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COMPLEX SYSTEM DYNAMICS

Fast and slow thinking – of networks

The complementary 'elite' and 'wisdom of crowds' of amino acid, neuronal and social networks

By Peter Csermely*

Complex systems may have billion components making consensus formation slow and difficult. Recently several overlapping stories emerged from various disciplines, including protein structures, neuroscience and social networks, showing that fast responses to known stimuli involve a network core of few, strongly connected nodes. In unexpected situations the core may fail to provide a coherent response, thus the stimulus propagates to the periphery of the network. Here the final response is determined by a large number of weakly connected nodes mobilizing the collective memory and opinion, i.e. the slow democracy exercising the 'wisdom of crowds'. This mechanism resembles to Kahneman's *"Thinking, Fast and Slow"* discriminating fast, pattern-based and slow, contemplative decision making. The generality of the response also shows that democracy is neither only a moral stance nor only a decision making technique, but a very efficient general learning strategy developed by complex systems during evolution. The duality of fast core and slow majority may increase our understanding of metabolic, signaling, ecosystem, swarming or market processes, as well as may help to construct novel methods to explore unusual network responses, deep-learning neural network structures and core-periphery targeting drug design strategies.

Complex systems may have an extreme number of components (called nodes in their network description), where consensus formation becomes extremely slow and difficult. This may be one reason, why multi-node systems often develop a core of a few well-connected nodes enabling fast and efficient responses. Recently several overlapping stories emerged from various disciplines including protein structures, neuroscience and social networks (*1-5*), which extended György Buzsáki's concept (*3, 4*) on the 'fast minority' and 'slow majority' of hippocampus place cells. These studies show that fast responses to known stimuli involve a network core of a few, strongly connected nodes ('fast minority'). In case of a novel challenge, the network core may fail to provide a coherent response, thus the stimulus propagates to the periphery of the network. Here the final response is determined by a large number of weakly connected nodes (*1-5*; 'slow majority') mobilizing the collective memory and opinion, the 'wisdom of crowds' (*6*). This two-tiered adaptation mechanism resembles to the duality described in Daniel Kahneman's *"Thinking, Fast and Slow"* (*7*) discriminating fast, pattern-based and slow, contemplative decision making. In summary, recent advances imply that fast and slow 'thinking' characterize the adaptive responses of a large number of complex systems.

*Semmelweis University, Department of Medical Chemistry, Budapest, 1094 Hungary.
csermely.peter@med.semmelweis-univ.hu

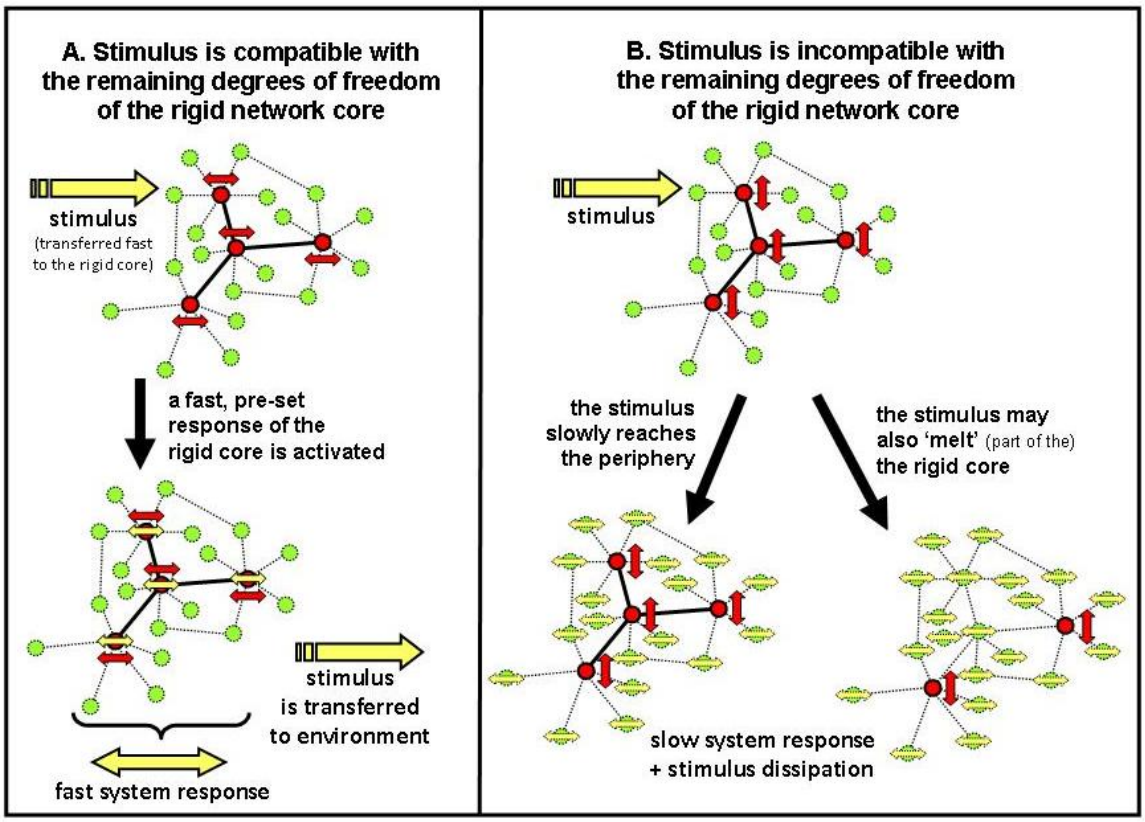
The first example of this two-tiered adaptation mechanism is centered on discrete breather amino acids of nonlinear elastic networks describing protein dynamics (*1*). These amino acids were mostly situated in the stiffest regions of their hosting proteins in close vicinity of the active centers and ligand binding sites. Energy received by the protein was efficiently concentrated on these nodes, and was transferred between them without the excitation of connecting protein structures (*1*). These results were supported by numerous experiments and simulations. Using femtosecond infrared laser pulses and ultrafast time-resolved infrared spectroscopy, a fast, anisotropic, ballistic energy flow was observed from albumin binding sites to the environment without heating surrounding alpha-helices. This energy transfer was followed by a slow, diffusive heat flow involving the entire protein structure (*2*). Protein structure networks seem to harbor a few amino acids playing a key role in energy transfer and dissipation. Their fast response is followed/refined by slower, diffusive processes involving the entire protein.

