') clusters correspond to the 'top' levels of neuronal networks organized in hierarchies (refer to sec. 6.5 later in this essay).

> As one goes down the scale in the hierarchies, one encounters *mesoscopic* and *microscopic* assemblies in terms of neuronal population size.

The tell-tale indicators of the ongoing process of self-organization in the brain are the *brain waves*. These are distributed over a number of frequency bands and appear as traveling and standing waves in various regions across large areas in the brain. On a smaller spatial scale, the 'local field potentials' (LFP) are indicators of ongoing neuronal activity in general, and of oscillatory processes in particular.

As mentioned earlier (sec. 3.1), the single neuron is capable, under appropriate conditions, of producing oscillatory signals. This basic phenomenon of generation of oscillations gets manifested in interacting neuronal assemblies of various population sizes in the form of brain waves, the latter being the result of a long process of biological evolution.

The brain waves are observed as rhythmic electrical (and magnetic) field fluctuations, mostly in the form of oscillatory bursts covering temporal spans of diverse durations, and constitute the principal vehicle of communication of information across macroscopic neuronal networks in the brain. The fluctuations are caused by oscillatory excitation patterns set up along concatenated neuronal paths in the 'connectome' making up the brain.

From a fundamental point of view, the brain waves constitute the basic mechanism for the setting up of *correlations* among dynamic excitation patterns in diverse local neuronal populations (mostly within large scale networks), resulting from intrinsic and evoked processes in the brain. These local excitation patterns are of an oscillatory nature too, where the oscillations are of diverse wave forms, mostly appearing as transient bursts.

In other words, the entire activity in the brain as a whole is, broadly speaking, a vastly complex interaction of *rhythms* of diverse wave forms and time durations—the relatively long range aspects of this interaction (connecting large scale neuronal networks) are determined by the brain waves. The brain waves and the local oscillatory bursts are produced by the same basic mechanism involving transport across ion channels in populations of neurons interacting through synapses.

How do the long range rhythms—the brain waves—and the localized ones interact? This is essentially the fundamental question mooted in sec. 4.4 earlier in this essay. An incomplete answer that can be put forward now is that, it is precisely the mutual interactions of the long range and the localized rhythms that constitute the basic mechanism of setting up of correlations between spontaneous excitation patterns, imprinted with evoked responses generated locally in neuronal populations.

1. It is to be recalled that the intrinsic and the evoked excitation patterns are themselves generated in the form of rhythmic bursts of diverse shapes and durations.
2. One has to distinguish between evoked patterns as generated by way of the direct recording of neuronal signals produced as the mind gets engaged in endogenous or exogenous tasks of various descriptions, and the patterns produced *after* these directly generated signals get imprinted on previously existing ones (intrinsic signals, some of which may be imprinted by previously produced evoked signals)—the 'imprints' are 'stamped' in a complex sequence.
3. The process of 'imprinting' is itself one in the nature of setting up of correlations among excitation patterns. Generally speaking, the directly generated evoked signals are of relatively lower frequency ranges as compared with the locally generated intrinsic excitation patterns on which these are imprinted.

The interactions between rhythms take place in diverse and subtle manners. Generally speaking, the ones of relatively longer periods *modulate* the shorter ones, while those with frequencies close to one another get *phase locked*.

Oscillatory excitations of approximately identical frequencies generated in neuronal populations located close to one another (and interacting by synaptic communication through only few links) get correlated by means of phase locking, where the phase difference between these remains constant, and the frequencies get modified to a common value.

> This is the simplest (or the $1:1$) phase locking, while $m:n$ phase locking, with m and n small positive integers, are also likely to be involved in brain processes. The theoretical investigation of phase locking is of a technical nature, based on the so-called phase-resetting curves and on bifurcation analysis, often quite intricate.

This process of phase locking is believed to establish correlations among excitation patterns generated in even remotely distributed brain networks, where *phase resetting* plays a significant role (see,e.g., [44]). The latter is a process where the phase of an oscillatory pattern gets reset as it gets perturbed by some pulse (say, the first spike, or the first few spikes, in an oscillatory burst) arriving at the relevant neuronal population.

The brain waves set up correlations of oscillatory patterns in large scale neuronal networks across separated regions in the brain, such processes being widely believed to correspond to higher order cognitive activities of the mind—both unconscious and conscious. We repeat that these waves propagate along concatenated ('polysynaptic') neuronal paths in the form of oscillatory excitation patterns of diverse waveforms, and are of a transient nature—their duration being sufficiently stretched so as to be sufficient for setting up the correlations. They appear and then die down in incessant succession, resulting in transient interactions among large scale neuronal networks, in keeping with the dynamic changes in the configuration of the networks themselves (refer to sec. 6.5 below).

- All the while, local interactions between relatively small populations within single networks continue to play an important role in the complex process of the setting up of correlations among excitation patterns across the entire brain.
- In keeping with what has been mentioned above, oscillations can interact in a large number of ways, giving rise to enormously complex scenarios. The interaction of intrinsic and evoked patterns in the brain is likely to involve processes more varied than phase locking and phase resetting (see, e.g., [27]).

5 Spontaneous activity and the mind

5.1 The fundamental duality

The mind is an emergent entity based on the structural and functional organization of the brain—more precisely, it is an emergent *mode* of brain activity where a large number of neuronal aggregates and their interactions play a dominant role. The neuronal aggregates and their interconnections themselves evolve in time in a complex manner, giving rise to the enormous complexity that characterizes the working of the mind. Put differently, the functioning of the mind is based on *collective* features of neuronal assemblies of various sizes (where an assembly or an aggregate need not be localized in some specific region of the brain) resulting from the interactions among neurons—this indeed is the general characteristic of emergence in complex systems.

There is a duality between spontaneous activity and the mind, which is part of the larger duality between the latter and the brain itself. The brain and the mind constitute *complementary* aspects in the description of a complex reality—while the mind emerges from the incessant activity of the neuronal mass in the brain (aided by a complex array of physiological processes), its functioning is fundamentally *non-determinable* in terms of neuronal excitations. In other words, the mind is not explicable (or predictable) in neuronal terms (and, conversely too)—though a correlation between the two exists all along, that correlation cannot be determined with any degree of precision and completeness. Of course, fMRI studies and a number of other diagnostics inform us as to which brain regions are involved in certain mental activities, but that does not constitute a detailed explanation of mental activities in neural terms—this is a seemingly pessimistic position to adopt but it is the foundational metaphysics this paper is based on.

The mind is structurally and functionally complex. It has its unconscious and conscious layers, with a complex interpenetration between the two. It has its enormously intricate and intriguing ingredients such as concepts, heuristics, preferences and aversions, beliefs, reasoning ability, intents, wishes, will, fantasies, cravings, obsessions, socially acquired propensities and traits, and so on. All these interact in untold ways so as to generate the behavior pattern of individuals where, moreover, the minds of particular persons are but atoms in a vast social network. However, all this notwithstanding, the mind of an individual is based on, and rooted in, her neuronal excitations, aided by diverse physiological processes.

