The network theory of mind

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Introduction: self-organization, complexity and networks

The world we live in can be thought of as one immense self-organizing matrix of interacting, interconnected and interdependent complex systems that co-exist and co-evolve on different spatio-temporal scales. On one scale molecules are self-organizing into cells, on another scale cells are self-organizing into organisms, on yet another spatio-temporal scale organisms are self-organizing into

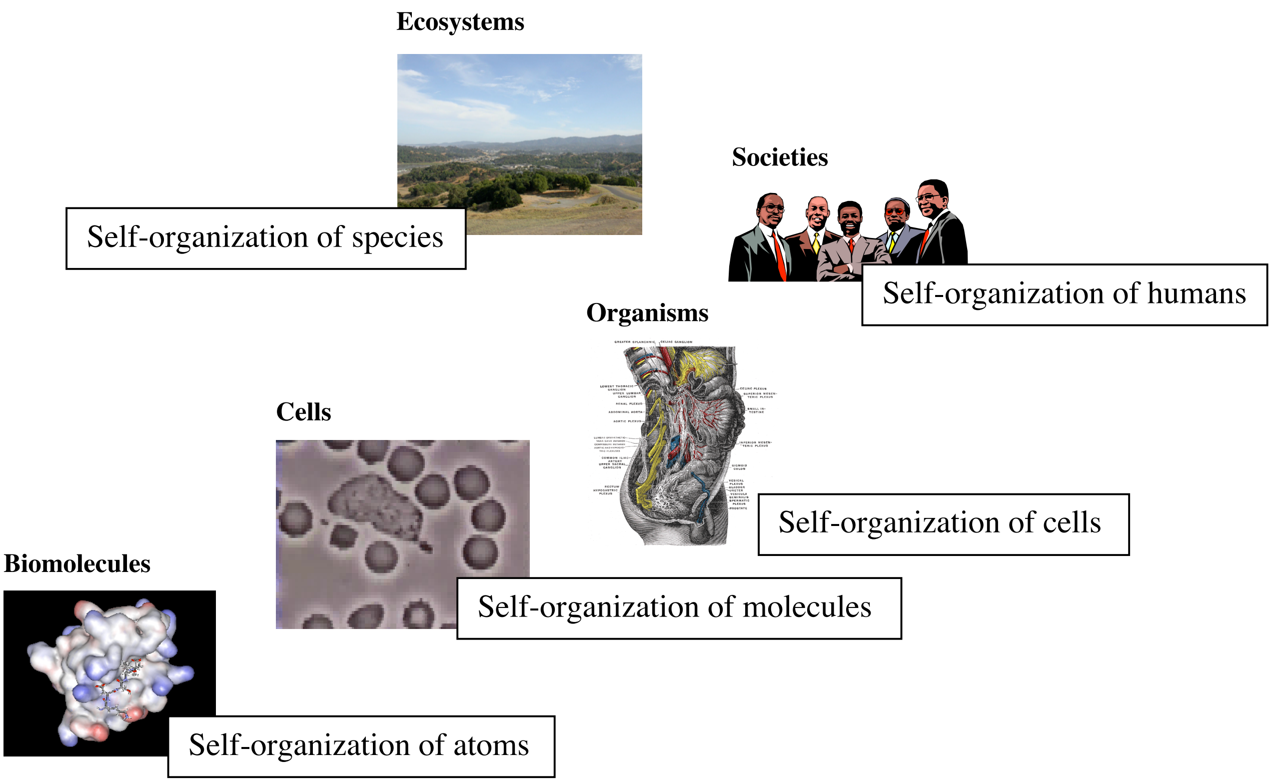


Fig. 1. The world as a phenomenon of self-organization.

organizations and ecosystems, and so on, up and down the scale. Until recently the complex systems of different scales have been considered in isolation and studied separately within the confines of specialized disciplines such as physics, molecular and cell biology, physiology, sociology, economics, ecology, etc. with no or little interaction or overlap between them. It is generally agreed, however, that there is one feature that is common to these different systems. They are all recognized as being "complex". What does it mean to be "complex"? The perception of complexity is a property of the Observer. The term "complex" may simply mean that at present we, the Observer, do not have appropriate and relatively simple concepts and models that are adequate enough to grasp essential characteristics of these systems and to predict their behavior and dynamics when we are practically dealing with them. Recently, physicists and mathematicians such as Steven Strogatz, Laslo Barabasi and others initiated a breakthrough in the conceptualization of complexity by suggesting that the representation of complex phenomena in terms of networks may provide a general and adequate approximation for understanding, modeling and study of biological and non-biological, as defined by conventional views, systems.

Each of the complex organizations shown in Fig. 1 and many others can be represented as a network, i.e. as an ensemble of nodes and connections between them. Think the brain as a network of interconnected neurons, the society as a network of people interconnected through their socio-economical interactions, the cell as a network of molecular interactions, and protein molecule as a network of interacting atoms. In addition to providing a general and unifying conceptualization, the formalization of complex systems in terms of networks has two important practical implications: 1) the power of mathematical analysis and computer simulation can now be readily applied to analysis and modeling of a wide spectrum of different nature complex systems, and 2) the network formalization, by providing a common language to different disciplines, has a great potential to become an efficient means for communication of the knowledge and methodology across borders of different disciplines.

The first fruits of this new conceptualization are 1) an awe-inspiring feeling of unity underlying the structure and dynamics of self-organizing systems of very different nature and 2) insights into the origin and nature of those emergent properties of complex system that stem from organizational structure of relationships between elements of the system and that are independent on nature of the components and links comprising the system. Let us consider briefly both of these fruits.

Thanks to computers, it is possible today to collect and analyze topological data for many naturally occurring networks such as Internet, airport networks, neuronal systems of simple organisms, networks of words in languages, protein interaction and metabolic networks of the cell, as well as various social and economical networks. It has turned out that many naturally occurring networks belong to one particular topological class of networks, which are called "scale-free networks". The scale-free networks are defined by the characteristic power law distribution of links between their nodes.