Pyramidal neurons of the hippocampus encoding spatial maps of our surrounding have a few highly active, fast-firing neurons. However, the majority of neurons are less active and slower. Learning of spatial representations emerges as a fast-matching and slow refinement process. A fast minority of neurons (which may also possess especially complex firing patterns) may be responsible for the recognition of a known environment, while the slow majority constitutes a large reservoir that can be mobilized to incorporate novel places as distinct. Fast-matching is often imprecise, which increasingly occurs, when experiencing new locations. In this latter case the refinement by the giant, weakly connected network of the majority of neurons becomes especially important (*3, 4*). According to recent data, this majority may also include neurons of the prefrontal cortex (*8*). Moreover, a recent study showed that much of the motor cortex may belong to the giant, weakly connected network involved in learning of novel motor tasks, while motor cortex lesions had no discernible effect on motor skills acquired before (*9*). Importantly, in memory retrieval the core of a few, highly correlated neurons acts before, and probably leads the emergence of correlated neuron pairs in the network periphery showing that the core indeed acts as an 'opinion leader' in known stimuli (*10*).

As an additional example, GABAergic inhibitory interneurons have parvalbumin- and cholecystokinin-containing basket cells. While the parvalbumin-containing cells form a skeleton of clockwork setting the synchrony of neuronal assemblies, fine-tuning is achieved by the cholecystokinin-containing basket cells synchronizing a larger network (*11*). A recent study showed that the core of 34 mushroom body output neurons, where the 2000 Kenyon cells of the *Drosophila* olfactory system converge, encodes various odours in a highly correlated manner. In contrast the peripheral layers of sensory input remain highly decorrelated (*12*). Additionally, whole-brain imaging indicated that task-related neuronal activation patterns often include an activity-shift from the majority of loosely connected peripheral neurons to the minority of a tightly connected core (*5*). Last but not least, as Kahneman described (*7*), fast thinking determines our actions, if we encounter a familiar situation. However, if an event occurs, which violates the model of the world encoded by the fast thinking system, the slow, contemplative thinking system becomes activated for a more detailed and more specific processing. Such a division of labor is highly efficient minimizing effort and maximizing performance (*7*). Thus, a number of current data (*3-5, 8, 9, 12*) show that the complementary action of the fast minority and the slow majority may characterize a large number of specific and general brain functions.

The third example is perhaps the most familiar situation of social networks. Well-known people know each other. This influential minority of the opinion leader social 'elite' forms coalitions establishing a tightly connected core of the social network (*5, 13*). Moreover, as a study of a representative sample of 1.3 million Facebook users showed (*13*), influential people are less susceptible to influence than others, making the fast-acting core relatively rigid. On the contrary, the collective opinion of James Surowiecki's proverbial *"Wisdom of crowds"* (*6*) is mostly provided by the loosely connected majority of the network periphery. If the elite fails to reach a consensus, and breaks to feuding factions, an uninformed, diverse majority exhibiting weak preferences may still restore the control of the democratic majority (*14*).

Besides the three salient examples mentioned before, adaptive responses of numerous other complex systems, such as 1.) the minimal gene-set related core *versus* the environment-dependent periphery of metabolic networks (*15*); 2.) positive *versus* negative feedbacks of cellular signaling (*16*); 2.) the specific *versus* general resilience/memory of ecosystems against identified *versus* surprising changes of the environment (*17-19*); 3.) the behavior of ant, *Drosophila* and fish colonies (*20-22*), as well as 4.) slow and fast bifurcation patterns of market regime transitions (*23*), may also be organized along the two-tiered mechanism of a fast-acting minority followed by a slow majority.



