Harmonious Solution to the Binding Problem

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The model of reality created by our brain is like a jigsaw puzzle consisting of many pieces connected into a unified picture. How do they combine together while keeping individual characteristics? In neuroscience and philosophy of mind, this question is called the binding problem. The article reveals various aspects of the problem and offers a solution based on the Teleological Transduction Theory.

Keywords: binding problem, explanatory gap, reality model, signal processing, neural code, synchronization.

The signals from the external environment and the body entering the sensory systems of perception modalities are diverse and dynamic. The number of representations of these signals created by the brain is huge, and each of them has many parameters. Nevertheless, a normally functioning brain binds it all together in a unified picture of the world and an inner feeling of a single I as a stable center for observing this world, experiencing one's own body and a source of purposeful actions. In certain pathologies or under the influence of psychoactive substances that disrupt the functioning of the brain, there is a violation of the holistic state of the reality model and the disintegration of the unified Self. Such maladaptive states show that solving the binding problem is a special function of the brain and the key to survival.

The binding problem has two aspects:

1. The segregation problem (BP1) concerns the question of the mechanisms which allow the brain to differentiate various signals of the environment received by the sensors of our perception modalities.
2. The combination problem (BP2) is about the mechanism that integrates the representations of the signals of the outer and inner world into a coherent model of reality.

The term was coined in the nineteenth century by William James who considered the ways the unity of consciousness might be explained by a known physical mechanism and found no satisfactory answer (James, 1890). With the development of physiological knowledge about the brain, the focus shifted to functional-anatomic aspects of the problem. Trying to explain segregation and combination by anatomical structure has its grounds in the obvious spatial aspects: the brain has areas that specialize in processing modality-specific signals and various aspects of these signals, while areas further in the hierarchy are engaged in associative processing and integration. The connections between these areas start as specialized labeled lines, then converge in some regions, then diverge and converge again.

The question arises: how do signals keep their identity while neural pathways converge and how does the overall picture stay integrated if there are so many diverging channels? Even if information flows converge in association areas of the cortex, the binding problem remains. First, these zones themselves have numerous communication channels and consist of a huge number of neurons. Second, integration in these zones must also be combined with differentiation. Third, the convergence of flows in space cannot explain how we get a picture

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of the world with all its constituent details at the same time. The binding mechanism must involve both a spatial and a temporal aspect.

There is an old hypothesis that the binding problem is solved by the brain via the synchronous firing of cortical neurons at a specific frequency. For example, the authors of the article "The neuronal basis for consciousness" wrote: "The system would function on the basis of temporal coherence. Such coherence would be embodied by the simultaneity of neuronal firing … In this fashion the time-coherent activity of the specific and non-specific oscillatory inputs, by summing distal and proximal activity in given dendritic elements, would enhance de facto 40 Hz cortical coherence by their multimodal character and in this way would provide one mechanism for global binding" (Llinas et al., 1998).

Obviously, firing in unison binds in time. But how does it keep the identity of each encoded signal? This hypothesis does not solve the differentiation problem. One of the initial proponents of the theory, Christoph Von der Malsburg suggested that segregation should be supported by another mechanism without giving a hint of what it might be (Von der Malsburg, 1999). Unfortunately, the binding-by-synchrony hypothesis does not solve the combination problem too. The neuronal activity encodes signals with many parameters. How can all those parameters be combined by simultaneous firing at one frequency? This is the same as reducing a symphony to one note played by all the musicians of the orchestra at the same time. It is not a combination but a fusion. The musical analogy shows that BP1 and BP2 cannot be solved separately. It may also give us a clue about how the brain solves them.

One of the adherents of the model, Wolf Singer explained segregation by labeled line coding where "the responses of a given unit have a fixed label attached to them" (Singer, 1999). But what label can be attached to a tone of one frequency? The author failed to explain the mechanism of this labeling and had to concede: "The application of the new methods required to test the hypothesis will undoubtedly provide new insights into the dynamics of neuronal interactions. If it then turns out that the hypothesis falls short of the real complexity — which is bound to be the case — we will have learned something about the role of time in neuronal processing that we would not have learned otherwise" (Ibid).