As an introduction to network description, let us consider two major classes of networks, random and scale-free networks (Fig. 2).

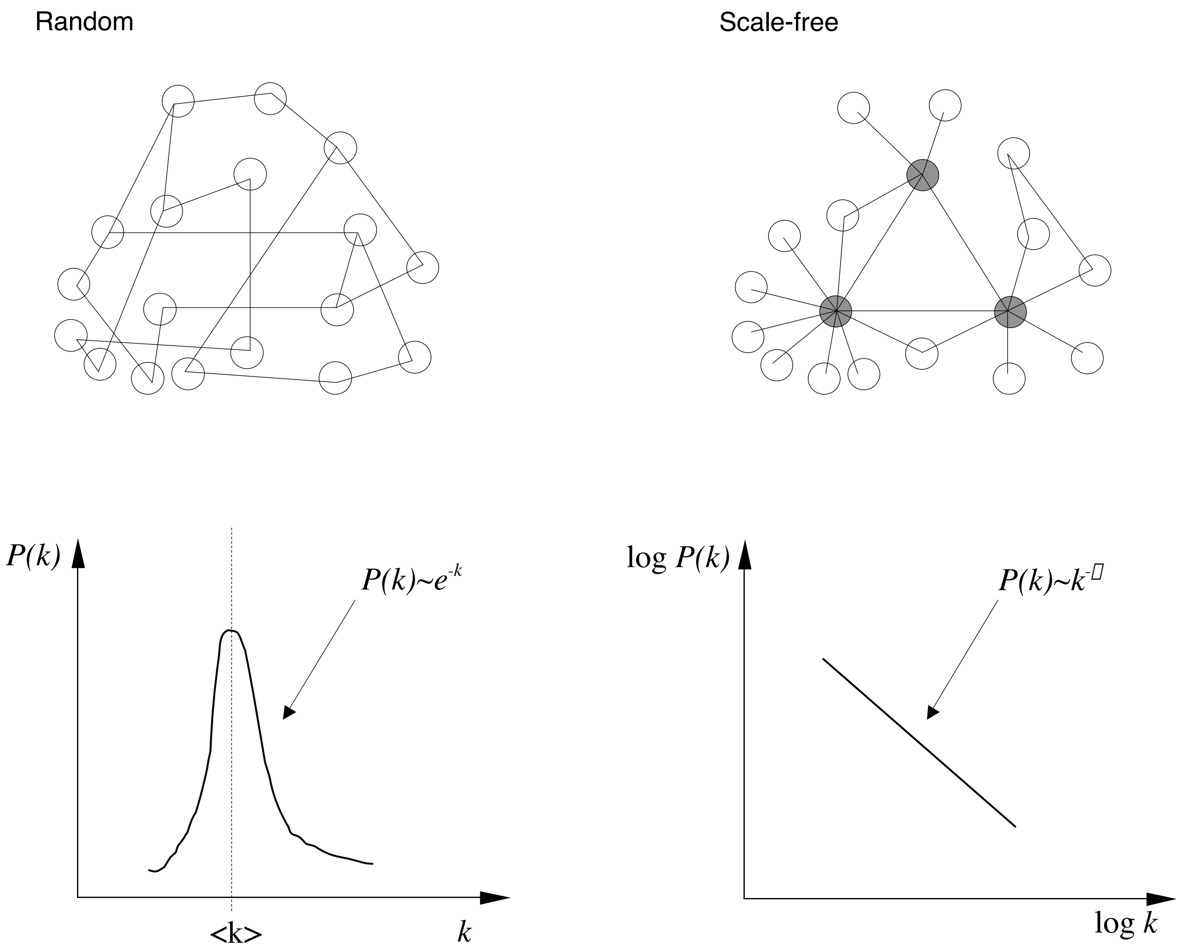


Fig. 2. Random and scale-free networks. The examples of random (left panel) and scale-free (right panel) networks are shown. Both networks have 18 nodes and 21 links. What makes a difference however is *the organization* of relationships between nodes. In the random network nodes have approximately the same number of links, making distribution of connectivities homogeneous. In the scale-free network contribution of hubs or highly connected nodes (colored grey) to overall connectivity of the network is dominating. *P(k)* is connectivity distribution, defined as the probability that a randomly chosen node in a network has exactly *k* links. For a given network *P(k)* is a fraction of nodes that have *k* links. For random network *P(k)* follows Poisson distribution – it peaks at average connectivity <k> and exponentially decays at larger *k*. In scale-free networks dominated by a relatively small number of hubs *P(k)* follows power law.

Adopted from Jeong H, Tombor B, Albert R, Oltvai ZN, Barabasi AL. 2000. The large-scale organization of metabolic networks. Nature. 407(6804): 651-4.

On the left side in Fig. 2 you can see an example of random network and on the right side an example of scale-free network. Both networks have the same number of nodes and links – 18 and 21, correspondingly. The nodes even have the same, relative to each other, spatial positions in both examples. What is different between these two networks is *the organization* of relationships or connections between the nodes. In the random network each node has approximately the same number of links. It is homogeneous in this sense. The contribution of any node to the overall connectivity of the network is approximately the same. The scale-free network, on the other hand, is characterized by very inhomogeneous distribution of links. There is a small but significant number of nodes that have many connections, while most of the nodes have very few links, implying that the contribution of highly connected nodes, or hubs, to the overall connectivity and thus to the function of the network is dominating, while the contribution of most of the nodes is relatively insignificant. The connectivity distribution is one of the mathematical parameters that can be used for classification of networks. If you have a complex system/phenomenon to study, you can often represent this system as a network, or an ensemble of nodes and connections between them, and analyze the connectivity distribution of this network. If it follows Poisson distribution (Fig. 2, left panel) your system or phenomenon can be approximated by random network models. If the connectivity distribution of your system obeys power law (Fig. 2, right panel), then it can be modeled as a scale-free network. In general, there are multiple types of networks, each defined by certain parameters such as connectivity distribution, clustering coefficient and others. Having properly classified your system or phenomenon, you can apply respective mathematical models to analyze the emergent properties of your system that stem from its organizational structure.