5.2 The unconscious and the conscious

> An exceptionally rich and lucidly explained background to the 'unconscious' and the 'conscious' is to be found in [12]; see, especially, chapter 5 in it.

Among all this diversity, we look at the (tenuous) distinction between unconscious and conscious processes in the mind. Among these, the latter are associated with the execution of exogenously and endogenously evoked tasks, while the former involves neuronal excitation patterns that merge with intrinsically generated ones.

Standing by the side of a river, I am idly enjoying a serene natural canvass. My mind is unconsciously registering numerous features of the scenario and regularities therein, depending on the way it gets exposed to those features and on its storehouse of impressions generated in the past. At some point of time I observe a boat sailing by in the distant horizon and instantly my mind is alerted by the long-lost memory of an acutely poignant childhood event. This last is an evoked response of my conscious mind. Described in neuronal terms, it involves an induced excitation pattern imprinted on spontaneously generated ones.

In other words, evoked mental activity is, generally speaking, associated with conscious processes in the mind and result in excitation patterns to be imprinted upon but distinct from intrinsically generated ones. Excitation patterns resulting from unconscious processes, on the other hand, merge continuously with spontaneously produced ones. In this context, one has to note that unconscious mental processes occur at various *levels*—for instance, these are ubiquitous even during evoked activity since these provide the substratum on which the latter is enacted. Additionally, the mind continues to map its external and internal world in its conscious but unfocused state (*absently looking at ripples on a river surface*; in this context, see [36]), while it marginally retains such activity during sleep too (*awakening suddenly on hearing a soft footfall*). All these various levels of unconscious activity (i.e., activity we are not aware of) generate excitation patterns that cannot be easily segregated from intrinsically generated ones. Finally, an unconscious state resulting from brain injury or disease or, say, from drug-induced loss of consciousness is not associated with discernible mental activity but still continues to generate intrinsic excitation patterns in neuronal assemblies—what is distinct in these cases is a partial loss of global connectivity (in this context, see [45]) in the brain. In other words, the 'global workspace'([12],chapter 5; Dehaene refers to Bernard Baars to observe that '...consciousness is just brain-wide information sharing') ceases to be operative to a considerable extent in relatively severe cases of loss of consciousness.

The observed inverse relation between evoked and intrinsic neuronal activity then suggests the following clue regarding the way the conscious mind is related to the unconscious: *consciousness involves a partial loss of intrinsic activity in numerous neuronal networks across the brain, with an attendant rise in the excitation level in certain task-related networks*, resulting in a focused perception of the world.

The diffuse activity in distributed networks across brain regions in unconscious processes (especially ones in the absence of conscious awareness) corresponds to the generation of *implicit* mental representations that, generally speaking, enables the mind to perceive *conflicting and contrary* aspects of reality (the various networks registering distinct aspects of an event or object, where these may be in conflict with one another). Conscious activity, on the other hand, involves the excitation of relatively few networks at a time (with reduced levels of spontaneous global activity—crucially, however, the global workspace remains accessible, and is made use of sequentially) and is thus of an *explicit* nature, where reality is captured in unequivocal terms, largely purged of contrary aspects. For instance, when an individual appraises the traits of a neighbor unconsciously, she simultaneously captures contrary and complex aspects of the latter, but when she is asked to explicitly describe what she discerns, she relates only one aspect at a time and cannot, in the end, quite reconcile the multiplicity and complexity of her neighbor's mental profile, instead resorting to an affect-laden and judgmental appraisal like 'good' or 'bad', 'honest' or 'dishonest'—all the while unconsciously feeling on the basis of her experience that the neighbor has good *and* bad, honest *and* dishonest aspects woven into his character. It is to be noted that the diffuse implicit view of an event can result in a sharp affect-based valuation ('good-bad') and, at the same time, in a more complex emotional appraisal, often involving contrary emotions.

As the evolving world gets imprinted on our mind in degrees, our appraisal of it is simultaneously explicit and implicit—the former developing serially from one conflict-free premise to the next (the logic of the *excluded middle*) and the latter developing in a vastly ramified view of reality which, however, is equivocal (in the sense of being complex and contrary) and lacks in precision and clarity. While one is focused but an essentially impoverished view of perceivable reality, the other is enormously rich in comparison though vague and diffuse. The two together make up our world-view.

> The above two types of mental functioning, associated with corresponding types of neuronal activity in the brain, are analogous to what Buzsáki refers to in [7], chapter 13, citing the work of Daniel Kahneman. It is not unlikely that there are two types of neuronal populations in the brain with, however, a continuous distribution in between.
>
> While Buzsáki's conjectures and views pertain to neuronal activities, Kahneman's are oriented toward the mental and the psychological. The two appear to correspond to each other but are complementary nevertheless—one cannot be reduced to the other.

Returning to the distinction between intrinsic and evoked excitations in neuronal populations in the brain, it is only partially justified to state that evoked excitations are associated with conscious processes in the mind—while the latter give rise to the former, the reverse statement needs qualification. Unconscious mental processes can certainly give rise to what can be described as evoked excitation patterns—for instance, the mind registers numerous regularities in the world while operating below the level of awareness,and these regularities get registered in the form of neuronal excitation patterns having features analogous to ones generated in conscious and task-evoked mental processes. However, as mentioned above, it seems likely that unconsciously generated excitation patterns cover a spectrum that merge continuously with intrinsically produced ones, the latter having distinctive spatiotemporal structure distributed over a wide spectrum of spatial and temporal scales.

> In a manner of speaking—and in a somewhat adventurous spirit—it may be stated that a state of consciousness with, explicit awareness of what the mind is focused on, represents a phase in the course of a complex (and obscure) evolution of the mind where a large number of interconnections among neuronal networks are partly deactivated, and only certain connections among them, along with their dynamical excitation patterns remain activated, reinforced at a relatively high level. This is consistent with the observed inverse correlation between evoked and intrinsic activity, and constitutes a generalization of that inverse correlation: *conscious awareness is the result of a partial deactivation of numerous ongoing interactions between widely distributed neuronal networks, along with a reinforcement of the remaining ones* that continue ceaselessly in the brain. Among these ongoing interactions, the intrinsic neuronal activity constitutes a major part.
>
> In other words, the conscious state of the mind being a focused one, must correspond to an analogously 'focused' configuration of the neural networks within it.

All the while, as the mind remains active (whether or not in a focused state), the so-called global workspace remains accessible, i.e., the large scale integration among neuronal networks that remain in a near-critical fluid state (see sec. 6.5 later in this essay) gets continually reconfigured as successive states of the mind are passed through.