This hypothesis falls short of the true complexity of the binding problem and does not reflect the reality of brain functioning. Empirical studies have shown that there is no direct correlation between neural synchrony as simultaneous firing and perceptual binding (Thiele, Stoner, 2003; Dong et al., 2008). The authors of a review article called "Synchrony Unbound" summed up: "The theory is incomplete in that it describes the signature of binding without detailing how binding is computed … Nonetheless, the theory has sparked renewed interest in the problem of binding and has provoked a great deal of important research. It has also highlighted the crucial question of neural timing and the role of time in nervous system function" (Shadlen, Movshon, 1999).

It is true that previously most of the theories were concerned only with the spatial aspects of the brain's functional-anatomic structure. But space and time are conjugate variables, and we cannot ignore one or the other. Some theories try to combine space and time in their modeling. For example, Integrated Information Theory (IIT) introduces a time- and state-dependent variable φ as a measure to characterize the capacity of the system to integrate information (Balduzzi, Tononi, 2008). The authors suggest that a network architecture that combines functional specialization with functional integration leads to high φ values. The theory has a substantial mathematical formalization but "the integration measure proposed by IIT is computationally infeasible to evaluate for large systems, growing super-exponentially with the system's information content" (Tegmark, 2016).

Still, the main problem of the model is that it does not answer the question of the physical mechanism that underlies the integrated information measure and the ability of a system to provide for specialization and integration. Thus, it does not explain the binding problem

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solution but only confirms that the brain solves it with varying degrees of success. The theory has been criticized for failing to answer the basic questions required of a theory of consciousness: “As long as proponents of IIT do not address these questions, they have not put a clear theory on the table that can be evaluated as true or false” (Pautz, 2019).

One more popular model, Global Workspace Theory (GWT), suggests that signals enter a specific workspace within which they spread to many sites in the cortex for parallel processing (Baars, 1997). There are detailed neuroanatomical versions of such a workspace (Dehaene et al., 2003). They are relying on the physiological fact that many cortex regions send and receive numerous projections to and from a broad variety of distant brain regions, allowing them to integrate information over space and time. Multiple sensory data can therefore converge onto a single coherent interpretation. This global interpretation is broadcast back to the global workspace creating the conditions for the emergence of a single state of consciousness, at once differentiated and integrated. However, GWT does not tackle the issue of the physical mechanism that performs differentiation and integration. It only postulates the existence of some place where the function is located.

The absence of a physical solution to the problem led to the idea that the problem does not exist. Philosopher Daniel Dennett has proposed that our sense of unified experiences is illusory and that, instead, at any one time at multiple sites there are “multiple drafts” of experience (Dennet, 1981). Some neuroscientists argue that there is in fact a disunity of consciousness in the sense that the brain processes various signals by different cell populations and this activity is not coinciding in time (Zeki, 2003). But this physiological fact does not make the binding problem non-existent. Moreover, it stresses the existence of a binding mechanism as in normal conditions we perceive the world as a whole and not as a rotating kaleidoscope of “multiple drafts.” The model of reality breaks down into pieces only in pathological states showing that some binding mechanism malfunctions. There is no way we can solve the problem by stating that it does not exist.

Some modern theories are in a controversial state. On the one hand, they claim that the problem does not exist, and on the other hand, they claim that it is somehow solved by the brain. For example, the author of the Thousand Brains Theory (TBT), Jeff Hawkins states: “The binding problem is based on the assumption that the neocortex has a single model for each object in the world. The Thousand Brains Theory flips this around and says that there are thousands of models of every object. The varied inputs to the brain aren’t bound or combined into a single model.” (Hawkins, 2021). So, nothing is combined — no binding problem.