As mentioned before, it has come as a surprise that many natural networks are well approximated by scale-free network models. Why the naturally occurring complex systems tend to self-organize themselves into scale-free networks is not clear at present, but the power law connectivity distribution appears to emerge as one of the very few universal mathematical laws of life. It has been suggested that the scale-free organizational structure of natural complex systems is responsible for a number of common emergent properties that are shared by different complex systems. These properties are:

- *existence of hubs;*

Scale-free networks are characterized by a relatively small, but significant number of highly-connected nodes.

- *self-similarity (i.e. any part of the network is statistically similar to the whole);*

Scale free networks are called “scale free” because there is no characteristic scale in the network and any part of it is statistically representative of a whole.

- *a relatively small diameter (i.e. any two arbitrary chosen nodes, even in a very large network, can be connected via few other intermediary nodes);*

In reference to social networks this property is commonly known as “six degrees of separation”, meaning that any two randomly picked up persons on the planet can be connected via at most five intermediary acquaintances.

- *high degree of tolerance to random removal of nodes;*

Most of the nodes in scale-free networks contribute few connections each, thus a random removal of a few nodes in large networks is likely to affect overall connectivity of the network only insignificantly.

- *susceptibility to failure of highly-connected nodes.*

Tolerance to random failures comes at the expense of susceptibility to failure of hubs in scale-free networks. Informed removal of hubs rapidly fragments the system into many isolated "islands" and the system stops functioning as a whole.

Scale-free networks constitute a part of a larger class of networks called "small-world" networks, and thus share with the latter the following "small-world" properties:

- *combination of high global conduction (small diameter) with highly developed local structure (clustering);*
- *rapid propagation of information and energy in the network;*
- *rapid synchronization of distant nodes;*
- *enhanced computational power.*

The initial research efforts in application of graph theory to complex systems have been largely concentrated on the static aspects of networks, such as network representation of different natural and artificial phenomena, elucidation of topology of the corresponding networks and analysis of emergent systemic properties that result from a particular topology. However, life systems, as we know them, are not machines of a fixed design, rather they are dynamic self-organizing processes. Therefore the real excitement lays ahead of us in the future studies of dynamic self-organizing networks. There are relatively few examples of the network dynamics research at present, however the message that comes from the models being developed suggests that there is a remarkable similarity in the spatio-temporal patterns of organizational dynamics underlying evolution of many complex phenomena of very different nature, ranging from protein folding to evolution of the business organization and of ecosystems. Let us however move closer to the topic of the Conference - mind, psyche and the world. Here is my humble interpretation of what it is all about.

Mind-world relationship

Shown on the left side in Fig. 3 is a symbolic representation of the objective external world, which is a constantly evolving dynamic matrix of interacting, interconnected and interdependent complex systems that co-exist and co-evolve on different spatio-temporal scales. On the right side is a symbolic representation of our cognition, or our mind, which can be thought of as another ever-evolving complex system of interacting and interconnected perceptions, concepts, paradigms and emotions that represent the outside world inside us. In other words, one evolving system or process, our mind, is trying to make a proper representation or to model another evolving system or process, the outside world. Even assuming, for the sake of simplification, that the outside world is static, it is still so immense in its complexity that it would take an eternity for an individual human mind to achieve sufficient degree of sophistication that is required to comprehensively represent the outside world in all its minute details. Therefore, the