5.3 The resources of the mind

The mind has a complex structure, based on which it can engage in an enormously complex repertoire of functional modes, making use of numerous *resources*. For instance, it has its preferences and aversions (based on the *affect* system in the brain), a highly rich and complex array of emotions, drives, whims, moods, cravings, fantasies, phobias, feelings of guilt, heuristics, beliefs, moral convictions, social sensibilities, concepts, reason and logic, conscience, and so on—the list is almost unending because all these 'resources' are made use of in complex combinations.

As for the structure of the mind, one has its unconscious and the conscious layers, including a spectrum made up of intermediate levels of consciousness (see, for instance, [9]), and, notably, the *self* assembled around the axis provided by such mental ingredients as our preferences (and aversions), emotions, beliefs, as well as our repressed feelings in conflict with the rest of our mind.

All this complex structure of the mind and the stupendously complex array of its resources emerge on the basis of the ongoing process of the setting up of correlations (see sec. 6.3) among spontaneously generated neuronal excitation patterns imprinted with signals arising from mental processes corresponding to engagements with the external and internal realities that the mind encounters.

In summary, one way of looking at the mind would be to describe it as an emergent quality of the intrinsically active brain in which excitation patterns in groups of neurons are correlated across its complex architecture.

6 Intrinsic neuronal activity: what it stands for

As mentioned above, the level of intrinsic neuronal activity varies across mental states of diverse descriptions, though it occurs incessantly and is widely distributed across brain regions. Its characteristic features are most clearly defined in the so-called 'resting state' ([35]) of the brain-mind complex.

Generally speaking, the intrinsic activity is geared toward 'information processing for interpreting, responding to and predicting environmental demands' ([35], [20]). At the fundamental level, however, the intrinsic activity accomplishes the task of ceaselessly establishing correlations among neuronal excitation patterns associated with the experience-generating interactions between the brain-mind complex and the world at large (refer back to sec. 4.3). As already explained, these are nothing but previously existing patterns generated spontaneously in neuronal aggregates of diverse population size, where these previously generated patterns are imprinted with the identity of experiences arising from the aforementioned interaction. We will presently explain this further, after we mention a couple of other aspects of spontaneous neuronal activity in the context of brain functioning.

6.1 Intrinsic activity facilitates self-organization in brain

First, the spontaneous activity is fundamentally indicative of the process of *self-organization* ([42]; [12] chapters 5,7; [37]) of the neuronal assembly in the brain, largely contributing to the formation of functional neuronal aggregates across brain regions, where these aggregates keep on being reformed in space and time. Put differently, the enormously ramified and complex interactions between the neurons result in a complex evolution of neuronal aggregates of multifarious population size and equally multifarious collective features that enable the brain to progressively interact with the world in an adaptive manner. In this ongoing self-organization of the brain, the setting up and activation of myriads of neuronal synapses (an essential aspect of 'neuroplasticity') is of fundamental relevance, where the term 'activation' is used in an inclusive sense referring to both excitatory and inhibitory processes. What is more, the ceaselessly continuing activity of setting up of correlations between neuronal excitation patterns in aggregates of diverse descriptions mentioned above is, in a broad sense, a component of the self-organization process too.

6.2 Intrinsic activity facilitates detection of signals

The second of the two aspects of intrinsic activity mentioned above relates to its role in facilitating the reception of evoked signals from the world that results in the association between ongoing experience on the one hand and intrinsically generated neuronal excitation patterns on the other, this being the fundamental response of the brain to influences exerted on it by the world at large. A noteworthy feature of this process of reception is that the brain often receives and registers relatively *weak* signals that play a significant role in its overall response. As a signal generates excitations in one or more neuronal aggregates, the latter feel the influence of a largely uncorrelated array of intrinsically generated signals from all the rest of the interacting neurons. A phenomenon of a somewhat paradoxical nature is that this uncorrelated background 'noise' is capable of *facilitating* the reception of the evoked weak signal in question—this is referred to as *stochastic resonance* ([42], [28]).

> Generally speaking, evoked signals are weak in comparison with intrinsically generated ones (see, for instance, [20]).

It is now time to return to addressing the issue of how the setting up of correlations between neuronal excitation patterns in the brain enables the mind to generate its view of the world.

6.3 Intrinsic activity correlates neuronal excitation patterns

We get to know the world little by little through small bits of experience, where 'experience' is meant to include observation, experimentation, introspection, registering sequences of events, and learning. Every little bit of experience involves signals of diverse types received by the brain that generate excitation patterns in neuronal assemblies of various population size. Our belief and knowledge of the world at large is built by patching up all these tiny pieces of experience. For instance, I observe my neighbor engaged in some action (gardening, talking, arguing, and so on) every day. All these partial experiences are patched up in my mind to generate a relatively complete profile of the person I observe. Each of these bits of experience leaves a trace in my brain in the form of an excitation pattern in some neuronal ensemble or other, which is essentially a small perturbation over one generated by the spontaneous activity in my brain, now associated with the relatively weak excitation produced by the signals resulting from the experience in question. However, this imprinting of the intrinsic excitation pattern with the (much weaker) evoked pattern has no significance unless it is correlated with similar other patterns, associated with related patches of experience (for instance, what kind of activity the neighbor engages in on various different occasions, how he treats his children and wife, and so on), that generate *meaning* for that particular bit of experience. In other words, the patching up of perceptions corresponding to bits of experience that takes place in my mind so as to generate a more or less complete composite picture in it goes hand in hand with correlations being set up between the excitation patterns in neuronal assemblies (perhaps, of relatively small population size). *It is the job of the intrinsic activity of neurons to set up all these enormously proliferating correlations—an activity of vast magnitude and significance.*

What exactly constitutes such correlations and how are those established? This is a question that may never be answered fully since it commonly involves processes linking neuronal assemblies excited at widely distinct points of time, and at distant regions in the brain, and may involve quite distinct types of signals generated from seemingly disparate sets of entities in the world. It is altogether an awesome job to correlate all these so as to make up a coherent whole—one that is, moreover, correlated with yet other composites so as to give rise to coherent pictures of the world evolving in time—all these patched up pictures get woven into one another, thus making up our phenomenal world that keeps on evolving incessantly. It is this process of setting up of correlations between fantastically diverse excitation patterns that requires perpetual intrinsic activity of the neurons in the brain, and it is this perpetual activity that generates all the perceptions and interpretations in our mind, thereby making up our perceived world.

While the basic process of setting up of correlations among neuronal excitation patterns constitutes the *syntax* of the language of the brain, the bigger picture that emerges through the continuing proliferation of the correlations brings forth the *semantics*. It is much like words being correlated by syntactical rules, based on which there emerges a meaningful composition, such as a piece of poetry. Of course, just the composition of neuronal excitation patterns according to some syntactic rules—or, for that matter, just a collection of syntactically connected English words—is not sufficient to generate meaning since it requires constant reference to the world of reality and comparison with the mental pictures resulting from the composite excitation patterns for the neuronal activity to ultimately make sense in our mind.