But even the name of the theory speaks about the problem: how do all those thousand brains integrate into one brain? The author attempts to answer: “Voting among cortical columns solves the binding problem. It allows the brain to unite numerous types of sensory input into a single representation of what is being sensed.” (Ibid). But the question of the binding mechanism remains open despite the fact that the author claims that he has closed it. Using the voting metaphor proposed by the author, we can formulate it as follows: how do votes remain individual for counting when placed in a common ballot box? This is the essence of the binding problem which has two sides: combination and segregation. They have to be solved simultaneously and there has to be a physical mechanism for that. Without an idea about the mechanism, the author has to acknowledge: “Exactly how the neocortex does this is still unclear” (Ibid).

It is impossible to answer the question of how representations integrate while retaining their identity without showing what representations are physically and how they are produced technologically by the brain. Answering this question would mean closing the explanatory gap between physiological and mental phenomena (Levine, 1983). We should get back to the initial dilemma that William James faced in the nineteenth century when he contemplated the unity of consciousness: how can it be explained physically?

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Previous models focus on physiology and forget that it is the embodiment of physical processes that employ a physical mechanism. Unfortunately, many neuroscientists perceive the question “What is it physically?” as the question “What is the physiology?” They try to “jump over” the explanatory gap. They are trying to understand how the binding problem is solved without formulating the problem in physical terms. The same goes for all other aspects of the Mind. They are in search of neural correlates of consciousness without even defining what consciousness is in physical terms. They are looking for a black cat in a dark room without specifying what a cat is. When they fail inevitably, the old dualistic theme resurfaces: could it be that there is a fundamental difference between the nature of nervous activity and the nature of mental processes? Many express their disappointment by saying that if the Mind is irreducible to physiology, it cannot be explained at all. They call attempts to find an explanation “physicalism” and “reductionism,” implying that it is a waste of time.

Indeed, the psyche is not reducible to physiology, but not because the psyche is something of “another world.” They are just different categories. The brain is an object. The psyche is a process. We cannot reduce one to another for a simple reason: it will be a category error (basic ontological and logical fallacy). For example, we cannot reduce the flow (process) to a river (object). We cannot explain the flow simply by saying that the river is flowing. Even if we describe the river in the smallest detail down to the molecules, there will be an explanatory gap. To overcome the gap, it is necessary to understand the physical mechanisms of the flow process and how they are embodied in this particular substrate.

We cannot explain consciousness by simply stating that it is created by neurons and describing their activity. No matter what details we provide, even down to molecules, description is not an explanation. Phenomenological models are useful but they do not cover the explanatory gap. The search for correlates of consciousness means an explanation of physical mechanisms that underlie the observed physiological processes and lead to mental phenomena. Otherwise, we will remain in the old vicious circle of dualism and the explanatory gap between body and soul. True physicalism is about physics. The gap should be covered with a physical bridge in all aspects of the Mind. Dealing with the binding problem is part of this bridge. If we want to find an answer in physical terms, we need to posit the question in physical terms too. There is no other way.

Here is an example of how this problem is formulated in neuroscience: “In its most general form, “The Binding Problem” concerns how items that are encoded by distinct brain circuits can be combined for perception, decision, and action. In Science, something is called “a problem” when there is no plausible model for its substrate” (Feldman, 2013). This definition is quite precise but it is still about physiology resulting in mental phenomena. There is a gap even in the formulation of the problem. It is not surprising that there is still a gap in solving it.

Let’s try to build a physical bridge on the level of the questions asked. What are the encoded items physically? What are the physics and technology of the encoding process? What are the brain circuits physically (not physiologically!) and what do they do technologically? These questions seem so simple, but they are the stumbling block that neuroscience has encountered in building a plausible model. Amazingly, if formulated briefly, the answers seem to be simple too.