Network decision making. Stimulus is rapidly concentrated at the rigid core of the network (red nodes) due to the core's central position and large weight edges (*solid lines*). On ***Panel A*** the stimulus (*yellow arrow*) is compatible with the remaining degrees of freedom of the rigid core (*red double arrows*), and provokes a fast, pre-set, matching response (*solid line, yellow double arrows*) leading to the transmission of the stimulus to the environment. On ***Panel B*** the stimulus is incompatible with remaining degrees of freedom of core-nodes (*red*), reaches the network periphery (*green nodes*), and induces a slow, system-level, integrative response (*dashed line, yellow double arrows*), while getting dissipated. Here a collective decision of the whole network (the slow democracy exercising the 'wisdom of crowds') emerges. Mismatched stimulus may also generate a tension in the core decreasing its edge weights and rigidity. Complex systems may adapt with an initial, approximate, but fast response of their core, which becomes refined by the inclusion of the periphery later. If none of these solutions work, the adequate response may be discovered by another complex system of a diverse population. The emergence of fast and slow responses is also illustrated by three pairs of videos on a neural network and on social networks of network scientists and high school students downloadable from this web-page: http://networkdecisions.linkgroup.hu.

From these examples a rather general response-pattern of complex systems emerges. A fast-acting network core provides responses pre-set by previous experiences. If the core fails to reach a consensus, a majority of weakly linked, peripheral nodes generates novel responses. The consensus of the core dissipates the stimulus fast to the environment. If the stimulus is from a novel, unexpected situation, a conflict may develop between the stimulus and the constraints previously encoded by various segments of the rigid core. In such

situations none of the encoded responses (appearing as attractors of the original network configuration) becomes stabilized, and the system fluctuates between these attractors remaining unstable. In this latter case the stimulus will propagate to the weakly connected, peripheral nodes, and a collective decision of (practically) the whole network, the "wisdom of crowds" stabilizes the system allowing a slow (but creative) dissipation of the stimulus. This mechanism may contribute to the stabilizing "strength of weak ties", which was first described in social networks by Mark Granovetter (*24*), and was generalized to many complex systems later (*25*).

In case of a novel, unexpected stimulus, its slow dissipation may partially 'melt' the rigid core making the whole system more plastic. Increased plasticity helps to generate novel attractors or makes hidden attractors accessible. If the slow majority finds an optimal response/dissipation pattern, the same stimulus, if repeated, may modify the network (*via* Hebbian learning or similar processes) encoding a novel set of constraints. This makes the network more rigid again, reconfiguring its core ('electing new leaders') and enriching the system with a novel encoded response. Such plasticity → rigidity cycles characterize a large number of adaptive processes (*26, 27*).

Complex systems may adapt with an initial, approximate, but fast response of their core, which becomes refined by the inclusion of the periphery later. The mediation of initial core-responses and the development of refining whole-network responses may often be mediated by low-degree, influential nodes connecting hubs (*28*). A special, highly dynamic segment of these influential nodes was termed earlier as "creative nodes" (*29*). If none of the above solutions work, the adequate response may be discovered by another complex system of a diverse population.

The above generalization of the fast and slow decision making process is currently, in part, hypothetical. More experiments and simulations are needed to show how efficiently a stimulus is transferred from an entry point to the rigid, fast-acting network core. Note, that the fast-acting core may sometimes have an excessive number of constraints. This extreme rigidity of the core severely limits its portfolio of fast responses. Such 'super-rigid' cores reject most stimuli, and may seem 'purposefully slow', like the example of bureaucracies. Additionally, core and periphery nodes may not be readily discriminated or may even be shuffled. Such core/periphery fluctuations may be especially prevalent in the complex systems of neuronal and social networks (*5*). On the contrary, 'simple' systems, such as protein structures, may not be able to 'learn' novel responses, but reflect the constraints of previous evolutionary selection. On the other end of the spectrum, highly specified, engineered networks may often lack a multitude of different stimuli. Additionally, the “wisdom of crowds” (*6*) may be shifted to the “madness of crowds” (*30*) leading to widespread popular delusions. Creative nodes (*29*) may prevent such catastrophes. Further studies are needed to assess, whether cellular metabolism and signaling, ecosystem, animal community or market responses show similarities to the mechanism outlined in this paper. With all these limitations included, I hope that the network dynamic adaptation model described here will prompt further work in the field.

In conclusion, recent data indicate that the adaptive response of many complex systems first mobilizes a fast, pre-set response of a well-connected network core. If this fails, the stimulus propagates to the weakly linked network periphery, and a slow, integrative response of the whole system develops. This dual adaptive mechanism may increase our understanding of metabolic, signaling, ecosystem, swarming or market processes, as well as may help to construct novel a.) methods to explore unusual network responses; b.) deep-learning neural network structures; and c.) core-periphery targeting drug design strategies (*26*).

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