6.4 Intrinsic activity generates a model of the world

By relentlessly correlating neuronal excitation patterns resulting from the fundamental process of the imprinting of evoked patterns on spontaneously generated ones, the brain gradually builds up an internal representation of our experienced world. In this, spontaneous brain activity provides the basis on which the mind makes a *model* of the world—a model in which all our fragmentary bits of perception are patched up and woven into one another so as to make up a complex but coherent mosaic that keeps on evolving.

It is this mentally generated representation of our reality—one that includes our external *and* internal worlds—that makes us *respond* to it. In turn, this representation results from the correlations—set up by the spontaneous brain activity—among the excitation patterns in the vast number of neuronal assemblies in the brain, large and small (i.e.,macroscopic, mesoscopic, and microscopic ones). This process of setting up of correlations is made possible by the modulation of synaptic strengths, by the perpetually occurring augmentation of effectively operating neuronal connections *and* by means of waves of electrical activity belonging to a number of frequency bands, where the waves modulate a large chunk of all the rest of the neuronal activity. All these are results of the process of self-organization issuing from the intrinsic neuronal activity in the brain.

1. The organization of neuronal populations associated with intrinsic brain activity involves a hierarchy from the microscopic to the macroscopic, where the macroscopic neuronal assemblies ('hubs', as referred to in [35]) are not always associated with known brain regions with specific functionality. According to current understanding, the *default mode network* resides at the top of the hierarchy ([35], [36]) (refer back to sec. 4.6). Excitations in this network get attenuated as the brain gets engaged in task-evoked functions of various descriptions.
2. The spatiotemporal organization characterizing intrinsic activity is found in known networks too ([42]). It needs to be mentioned, though, that intrinsic activity occurs at all scales (referred to in terms of neuronal populations) and the spatiotemporal characteristics vary with scale, with the underlying dimensionality of the dynamics being scale dependent.
3. The process of proliferation of effectively operating neuronal connections across the brain is referred to as *neuroplasticity* (see [5] for background). Neuroplasticity results from intrinsic as well as task-evoked activities in the brain, where the relative contributions of the two types varies during the developmental process of an individual.

Based on the mentally assembled model of the world, we respond to the latter by making decisions and inferences, producing plans, forming intents, building up theories, and generating expectations and predictions. Every fresh bit of experience tests in some way or other the degree of validity of the currently generated mental model—one resulting from the ceaseless process of generation of intrinsic neuronal excitations—relative to the evolving canvass of reality. Of course, the term 'reality' is to be interpreted as our perceived world because the mind knows of no other world beyond the perceived one.

Any mismatch between the two gives rise to a revised mental model based on an altered correlation among a modified configuration of excitation patterns. It is this perpetual process that results in the evolution of our world-view—a view that is perennially ridden with a tension between fidelity to an 'objectively' existing reality and relevance to the multifarious 'needs' and 'inclinations' of the mind.

At the beginning of life, the perceived world of an individual has little to do with her psychological needs beyond her innate drives. At this early stage of ontogenic development, the tension between the perception-generating reality and the psychological needs is relatively unimportant. Consequently, the process of revising the configuration of correlated excitation patterns is more or less direct, being mostly driven by the external reality itself. However, as our internal world gets more and more complex, the tension grows and the process of adjustment becomes more complex too.

1. Berkes *et al* speak of ”the progressive adaptation of internal models to the statistics of natural stimuli at the neural level” ([4]). However, the process of this adaptation is not a simple or straightforward one, as can be seen in [2].
2. Considered from the point of view of how the mind adapts the brain in its interactions with the world, the great complexity of that interaction is based on the analogous complexity of the process of adaptation at the neural level mentioned above. We recall that the world that the mind adapts to is the phenomenal world which we build in the course of our journey through life, and is as much an ‘objectively determined’ one as it is rooted in our mentally generated interpretations. The phenomenal reality is strangely interwoven with the mind-independent objective reality on the one hand and the mind itself on the other.

   There are only (relatively) few innately generated patterns in the brain — the ones that are etched phylogenetically during prenatal and immediate postnatal development (our elemental phobias, anxieties, drives, and instincts). However, intrinsic activity starts right from early days, which is at first ‘meaningless’ i.e., uncorrelated with the world at large (mostly, the external world, though the newborn does not have a clearcut separation between the internal and the external); it is only gradually that the intrinsic excitation patterns get imprinted with externally (and internally) generated signals. As mentioned earlier, internally generated signals are to be distinguished from intrinsic ones—the latter are uncorrelated patterns that get correlated in a continuing process; a number of correlated intrinsically generated patterns get to be elevated to the role of internal ones in an ongoing process.
3. Following the Kantian tradition of metaphysics, the objective reality is an independently existing self-determined entity that is, in the ultimate analysis, inaccessible *as it is*, and is perceived by us only in fragmentary patches, through the lens of our own internally generated mental world (for background, see [25]).

In all this, it is important to note that the ‘response’ of the brain to signals received from the world at large is, to a large extent, an *anticipatory* one, based on the mosaic of models (refer to [33]) already generated in the form of correlated excitation patterns. It is precisely in this sense that the spontaneously active brain (and the mind emerging within its complex dynamics) is proactive with respect to the world—it forms expectations and predictions, and modifies the latter only when signals received from the world reveal an anomaly, small or large. This is analogous to the Bayesian process of hypothesis generation as seen in our scientific endeavor at large. It is far more effective than responding piecemeal to the succession of arriving signals and is based on the principle of ‘making use of the past to anticipate the future’. As far as the mind is concerned, it always forms perceptions on the basis of interpretations of newly acquired experiences in the light of past ones—the mind predicts and *then* learns (i.e., registers newly perceived correlations residing in reality). In this process of constantly anticipating the world and adapting to it, the mind is served in a major way by our vast and constantly evolving array of *emotions* (refer to [3]). Emotions constitute an *implicit* language for classifying all our experiences of the world—the classification is only marginally altered (if at all) with each newly perceived bit of experience (of course, the alteration is dramatic in the case of an infant). If, however, a new experience challenges the entire scheme of classification, there results a phase of disorientation from which one may come out with a transformed scheme that is again in keeping with experience in some new context or, unfortunately, may not.

6.5 Spontaneous activity and self-organized criticality

A number of features of nonlinear dynamical systems have been indicated in sec. 2.2, with particular emphasis on what has been referred to as the *context effect*—this involves a sensitive dependence on initial conditions and also on the physical parameters characterizing the system at certain transitions through instability in the course of its dynamical evolution.

> The physical parameters characterizing a system may get altered in virtue of environmental effects.

In addition, sec. 2.3 includes a few basic ideas on *self-organized criticality* and on the scale-free nature of processes (characterized by power-law probability distributions) in systems involving numerous large-scale clusters brought close to criticality.