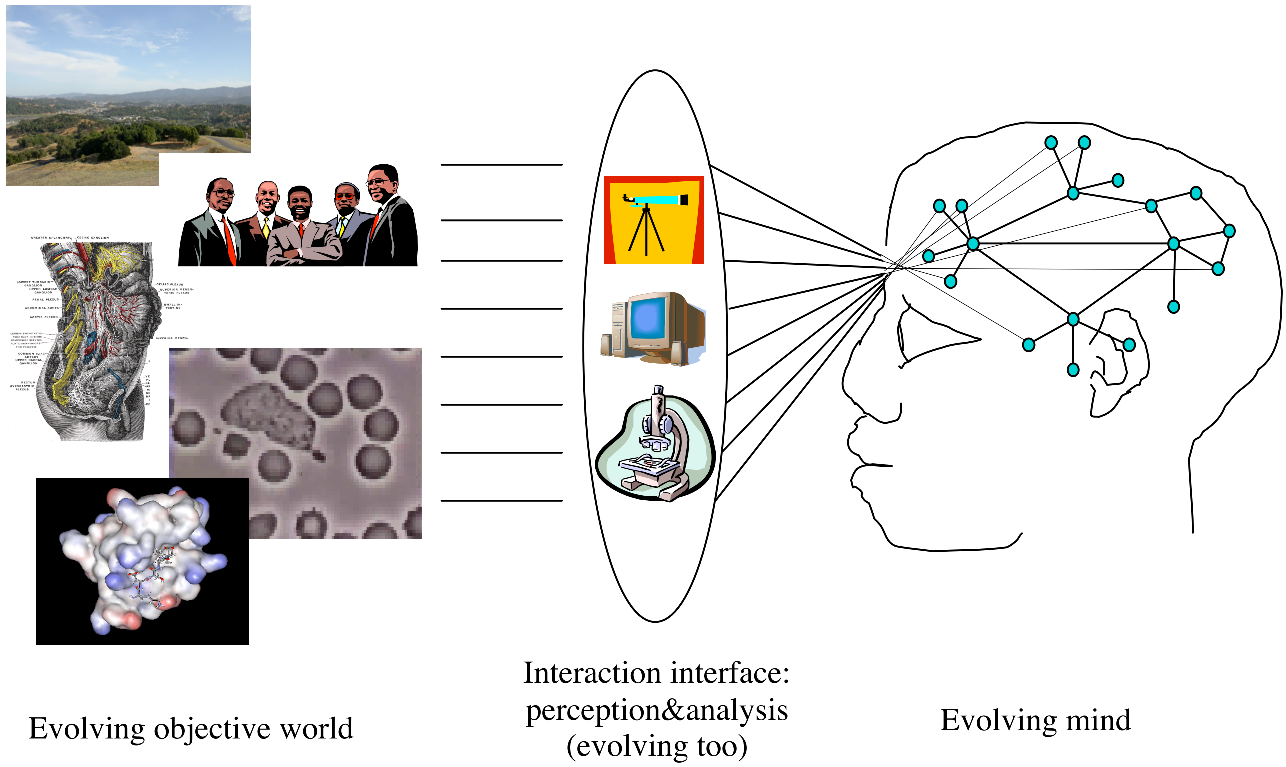


Fig. 3. Mind-world relationship. One process, evolving mind, is trying to create an adequate representation of another process, evolving objective world. Both the external world and the mind can be modeled as co-evolving networks that are coupled through perception/interaction.

individual human mind does its best. It generates during our short lifetime crude but progressively more and more adequate representations-models of the outside world as we acquire experience and mature. It is a chain of representations. One model becomes obsolete and inadequate with time passing and is replaced by a newer, more adequate one. The adequacy of any model of the reality is constantly tested through our interactions with the outside world. Every time we interact with the world, and we interact all the time except maybe when we are sleeping, we have a model of the situation and of the external world, even though we may not be aware of it. Our unconscious simulates a certain development of the situation in accord with this model. If the reactions of the outside world are anticipated by the model, there is no confusion or surprise, the model is adequate. If there is a persistent anomaly and unexpected reactions from the outside world, we tend to adjust our model or even discard the old model and replace it by a new one. The real situation is even more complicated. The outside world is constantly changing. Therefore, our mind generating a chain of progressively more adequate representations strives to do two things simultaneously: 1) to keep up with the changing world, through continuing adaptation and adjustment, and 2) to model relatively slowly changing aspects of the outside reality to a more and more precise degree.

It is worth mentioning at this point a difference between human mind and animal mind. The human mind, unlike the animal mind, is always embedded into and is a part of the collective unconscious or the human collective mind in the following sense. Imagine a fictitious living creature-animal that has a mind able to model the world. Let us plot along axis X the time and along axis Y the relative adequacy of the creature's world representation or the maturity of the creature's mind (see Fig. 4, left chart, box #1). Somewhere in the evolutionary past the first generation animal is born and its mind starts modeling the world. The creature through its unique experiences and interactions with the outside world builds up a better and more adequate model of the outside world as its life progresses (Fig. 4, left chart, red line in the box #1). With time passing our creature becomes old and wise, and then it dies.

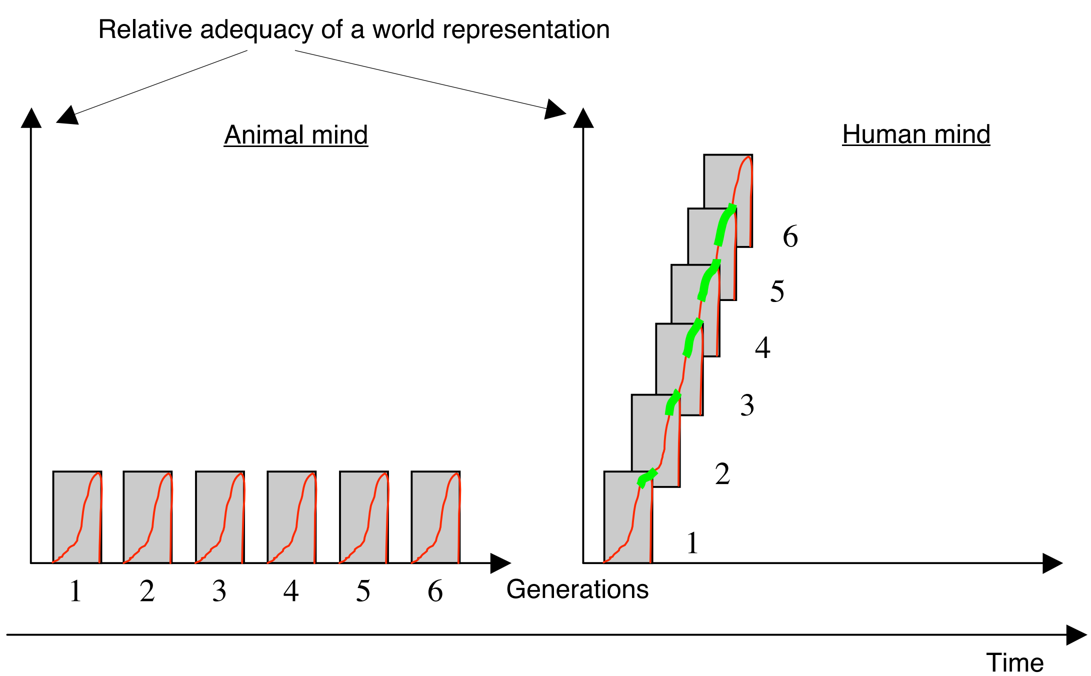


Fig. 4. Temporal evolution of the world representation in animals and humans. Organization of humans through cultural development into one collective unconscious permits for potentially unlimited improvement of the world representation being developed as a combined product of human culture and experience. The Y axis is the relative adequacy of world representation, the X axis is time.

