Physics of Life Reviews 31: 28-31, https://doi.org/10.1016/j.plrev.2019.01.023

Mind as a shadow of neurodynamics.

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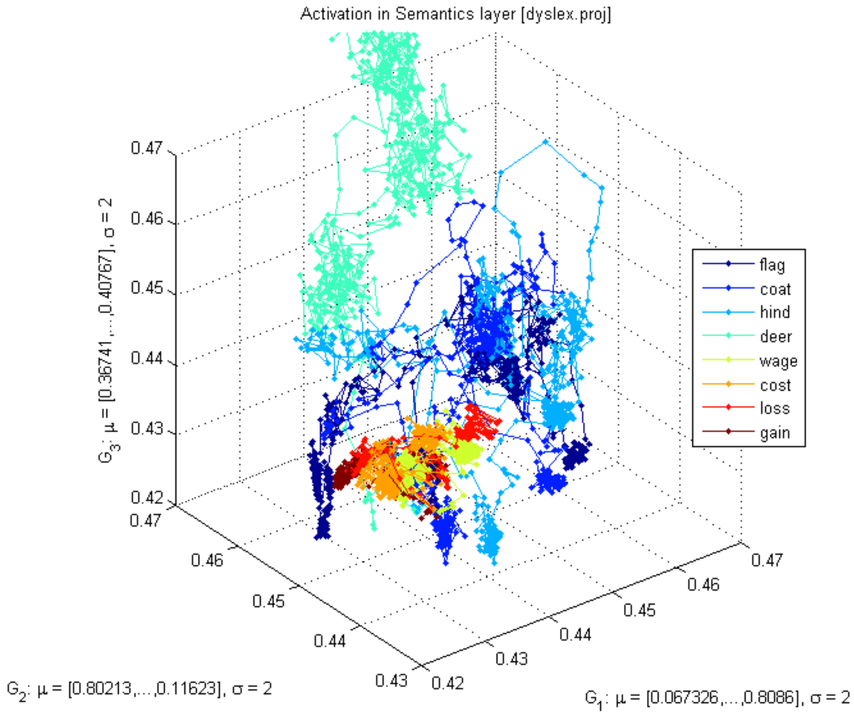
The laws of physics describe processes that govern behavior of matter. Physics of mind should describe processes that govern mental events. Attempt to use physics ideas in psychology have a long history, starting with psychophysics in XIX century. Kurt Lewin introduced field theory and topological ideas to social psychology, leading to the development of Gestalt approach, avoidance conflict model, personality psychology, and more recently Decision Field Theory and Discrete Process Model (DPM). Psychic forces are defined as the probability of transition from one cognitive state in valence field to another (Lewin's impact is reviewed in Duch, 2018). Dynamical theory of mental processes should be based on forces that operate on mental states, describing events in psychological spaces.

This idea was proposed in my 1996 article "Computational physics of the mind" (Duch, 1996) that showed a path from computational models of brain functions to models of the mind, from *physis* to *psyche*, complementary aspects of the same reality seen from different perspective. Brain processes in a given state $\mathbf{S}(t)$ are described at many levels, from molecular to neural activity and behavioral responses, forming a tensor $\mathbf{B}(\mathbf{S}(t))$. On the other hand the state of mind is expressed in terms of psychological constructs, including perceptions, beliefs, values, personality traits and other constructs. This information is represented in high-dimensional spaces, with particular dimensions for features that can be subjectively recognized. The state of mind $\mathbf{M}(\mathbf{S}(t))$ described in this way is "a shadow of neurodynamics" (Duch, 2012). Biophysics describes neural dynamics at different levels. Understanding the dynamics of mental events has been the subject of psychological theories (Duch, 2018). Only recently development of physics of mind linked to neuroimaging became a real possibility. Some aspects of nonlinear neurodynamics may be reconstructed and visualized as process in psychological spaces. This is a novel route to link psychology with neuroscience (Perlovsky, 2016).