> A well studied example of a system exhibiting the features of self-organized criticality is the *sand-pile* ([21]). If grains of sand are slowly added to a sand-pile it grows along a stable path, till it reaches a tipping point, when it collapses. The sequence is repeated if the slow process of adding sand grains is continued. The parameters associated with a collapse, such as the avalanche size, obey a power law statistics—the process of collapse occurs at all scales.

As mentioned at several places in this essay, the assembly of neurons in the brain are in perpetual unrest in virtue of their mutual interactions and of environment effects where the latter include ion flow, glial influence, the effect of the neurotransmitter and neuromodulator systems, and a number of other physiological influences, *along with* multifarious signals received from the world by way of perception and of internal mental processes.

> Recall that the world at large has an *internal component* in our mind (refer back to sec. 3.3). Processes of the mind involve neuronal signals originating in parts of the brain and received by other parts—these signals constitute our internal perception.

This spontaneous activity of the neurons, under the added influence of multifarious signals received in external and internal perception, is responsible for a continuing process of self-organization during the lifetime of an individual. Imagining the brain to be represented by a vast and complex network, the self-organization leads to the emergence of hierarchies of clusters representing neuronal circuits (or ‘networks’, as they are referred to in neuronal imaging and related studies), where these neuronal networks interact with one another and with their external and internal environment as *collective* entities, though interactions of single neurons and of neuronal assemblies of small population size continue to play a latent but effective role at relatively small space-time scales. It is this collective action of hierarchies of relatively large neuronal networks that, in the main, appear as processes of the *mind*.

The mind is an exceptionally active and fluid entity. It requires only a small perturbation (generated by means of external and internal perception) to set it in ever-new courses, ceaselessly generating myriads of thoughts, preferences, emotions, beliefs, intents, whims, fantasies, cravings, plans, predictions, expectations, and what not. Analogous to the (notional) ‘phase space’ of the neurons forming a complex system, the mind may also be imagined to be having its own ‘phase space’ in which its vastly complex evolution in any short interval can be visualized to be represented by a trajectory spanning an enormous number of dimensions. That trajectory is determined by the internal dynamics of its own ingredients (refer back to sec. 5.1) and also by effects from its internal and external environments. In the course of this enormously complex and obscure evolution, there takes place precipitous changes in the course of evolution, mostly by the operation of emotions that generate instabilities by their amplifying actions in the mind.

Indeed, the mind being an emergent property of the brain, mostly based on the activities of the relatively large neuronal networks, there is necessarily a close parallel between the *fluidity* of the brain (refer back to sec. 2.3) and that of the mind. It is mostly the large scale organization of neuronal networks in near-critical configurations that gives rise to the untold subtleties of processes of the mind—of course, the spontaneous neuronal activity over shorter space-time scales presumably plays a seminal role, largely opaque at our current level of understanding.

It appears to be a plausible conjecture that the brain is indeed a complex system with large scale neuronal networks operating in near-critical configurations, endowed with a fluidity in their evolution pattern that presumably gets reflected in the fluidity of the mind itself.

1. For background, see [21] (chapter 6), [12] (chapter 5), [32], [9], [18], [40].
2. Strictly speaking, the term 'criticality' applies to a system for which, in the network representation, large scale clusters have merged into one single giant cluster that has been brought to the edge of instability in virtue of one dominant Lyapunov exponent, corresponding to some relevant collective co-ordinate, passing through the value zero—alternatively, the real parts of a conjugate pair of exponents may cross zero value. In this case physical characteristics of the system close to criticality are stamped with the feature of *universality*. In this sense, the large scale neuronal networks in the brain form a system operating *near* criticality.

   Generally speaking, psychological processes are slower compared to those involving direct neuronal interactions because of the phenomenon of *critical slowing down*—however, this applies only to those psychological processes that involve the joint involvement of a considerable number of large neuronal networks.

6.6 Intrinsic activity generates inter-personal variability

Generally speaking, the process of self-organization in a complex system proceeds through a close succession of instabilities, where relevant stability exponents (refer back to sec. 2.2) change sign and the system dynamics becomes sensitive to small perturbations. The dynamics of neuronal populations accompanying the widespread intrinsic activity across brain regions is no exception. Consequently, different realizations of the dynamics under varying conditions of task-induced perturbations are expected to result in varying spatiotemporal patterns of activity when looked at in details while appearing to resemble one another in overall features. This is even more accentuated in the spontaneously active brain since the latter is, to all intents and purposes, a system operating close to criticality.

This is to be compared with the widespread variability of thought patterns and behavioral response to environmental perturbations *in individuals*, when one is inclined to interpret the two phenomena to be deeply correlated—the variability of intrinsic activity under perturbations provides the basis of inter-individual variability of behavior in response to influences exerted on the mind by the external and internal worlds within which it operates. This correlation essentially confirms the broader inference that the brain's repertoire of responses to the world is represented and updated in the brain's intrinsic functional architecture ([29]). The variability inherent in the operation of the brain networks close to criticality leads to great flexibility, where a large number of alternative network configurations are accessible and are realized in individuals having diverse developmental history.

> For a brief but illuminating overview of the significance of signal variability in intrinsic neuronal activity, see [42].

7 Summing up: the proto-mind and the mind

7.1 Three levels in a hierarchy

The fundamental statement that this essay attempts to make is about the way intrinsic activity involving neuronal populations of diverse size groups in the brain brings about a process of self-organization whereby the mass of neurons get hierarchically sorted in the form of groups of networks, where a neuronal network interacts with various others in the brain by means of *collective* co-ordinates. The formation of the networks—clusters of various size groups—corresponds to events of *emergence* in a complex system, and the various collective co-ordinates are related to state variables of single neurons in an ever-changing and complex manner, typical of the phenomenon of emergence.

1. The single-neuron description of the entire brain is an impossibly complex one where the synaptic

connections of each single neuron (among tens of billions) to all the others are to be specified in terms of the respective strengths of connection (assuming that a 'strength' can be identified unequivocally), a non-existent connection being assigned the strength zero. Clusters, on the other hand, are described in terms of their internal connectivity (specified in statistical terms in the case of sufficiently large clusters) and the effective strengths of connection (once again, specified statistically for clusters of sufficiently large size) between them—these represent the collective variables mentioned above. While this results in a drastically reduced description, it is nevertheless a vastly complex one in its own right. Adding to this complexity is the fact that the collective variables evolve in a stupendously intricate manner, and that the mesoscopic and microscopic clusters do not lend themselves to reduced description in terms of collective variables of the above type.

2. The process of emergence results from the interactions among the neurons and also from interactions with environmental systems such as the neurotransmitters, distributions of metabolic nutrients, the blood flow, and so on. These environmental interactions include the opening and closing of ion channels, the operation of ion pumps, and the diffusion of various chemicals through the neuronal membranes,

The self-organization process involves a non-trivial mix of neuronal populations of *all* size groups, from the microscopic clusters (roughly, less than a few millimeters; in this group we include single neurons in particular), through mesoscopic ones (several millimeters or more), right up to large scale or macroscopic networks (of the order of centimeters). For the purpose of this essay, we focus on these three broadly defined groups, keeping in mind that there are considerable overlaps between these. In particular, there takes place ceaseless transfer of neuronal populations into and out of all three of these.