The model dies together with the creature-animal. Its descendant, or second-generation creature, starts building the model of the world from scratch through its personal experiences as does the third generation creature and so on (Fig. 4, left chart, box #2, box #3, box #4 etc). In this scenario, the relative adequacy of the worldview remains primitive, never exceeding a certain level limited by the creature's lifespan and its experiences. That is how, in a crude approximation, the animal mind works. Probably for this reason our cats or dogs do not seem to be much smarter than cats or dogs which lived 100, 500 or 5000 years ago.

The humans, on the other hand, have developed a trick. They have invented language, culture, arts and sciences. Somewhere in the evolutionary past, a first-generation human mind, in the same manner as an animal's mind, develops a chain of more and more adequate models of the outside reality during the short span of human life. But the models do not die together with the first-generation humans. Instead, they are deposited outside the physical human beings as products of culture, arts and sciences. As language, writings, arts or skills that are passed by imitation. The second-generation human minds during their first, developing, learning phase (Fig. 4, right chart, thick green line) are formed and molded on the cultural template left by the first-generation human minds. During this early and relatively short phase they adopt and implant in their unconscious, uncritically and as given, the latest models of reality inherited from the previous generation. During the mature part of their lives the second-generation human minds, through their interactions with the outside world, test the adequacy of inherited worldview, adjust it or replace it altogether by second-generation models or paradigms of the outside reality. The improved models of the world are again deposited, as products of culture, to form the paradigm template for the third generation and so on. In this scenario, therefore, the development of a progressively more adequate model or representation of the outside world is dissociated from any physical human being, becomes independent of any individual and of the constraints and vagaries of individual human lives.

The development of human culture is conceptually equivalent to the development of the individual human mind, however it takes place on a much larger spatio-temporal scale. Propelled by individual developments of individual human minds that come and go in successive generations, the human culture as a whole builds up an increasingly more accurate representation or model of the outside reality.

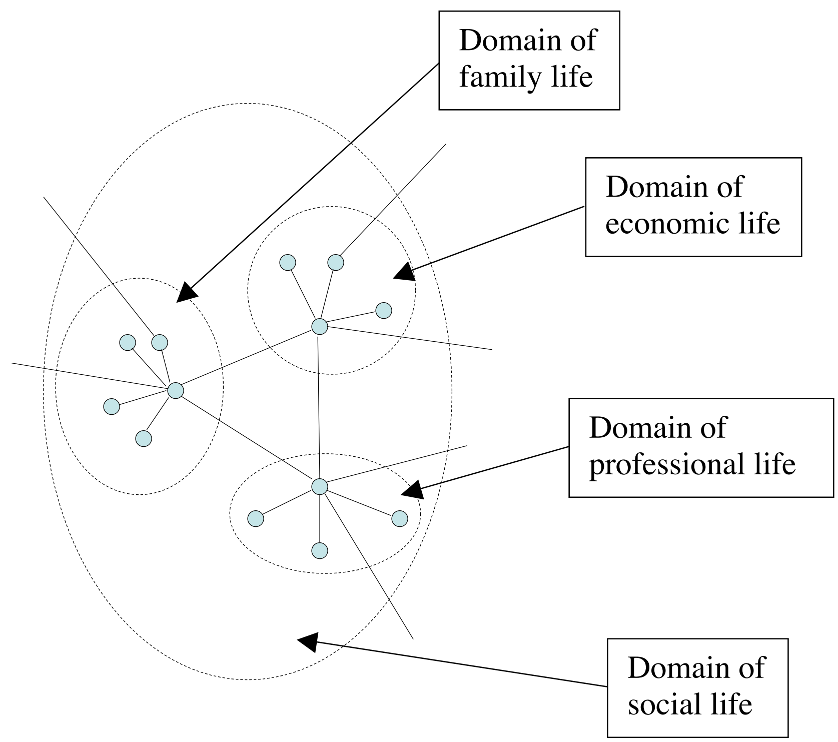
Mind as evolving network

Presented below is a model of how our mind is organized, how it develops and how it functions. It is by definition a hypothetical model, as all of them are and will be, and therefore should be taken as such. It is an approximation. One can test and decide for oneself whether this approximation is adequate enough by applying this model as a framework to structure one's own experience and knowledge.

Definition:

Mind is an evolving metastable system of interacting, interconnected and interdependent perceptions, concepts, paradigms and emotions, which reflects and at the same time creates the objective world as our subjective representation. It is both a substrate and an instrument for our analysis, decisions and actions directed towards the world. It is integrated and interconnected and, therefore, is *best represented as a dynamic self-organizing network of perceptions, concepts, paradigms and emotions. It is born with us, develops and evolves as we grow older and age.*

Consider example of a network:



The nodes of this network are our perceptions, concepts, notions and emotions. The links are relationships between them. The network shown has a structure of a system of interconnected domains or neighborhoods. Let us call the "domain" a set of tightly connected nodes and let us called the "paradigm" a set of nodes in the domain together with that specific organizational structure of relationships between the nodes that makes them a domain. Then we can talk about the domain of family life, the domain of professional life, the domain of economic life etc. Altogether they may constitute the domain of social life with its underlying paradigm, which is a more or less definite but at the same time ever evolving set of interrelated and interdependent perceptions, concepts, notions and emotions, and relationships between them.

Notice please the relativity of notions such as "node", "domain" and "network". We started to use these words in such a way that a system of tightly connected nodes we call "domain" and a system of interconnected domains we call a "network". But imagine an enormous beginningless and endless fractal-like network as one shown in Fig. 4. Then the notions we introduced, "node", "domain" and "network", can be differentiated only within a certain scale of observation. The same structure on one scale can be a node, but on the other scale it is a whole network and vice versa.