Understanding relations between brain and mind requires mapping $\mathbf{B}(\mathbf{S}(t)) \Leftrightarrow \mathbf{M}(\mathbf{S}(t))$. Brain states are characterized by phenomics at many levels, from genetic and molecular to subjective reports, as recommended in the Research Domain Criteria (RDoC) by National Institute of Mental Health (Insel et al., 2010). This is the most promising approach to understand mental disorders, based on analysis of the large-scale network dynamics, the flow of information through connectomes in the brain. Edelman, Elman (1995), Fauconnier (1994), Gärdenfors, Johnson-Laird, Kelly (1955), Lewin (1938), Shepard (1987), Turner, van Gelder (1995), and several other psychologists (Duch, 2012, 2018) introduced mental spaces as an arena for mental events. Physical properties of stimuli that were important from evolutionary point of view are at the foundations of mental constructions. Conservation of angular momentum of the Earth leads to 24-hour circadian rhythm. Perception of spatial relations, color space, color constancy, the pitch of sounds, tastes, numbers, objects and actions rely on neural transformations that support optimal generalization and categorization. Roger Shepard (1987) has shown how to construct psychological laws for perception and mental representations, finding regular mental structures and invariants that internalize universal principles of physics. Probabilities of generalization of behavioral reactions are inversely related to similarity of the inter-stimulus distances. Psychophysical laws are constrained by kinematic geometry in three-dimensional space. Mental representations corresponding to physical events show isomorphism at the level of second-order similarity, i.e. relations between representations are similar to relations between physical events. This is the basis for motor learning using mental imagery, as seen in mental rotation experiments, and imagery of body movements that helps gymnast and dancers improve their performance.

Temporal dynamics of perception, action, language and higher mental processes has been the subject of several books (Port & van Gelder, 1995; Elman 1995; Kelso, 1997; Spivey, 2007). Mental forces are related to the probability of transitions between brain states in neurodynamics (Duch, 1996; 2012). We can measure brain activity using many techniques, such as EEG, MEG, NIRS, PET, fMRI and other approaches. This activity is spread through the connectome to various brain regions and is the basis of mental events. They correspond to attractor states of neurodynamics, quasi-stable brain activations associated with linguistic tokens resulting from analysis of semantic features by specialized brain regions (Duch, 2012). Brain-computer interfaces interpret EEG signals as intentions related to motor actions or attention. FMRI scans for over 1700 concepts show specific distributions of brain activations in the "semantic space" (Huth et al. 2016). Mitchell et al. (2008) associated nouns with 25 verbs: sensory activity (see, hear, listen, taste, smell), motor actions (eat, touch, rub, lift etc), emotional and spatial relations. In this way nouns are localized in psychological spaces, with dimensions that can be related to inner experience and can be quantitatively evaluated. At the brain level they are regions of the state space. Mental representation of images has been done by Horikawa & Kamitani (2017) showing how visual features may be extracted from fMRI scans. This allows for "generic decoding of seen and imagined objects using hierarchical visual features". It is an example of mapping between mental and physical states. Similar analysis should soon be possible using high-density EEG.

Mental spaces based on elementary semantic features represent inner states, providing a simplified representation of physical objects and relations between them. Attractor states of neurodynamics correspond to mental objects in mental spaces. Evolution has created brains that internalize physical events and anticipate outcomes using imagery. Transitions between attractor states in the brain creates trajectory in the activation space of brain regions, corresponding to the transition between mental states. Mental trajectories allow for description of scenes. Elman (1995) described mental representations of concepts as regions of the state space. Transitions between these regions are responsible for grammatical rules, providing a clear example of dynamics at mental level that is a reflection of neurodynamical processes. Spivey (2007) tried to use symbolic dynamics to characterize psycholinguistic phenomena but this approach is not well suited to continuous processes. We have generalized it to the fuzzy symbolic dynamics (FSD), and used to illustrate transitions between attractors of neurodynamics in high-dimensional space (Duch and Dobosz, 2011). Below is an example of spontaneous transitions of 140-dimensional semantic layer activity that has been trained to recognize 40 words in a 3-way model of reading (with orthographic, phonological and semantic layers, implemented in Emergent software, see Aisa, Mingus, and O'Reilly 2008). Presenting selected word as input in orthographic or phonological layer the system reaches attractor state representing the semantics of this word, and the semantic layer pattern fluctuates within the basin of attraction representing activity distribution that gives meaning to the word. Dwell time in attractor basin determines the speed of attention shifts, changes of mental states. Transition between attractor state are rapid, driven by stochastic forces resulting from synaptic noise, more probable between concepts that share some features. Transitions at the semantic level result in activation of the phonological/orthographic layers producing a stream of words (thoughts) that label attractor basins.



Similar visualization of dynamics is possible with brain signals from EEG, MEG or fMRI (Duch and Dobosz, in preparation). Thinking, deliberation, problem solving, or in general intelligent behavior in new situations require flexibility at the global neuronal workspace level (Dehaene et al. 1998). A set of specialized and modular local perceptual, motor, memory, evaluative and attentional processes extracts relevant information in an automatic way. Coordinated global activity based on this information recruits additional brain regions, including regions that are usually active in the resting state (Finc et al. 2017). Functional networks that can be activated in this neural space depend on the properties of individual connectome that determine all personality traits, preferences, and cognitive abilities. Dynamics of these processes, defining logic of cognition, should be modeled using principles of physics.

Acknowledgements: This work has been supported by the National Science Center grant UMO-2016/20/W/NZ4/00354.

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