Processes involving these three groups of neuronal clusters are marked by broadly distinct time scales too. Generally speaking, the microscopic clusters evolve on the fastest time scale, the mesoscopic processes are comparatively slower, while those describing the evolution of the macroscopic clusters are the slowest.

Among these, operations of the *mind* mostly involve the large scale ('macroscopic') neuronal networks interacting with one another, where these networks are close to criticality, as a result of which they keep on changing their configurations and their mutual connectivity patterns, exhibiting an exceptional degree of plastic fluidity. This is in keeping with the proverbial fluidity of the mind itself.

However, the microscopic and the mesoscopic neuronal populations continue to play covert roles in the operations of the mind since all these are involved in the ongoing intrinsic activity that never ceases in the process of setting up of correlations among dynamical excitation patterns created in the neuronal assemblies of diverse descriptions, where the patterns themselves are generated in the same ongoing process of intrinsic activity, continually getting ‘imprinted’ with signatures of endogenously and exogenously evoked activities in the brain. It is this vast set of evolving correlations that generates dynamic *models* of bits and patches of reality, based on which the mind anticipates and responds to this evolving and complex world of ours—signals received from the world are made use of in improving the currently existing mosaic of models generated in virtue of the ongoing intrinsic activity .

Various imaging techniques like the fMRI scans establish correlations relating diverse mental functions with activities of large scale neuronal networks. However, mental functions are not generated *only* by interactions among and resulting changes in the large scale networks, since there occurs significant participation of fluctuations in the mesoscopic and the microscopic neuronal aggregates too—such fluctuations remain poorly detected by the imaging techniques since these contain a large degree of uncorrelated components (ones that resemble random fluctuations) in addition to ones correlated on short space-time scales. Put differently, these do not generate easily identifiable coherent phenomenon like the familiar brain waves.

7.2 The structured mind and its substratum

Reality at large is the *ultimate* in complexity. The human brain, which is but a tiny part of it is enormously complex. And the mind, which is an emergent property of the brain, is vastly complex too—in function and in structure. It is made up of the unconscious and the conscious layers of activity (refer back to sec. 5.2)—among the two we can be aware of only our conscious thoughts and actions. However, they merge continuously into each other and make use of overlapping sets of ingredients (sec. 5.3; it may be mentioned, though, that reasoning and logical discourse are predominantly in the terrain of conscious thought).

Both the conscious and unconscious minds make use of the entire repertoire of large scale neuronal networks operative at any given point of time, but the two differ in the way they invoke these networks. While the unconscious processes of the mind involve most of the networks operating jointly—mostly in parallel while, at the same time, communicating with one another—the conscious processes are enacted under a condition of partial deactivation of many of the communicating pathways, with the remaining ones interacting strongly, predominantly in a serial sequence. A conscious mental process always needs a 'preparation' realized by way of unconscious activity—what is more, the partially deactivated networks mentioned above are held in readiness to assist a consciously enacted process whenever the serial approach, based on the 'logic' of the excluded middle and making use of explicit and unique representations, faces an impasse. This happens when the mind faces a *decision juncture*, as is the most common thing in our journey through life.

> The 'representations' referred to above may pertain to inferences, plans, predictions, or diagnostics of parts of reality.

Thus, in a sense, the conscious springs from and is rooted in the unconscious, which is why the latter can be referred to as the 'substratum of the conscious'. However, the unconscious can be said to have a 'substratum' too, namely the spontaneously developed processes in the mesoscopic and the microscopic neuronal aggregates in the brain—these constitute the terrain in which the divide between the mind and the brain becomes blurred. In this essay, we call this terrain the 'proto-mind'.

Just as the unconscious mind prepares the ground for the conscious processes to be realized in, so does the proto-mind prepare the ground for the unconscious mental processes to play out their act. And, this it does by way of making up patchy models of parts of reality, by way of establishing correlations between dynamic excitation patterns generated in neuronal aggregates of multifarious sizes. These excitation patterns bear the signature of 'impressions' of reality stamped upon patterns generated intrinsically and incessantly, independently of perception or experience.

In particular, spontaneous activity in the brain prepares the ground for the emergence of the *self*. More specifically, the proto-mind generates the *proto-self*, the foundation on which the self resides.

7.3 The proto-mind and the proto-self

From a fundamental point of view, the self is made up of everything that distinguishes an individual from all that the individual is not. When we find something common in a group of individuals like, for instance, their political views or their views about the family or, say their behavior toward helpless and wretched people around them, our mind actually *ignores* their individual differences—the ability of the mind to detect similarities fundamentally depends on this capacity to ignore which, in turn, involves the weakening of relevant sets of neuronal interconnections on being triggered by endogenously generated cues. Indeed, our perception *always* involves the blurring of details since it is never endowed with an infinite resolving power. It is the blurring of individual and specific differences that lies at the root of similarity detection and category formation—of course, the association between elementary percepts (which is nothing but an instance of correlations) plays its seminal role here.

However, the self is commonly understood from a narrower point of view (refer back to sec. 5.3): it is built around the axis provided by our *affect and emotions*. It is primarily generated within the unconscious mind but eventually gets expressed in the conscious mind too. Our preferences, emotion-laden perceptions and thoughts, beliefs, fantasies, cravings and yearnings, guilt feelings, moral attitude, conscience, repressed agonies and ecstasies, privately formed plans and intents, all contribute to the formation of our selves. All these are ultimately based on *psychological valuation*—all that pertains to what we value and prefer in life.

The broader description of self, on the other hand, is neutral toward valuation and preference. It relates to all that makes an individual different from other persons and objects. The difference between two individuals is cumulatively generated through the minute and intricate differences in their life histories. The life history is a vast storehouse of all that is specific to an individual—it unfolds with scant regard to the way she values, judges, and attaches preferences to events and experiences in her life. And, the *details of life history is fundamentally and predominantly etched in her proto-mind* in the form of myriads of dynamical excitation patterns resulting from the innumerable signals received from the world (generated endogenously and exogenously) being 'imprinted' on patterns begotten by spontaneous neuronal activity.

> Recall that the 'imprinting' is, in the main, the result of complex interactions between oscillatory rhythms (refer back to sec. 4.7), instances of such interactions being provided by phase locking and phase resetting.