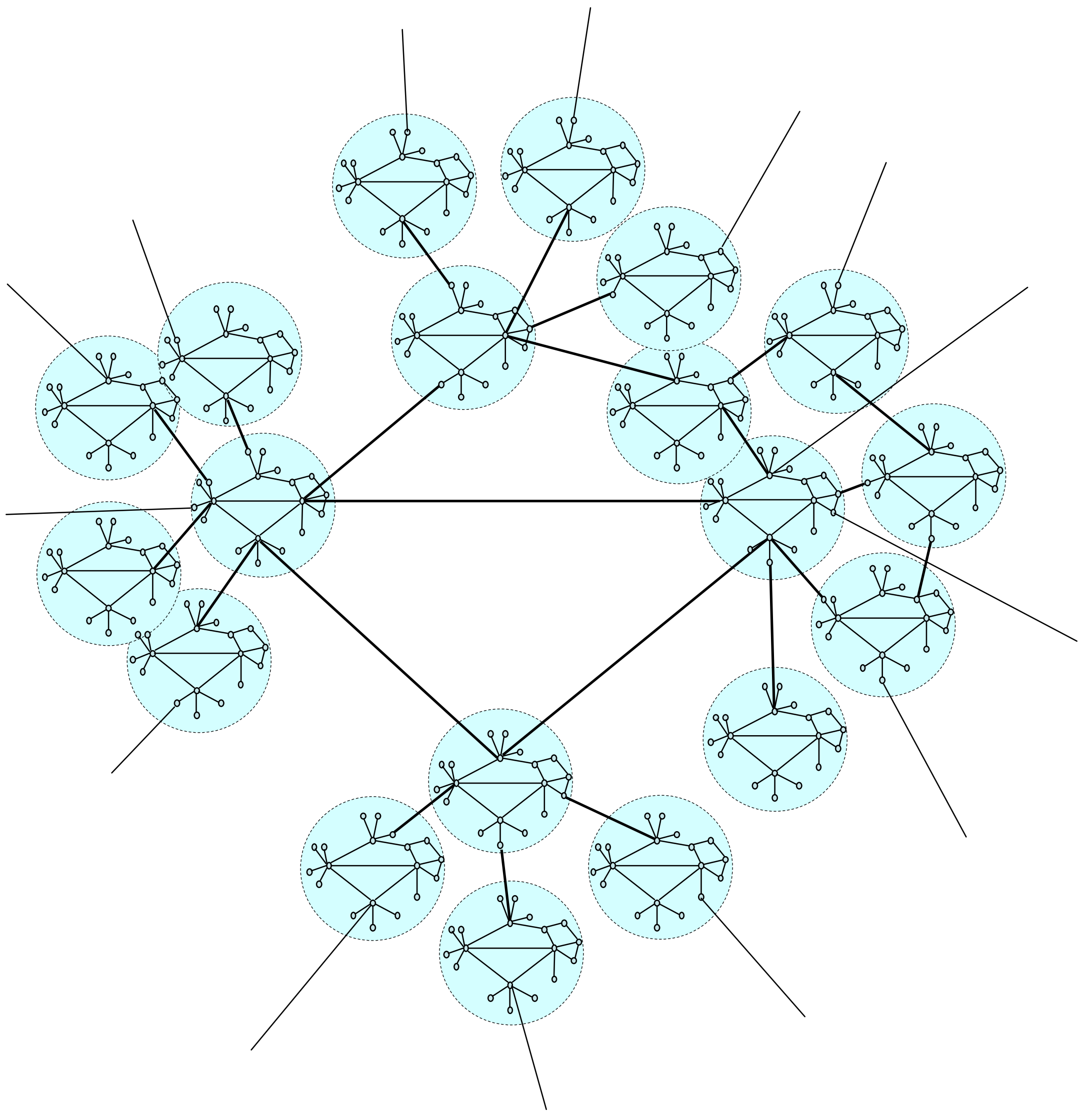


Fig. 4. Fragment of a beginningless and endless fractal-like network. Notions such as "node", "domain" and "network" are relative here and are defined only with respect to a certain scale of observation. The node on one scale can be the domain or the network of other scales and vice versa.

From perceptions to concepts and paradigms.

Let us consider how the mind network could emerge and develop. Assume, for the sake of simplification, that before the birth there was no structured mind network (Fig. 5, t=0). From the moment of birth on we are plunged into chaos of perceptions and information pouring from the external world through our sense organs onto developing molecular organizations of our brain and other organs of the body.

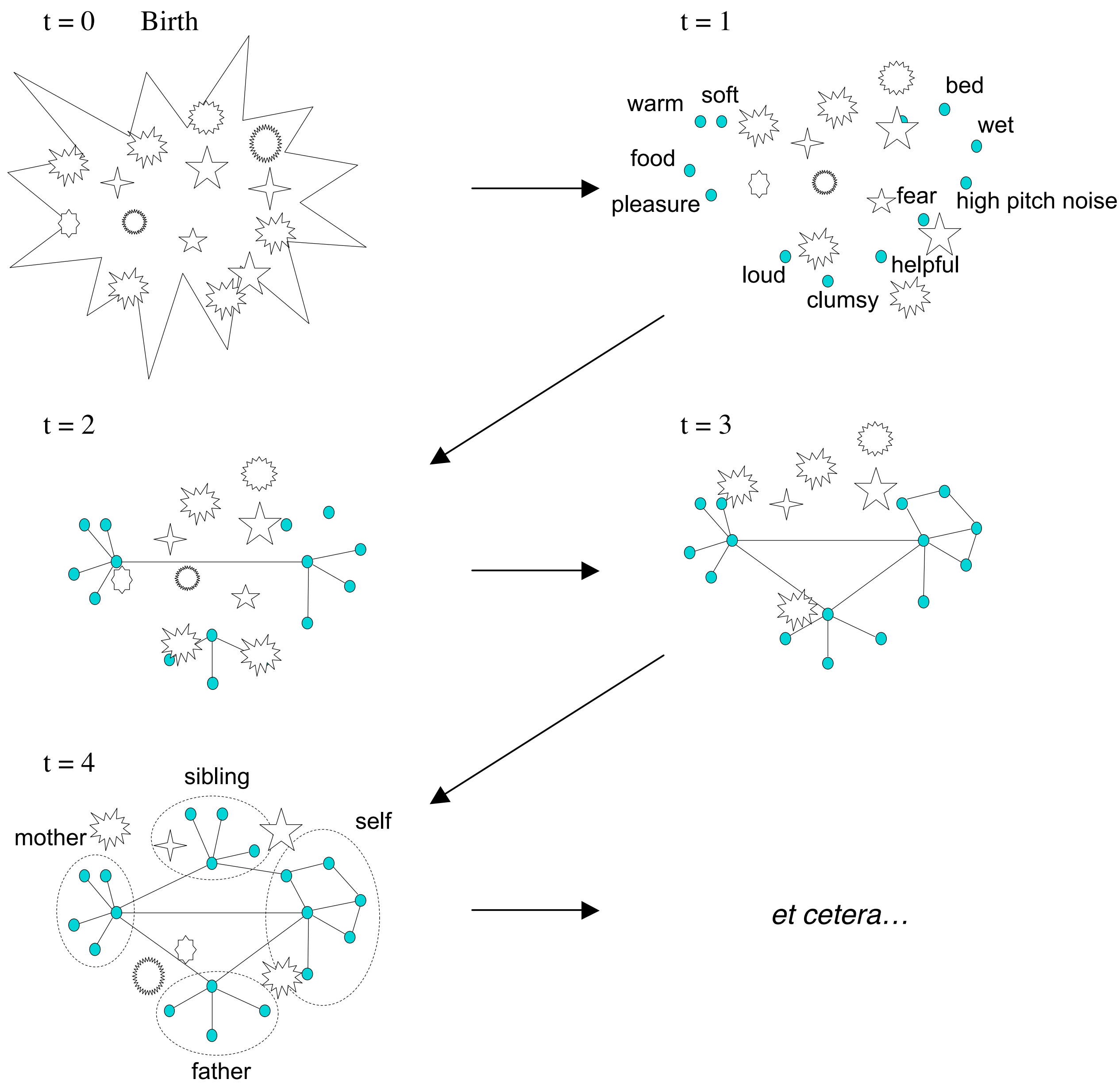


Fig. 5. From perceptions to concepts and paradigms. Schematic cartoon illustrates hypothetical scenario of how stable and/or repetitive patterns of external reality mold a chaos of perceptual activity of a newborn mind, igniting emergence and evolution of metastable mind network that models the outside reality. Stars symbolize chaotic activity of the mind, nodes of the network are perceptions, concepts and emotions, dotted lines delineate emerging domains.

Some of the perceptions or perceptual patterns are relatively stable or appear more frequently than others. For instance, consider perceptions of something that feels warm, soft and comfortable, is a source of food and pleasure. Each of those perceptions, being almost constantly present, may soon form a node of the virtual mind network and its respective physical correlate in the form of physico-chemical metastable molecular and/or cellular organization (Fig. 5, t=1). As the mentioned perceptions are synchronized, i.e. tend to appear simultaneously, they may give rise to a concept and, respectively, node of the mother, along with the wiring of appropriate connections (Fig. 5, t=2). First primitive and relatively undifferentiated, the concept/paradigm of mother and its corresponding node/domain/network will develop over time into a more complex and differentiated structure. The same is true for emergence and evolution of other concepts and paradigms (Fig. 5, t=3 and t=4). The general pattern is as follows. The chaos of self-organizing molecular and cellular activities of a newborn organism is gradually structured through interactions with the environment giving rise to ordered metastable molecular and cellular organizations, which are later connected into one integrated system, the mind network, that reflects or approximates the spatio-temporal organization of perceived aspects of the external objective world. The formation of those molecular and cellular organizations and the establishment of interrelationships between them can be represented, modeled and in the future hopefully simulated as a growing virtual mind network of interacting and interdependent perceptions, concepts, paradigms and emotions.

Properties of the mind network.

Though the properties postulated below refer to the mind, most of them represent in fact generic properties shared by many complex phenomena/system of different nature, where they may go under different names.

<u>Dynamics/metastability/evolution</u>

1. Connections and nodes are not constant. They may change and evolve during the course of individual life. Nodes may appear, disappear or be reconnected to other neighborhoods. Connections may grow stronger or weaker, appear and disappear;

<u>Interconnectedness/interdependence/"small world"/"butterfly effect"</u>

2. Domains are interconnected as within the same scale, so between different scales. Change in any node or connection may potentially affect structure of a neighborhood, higher-level domain or the whole system;

<u>Evolution and revolution/Gestalt switch/punctuated equilibrium/self-organized criticality</u>

3. Development of the mind network proceeds through the following main types of change:

a) *Evolution: neighborhood development – cumulative accumulation of small changes.*

b) *Revolution: Gestalt switch-like domain transition – large-scale structural rearrangement, paradigm shift.*

<u>Economics/optimization/adaptation</u>

4. Nodes and connections that are rarely used tend to weaken with the time. The frequently used ones are reinforced.

Consequence: no interaction with the external world goes unnoticed, without some change in our system of paradigms.

<u>The unconscious</u>

5. Most of the mind network operates unconsciously most of the time.

<u>Ying and Yang of paradigms/balance of plasticity and stability/the middle way</u>

6. The reality is always met by the mind with a pre-existing model of the reality upon interaction.

The pre-existing model constitutes the filter that selects experience on the one hand, and is being molded by experience on the other. It dictates our actions and is reinforced or changed according to the subjectively perceived success or failure of the interaction.