The process of self-organization of neuronal assemblies and of dynamical excitation patterns proceeds through innumerable *instabilities*, associated with *sensitive dependence on context* (refer back to sec. 2.2). As mentioned in sec. 6.6, this enormous variability of the course of self-organization is responsible for the inter-personal variability in the way various individuals respond to the world, though their overall patterns of response appear to be similar. This response is made up of two parts—one pertaining to the psychological valuation-based preferences of a person (anchored in her affect system in the brain) and the other largely valuation-neutral, generated by the vast and evolving set of correlations in her proto-mind. This valuation-neutral response pattern specific to an individual constitutes what may conveniently referred to as the *proto-self* (this idea of the proto-self is distinct from the one to be found,for instance, in [19], though there presumably lurks a link between the two).

One finds glimpses into one's valuation-based psychological self in the activities of her DMN—indeed it is the DMN where the self meets the non-self ([46]). In this context, it is important to note that the self is not something that is free of all contamination from socially shared perceptions and preferences. Indeed, the self may be said to have several layers within it where preferences and beliefs of diverse social groups get deposited on one's most private self that originates in her infancy.

> ”The self, however, has a layered structure. An individual generates preferences (and aversions), beliefs, and modes of reasoning (we refer to these—

> along with her desires, drives, and loathings—as psychological ‘resources’ or ‘ingredients’ of the mind) that have diverse origins in virtue of her membership to various social groups such as the family, circles of friends, colleagues at the workplace, like-minded political groups, and people sharing the same culture and religion. Ultimately, all these preferences get deposited on her self as so many layers in her repertoire of psychological resources, constituting her ‘self’ that segregates her being from the non-self part of her world. All these layers in the self generate a spectrum whose parts have varying degrees of ‘self-ness’—for instance, an individual may have only a very weak affiliation to a religious faith, in which case there may be only a weak linkage of religious faith to her self.” ([26])

Likewise, the valuation-neutral proto-self is also an intimate mix generated by neuronal correlations resulting from experiences gained without any contamination from socially acquired inputs and those that do result from our social interactions. While it is difficult to segregate the two, they are distinct aspects of the proto-self nevertheless. For instance, it is this distinction that enables us to recognize that the gait of a person engaged in walking resembles that of others in his family but is still specific to him.

In a sense, the self versus non-self distinction among the correlated excitation patterns in the proto-mind provides the basis on which the corresponding distinction in the unconscious and the conscious minds gets realized, though constrained now by a narrower criterion, namely, one relating to the axis provided by affect and emotions.

Analogously, one can speak of *memories* too.

7.4 Memory hinterland: microscopic and mesoscopic neuronal populations

Memories do not reside exclusively in the mind—they are distributed throughout the proto-mind as well, in microscopic and mesoscopic neuronal populations. The validity of this seemingly wild statement rests on a broad definition of memory: ”*memory is* *the way past events affect future function*" ([38]). In this broad sense, the imprinting of intrinsically generated neuronal excitation patterns with endogenously and exogenously evoked ones constitutes memory since this process of imprinting prepares a dynamically evolving model of the world, on the basis of which the brain anticipates and responds to subsequent signals received from it.

> We recall, once again, that the 'imprinting' is, in the main, the result of complex interactions between oscillatory rhythms (refer back to sec. 4.7), instances of such interactions being provided by phase locking and phase resetting. The wave forms of the excitation patterns generated intrinsically before the process of imprinting are altered only minimally by that process.

The imprinted patterns constitute tiny bits of memory defined in the broad sense indicated above, and are subsequently 'bound together' to constitute coherent representations of patches of dynamically evolving reality. It is this binding together of excitation patterns of an atomic nature that constitutes one instance of the process of setting up of *correlations* among neuronal populations (refer back to sections 4.3 and 4.4). It is a plausible hypothesis that the initial bits of representation are generated in microscopic and mesoscopic neuronal populations, whereafter the bound representations involving progressively larger chains of correlated bits are distributed over hierarchies of neuronal aggregates, ending up with macroscopic ones commonly associated with memory location and retrieval. It is equally compelling to postulate that the microscopic and mesoscopic populations mentioned above are distributed throughout the brain, and are likely to be nested within the known memory networks. In other words, the large scale memory networks (the hippocampus, for instance) are recruited in the storage and retrieval of large chunks of correlated and meaningful information that represent reasonably well defined pieces of experience.

Put differently, the known memory networks act more as *catalogs* of stored bits of information, holding the keys to enormously large numbers of smaller bits of an atomic nature rather than those bits themselves, the 'keys' being precisely the associations and correlations among these atomic bits.

> The terms 'atomic' and 'bits' are used here as convenient ones to denote tiny and elementary pieces of information represented as neuronal excitation patterns.

Thus, the proto-mind is seen yet again as the hinterland, providing the substratum to what is commonly referred to as memory—in keeping with our practice in this essay, we refer to this precursor as our *proto-memory*. More generally, precursors of recognizable mental activity are to be found scattered far and wide across, perhaps, the entire brain. Finally, we look at another mental activity commonly thought to occur, in large measure, at the fringe of consciousness, or even at the borderline of the unconscious mind.

7.5 Intrinsic activity in unconscious perceptual decisions

Decision making is, perhaps, the most basic mental process that one needs in order to navigate through the uncertainties in life. Decisions are made by an individual at several levels. Thus, *rational* decision making makes use of widely accepted logical, analytical, and computational methods invoked under the spotlight of *reason*, where one eventually engages in an optimization procedure. However, in real life, most decisions are made with quite glaring deviation from this approach, where biases, preferences, and beliefs that are scantly shared with larger sections of people, play important role—in other words many of our decisions are made on the basis of deeply *self-linked* or privately held preferences and beliefs. In other words, decisions can be reason-based or affect-based, with a spectrum lying in between, where the two are intimately intertwined. The more a decision makes use of affect and emotions, that much more the underlying activity leans on unconscious mental processes.

In the reason-based approach to decision making, the basic requirement on the decision to be arrived at is that of being 'right or wrong', accurate or inaccurate ('optimum or not', 'reason-based' or not). In the affect-based variety, on the other hand, the criterion is 'desirable or undesirable', i.e., a psychological valuation oriented one ('good or bad', 'gratifying or distressing'). Both these two types are realized in large-scale neuronal networks responsible for conscious and unconscious processes, though the underlying latent role of smaller neuronal populations remains ubiquitous.

However, there remains a *third* variety of decision making, namely the *perceptual decisions*—ones where preferences or beliefs play little role, to say nothing of reasoned mental processes.

For an introduction to the vast literature on perceptual decisions, refer to [16]

In particular, we will be interested here in perceptual decisions arrived at below the level of awareness. While absentmindedly navigating an uneven terrain, a person takes successions of steps regardless of whether those are psychologically preferred over other possibilities of placing the steps—indeed, 'other possibilities' are not even remotely considered either consciously or unconsciously. What seems likely is that the 'substratum of the unconscious', made up of mesoscopic neuronal populations in this case, help in the formation of the 'decisions', while smaller neuronal conglomerates continue to play a subservient role in what is essentially a hierarchical process.