<u>Steady-state/metastability</u>

7. The mind network in its physico-chemical description is a self-organizing molecular system. Between transitions it exists as a steady-state organization, which requires and is maintained by a continuous flow of energy and matter passing through it.

<u>Environment/embeddedness</u>

8. Organization and functioning of every individual mind network is intimately linked to and in significant part defined by its cultural and physical environment. It is born from the environment, it is part of the environment and it is shaped by the environment during the process of mind development and individuation. It is always connected to and remains an organic part of the collective unconscious and objective physical world.

Every human mind is born into both the objective world and the integrated system of subjective collective unconscious. The last one can be thought of as ever-evolving network of interacting, interconnected and interdependent individual minds, which in themselves are evolving networks of perceptions, concepts, paradigm and emotions. Each newborn mind therefore sprouts from, is molded by, and is integrated within one collective mind network, influencing and being influenced by the collective unconscious.

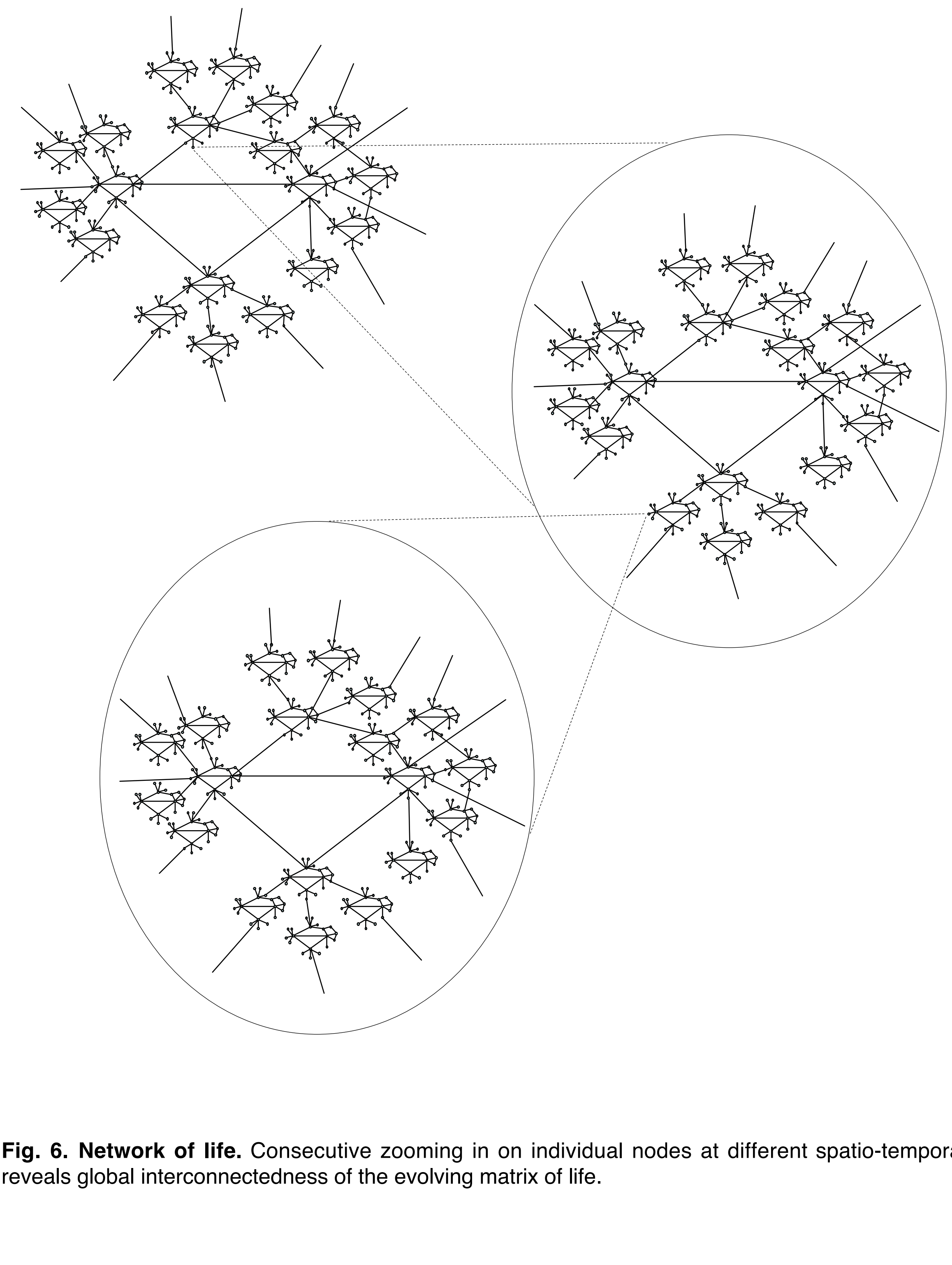


Fig. 6. Network of life. Consecutive zooming in on individual nodes at different spatio-temporal scales reveals global interconnectedness of the evolving matrix of life.

Consider the fragment of the beginningless and endless fractal-like network in Fig. 6 as a representation of the collective mind network. The nodes are individual human minds, domains are local or professional communities and larger scale networks are organizations and nation-states. The links are interactions of psycho-, socio- and economical nature between individual people. If we pick up individual node-mind and zoom in – it is a network in itself, in which the nodes are cells and the domains and larger scale networks are tissues, organs and the whole body, while the links are interactions between cells and organizations of cells. If we again pick up individual node-cell and zoom in further – the cell in itself becomes a network of interacting molecules and their organizations, where the nodes are individual molecules, the domains and larger scale networks are sub-cellular structures and organelles integrated through interdependent molecular interactions of physico-chemical nature. Therefore, life, when viewed through the looking glass of network conceptualization, emerges as nothing less but a process of self-cognition, which manifests itself on different spatio-temporal scales of observation as our familiar phenomena of socio-economical, biological, cellular, molecular and quantum nature.