One of the key criteria invoked in the setting up of correlations between neuronal excitation patterns, whether in large or small populations of neurons, is that of 'success or failure', which is clearly different from, or complementary to, what were described above as 'desirable or undesirable' and 'optimum or not'. *In past experience, the baby once stumbled while crossing the threshold of the room. That's why she raises her foot high while crossing it this time.* If this act be described as one involving a 'decision' (raising or not raising the foot high, and exactly how much to raise), then that decision is the result of a small bit of excitation pattern in what is most likely to be a mesoscopic neuronal population, one with some kind of a 'success or failure' tag attached (a tiny bit of 'model' of a part of reality), which makes the baby raise her feet this time as she is poised to cross the threshold.

Such decisions can be said to have been made by invoking elementary *heuristics* of an atomic nature. A huge repertoire of heuristics is lodged in the mind of every individual, and a constant and prolonged devotion to some particular field of activity results in a remarkable augmentation of the store of heuristics—the latter can be described as half-formed beliefs invoked routinely and often unconsciously in embarking on an action. Generally speaking, heuristics are formed on the basis of 'past success or failure', and heuristics of the most elementary and atomic nature relate to smallest bits of experience (such as placing a step in crossing a threshold at the door), in which past success or failure is associated as a tag with the excitation pattern resulting from it, where that pattern is likely to reside in a small neuronal population, and not in a large scale network typical of heuristics and beliefs made up of a relatively large number of components.

Compared to beliefs made up of a large number of conceptual components, heuristics have a high turnover rate and are relatively free of emotional ties. As mentioned, they are formed on the basis of success (or failure) in past actions and help in the making of decisions that depend on the criterion of 'success-or-failure' in the past and not on psychological valuation ('desirable-or-undesirable') or reason ('optimum or not'). Among these, the heuristics responsible for unconsciously made perceptual decisions are of an atomic type, associated with elementary excitation patterns (tagged with the neuronal equivalent of 'success' or 'failure') generated within the proto-mind, the substratum of the unconscious.

> It may even be the case that the experience of stumbling at the threshold need not necessitate a 'failure' tag for future evasive action—just a representation of the event of stumbling may be sufficient to make the next crossing quite safe and unremarkable.

A decision implies a choice among 'alternatives'. It is a plausible hypothesis that, in neuronal terms, this corresponds to a shift of the underlying neuronal processes from one set of neuronal networks to another.

Digression: what constitutes a decision?

> The issue of the mind adopting a decision is a deep and complex one. At any given point of time the myriads of dynamical patterns generated in neuronal networks, large and small, constitute so many fragmentary *models* of the dynamically evolving reality that the mind ceaselessly encounters. As it goes through a new bit of experience in the course of that encounter, it is generally the case that the complex mosaic of models in the neuronal assemblies, aided and abetted by the excitation patterns resulting from the new experience,

generate our behavior, i.e., seamlessly determines how we act back on reality. In other words, the proto-mind or the mind does not ordinarily face a juncture and make a choice as to which course to adopt among possible alternatives. Such a juncture appears only if the set of currently existing models generated in some particular set of neuronal aggregate fails to determine unequivocally the subsequent course of action. At such a juncture a 'search' is initiated in some *other* set of networks (even microscopic and mesoscopic networks are made of hierarchies of appropriate size groups), so as to find a suitable response that the mind needs.

For instance, in the course of reasoned response to the world (*drawing up the budget of a large business enterprise*) things may proceed smoothly till there occurs some juncture where the approach of rational optimization of resource allocation may prove to be ineffective (*how will a major competitor decide in respect of some particular upcoming line of production?*). This is where the board of directors takes a break and invokes *speculative beliefs* in coming up with a 'decision'—these beliefs are generally not well-reasoned ones and in recruiting these, some new set of neuronal networks (in, say, the brain of some member of the think-tank entrusted with the job) is brought into operation.

Commonly, we tend to proceed in our inferential and decision-making acts by making use of *socially shared* beliefs that may or may not be fully justified against available evidence. However, it is a common occurrence that these beliefs do not prove adequate for the inferential process to come to a conclusion. We then enter into the domain of *personally held* or *self-linked* beliefs, i.e., ones with a lesser degree of justification, on the basis of which we try to go ahead with the inferential process which now becomes an inductive one—fallible, but still of value.

Our inferences and decisions need the relatively solid support of shared and

> justified beliefs, and as our mind fails in providing these, at least in some measure, we fall back upon beliefs of lesser credentials, while we still see to it that those satisfy the requirement of 'past success' even though the 'success' itself turns out to be a matter of belief. This shifting of ground, when looked at from the neuronal perspective, means that the inferences and decisions are now based on different sets of neuronal aggregates, among which some may be mesoscopic or even microscopic ones. In other words, the arena of neuronal activity eventually shifts to the one corresponding to the proto-mind where psychological valuation or reasoned optimization holds no meaning. However, 'past success' and 'past failure' still remain meaningful in the form of neuronal excitation patterns constituting *models* of the evolving world, i.e., as snapshots of ongoing experience. And, at this level of neuronal hierarchy it becomes more and more difficult to distinguish between seamless processes based on massive correlations set up in the proto-mind and ones where the proto-mind takes a pause at facing an impasse and the neuronal process gets shifted to some different layer in the hierarchy of neuronal aggregates within which the correlations are of an yet more elementary level.

Unconscious perceptual decisions can often result in 'spontaneous action'—voluntary action initiated spontaneously. While the neuronal mechanism underlying such spontaneous action has been a subject of investigation for long, it appears that the neuronal trigger originates in small neuronal populations or even in single neurons ([15]).

7.6 And now: a few lines of summary

This is where I must put an end to this essay of mine, since it is already too speculative to feel comfortable with. I have stuck my neck out too far—and am now waiting to find it chopped off. But before that, here's a summary that may not sound so wild after all, if only because it is appropriately vague:

> **The** intrinsic activity of neurons in the brain results in an ongoing process of self-organization that gives rise to a hierarchy of neuronal assem-

blies where, moreover, these are nested within one another and are in a state of ceaseless flux—their neuronal content, topography, and interconnections keep on changing, giving rise to eternally mutating *mental* processes. Mental activities—including psychological ones—of various distinct types correspond to neuronal processes predominantly confined to distinct groups of networks within the hierarchy, while bottom-up and top-down information transfer between these groups continues to take place all along. Excitation patterns in neuronal populations of diverse description constitute myriads of models of tiny patches of the evolving reality that we are embedded in, among which a vast mosaic of correlations is established by the intrinsic activity itself. Our journey in life consists of a continuing process of updating of these models, with fresh correlations ever being set up among these.

Within this scenario, decision-making of some particular type presumably involves the shifting of the terrain of occurrence of the relevant neuronal processes from one group of neurons embedded in the hierarchy mentioned above to some other group, corresponding to the operation of beliefs of a more self-linked nature, including valuation-neutral heuristics lodged in the proto-mind.

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