The mind, as the perception of the elements of the world for making decisions and actions, is the process of transducing the signals coming from these elements into their representations for forming an adequate and adaptive model of reality. Any signal is a wave of energy vibrations. From a technological point of view, the brain is a signal-processing device. Physically, neurons are oscillatory systems that encode vibrations in the energy of the world. The encoding consists of initial analysis and subsequent synthesis. The analysis is the decomposition of waves into amplitude-frequency and phase components and the determination of the contribution of different components to a given signal. Synthesis is the

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reverse operation of transforming the discrete measurements of various parameters into a continuous wave representation of the incoming signal. Technologically, it is an analog-discrete-analog conversion. Physically, it is the transduction of signal waves into waves of neural code and integration into a unified wave structure of the reality model.

Based on such a description of the physics and technology of the mind, we can formulate the binding problem in physical terms: *how do waves of signal representations combine into a unified wave structure while maintaining their individual parameters?* This formulation clearly shows that segregation and combination are not only two aspects of the same process but that they may be carried out by the same physical mechanism. This mechanism is related to wave physics.

To create a plausible model of the binding process in the brain we need a plausible model of the wave processes in matter in general and a plausible model of the wave encoding process in the brain in particular. This is what the "Symphony of Matter and Mind" project is about (Tregub, 2021a,b,c,d,e,f,g,h). It includes the Theory of Energy Harmony (TEH) as a general theory of matter and the model of the universal mechanism of fundamental energy interactions and the Teleological Transduction Theory (TTT) as a general theory of the mind. They allow us to build a physical bridge to cover the explanatory gap between the physiological processes in the brain and the mental phenomena they create.

With respect to the binding problem, TTT goes back to the initial dilemma that William James faced in the nineteenth century: how can it be explained by a physical mechanism? But this means that we need to explain the physical mechanism of encoding, transmission, storage and retrieval of representations. Only then we can speak about the mechanism and technology of their integration. We cannot ignore the previous technological steps of the general algorithm and solve the binding problem in isolation from other fundamental issues. Combining the physical, physiological, functional, computational and technological aspects in one internally consistent model helps to resolve these issues leading to a solution to the binding problem.

If the brain is a signal-processing device, then technologically its networks are signal-transduction filters. This formulation sounds like a simple logical chain, but it means a fundamentally new approach to the nervous system, which builds a bridge from standard functional-anatomical schemes to a new physical-technological map of the brain as a configuration of filters, starting with primary sensors-converters, followed by intermediate modulators in the subcortical areas, and up to the higher integrators of the cortex responsible for the final product of a coherent and unified model of reality. TTT offers a description of this transduction process and its algorithms from the systemic level down to the intracellular details, showing how segregation (analysis) and combination (synthesis) are performed computationally (Tregub, 2021d).

Next, TTT proceeds to describe the component and composite technology of communication channels in the brain. Channels from the primary converters (receptors) represent a component aspect: various pathways process and transmit different signal parameters within the same modality and signals of different modalities. Component technology allows to avoid crosstalk during primary processing. Transition to composite solutions happens at the subsequent processing stages when the encoded information about many parameters is transmitted over common channels saving space, time and energy. Communication between system modules is very complex due to a large number of network elements, so the composite solution reduces complexity by using the same paths for different flows.

But for many brain researchers, this raises the puzzle of how channel convergence preserves signal specificity. The problem is that they proceed from the idea that brain circuits are wires that carry electrical impulses (spikes) of neurons. This electrical wire analogy is very old and underpins all major models of neuroscience. The simplicity of the initial assumption led us to

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the dead-ends of mysteries around which we have been walking for decades. But if we change the paradigm many riddles just evaporate. Electrical communication in the brain is carried out not by discrete impulses, but by oscillations and waves. This seems such an easy step as we have been studying brain waves for decades. It only remains to combine our knowledge as pieces of the puzzle into a coherent picture. TTT puts communication issues within the framework of its general concept based on wave physics. It looks at transmission channels of the brain as waveguides. This is a logical step that seems self-evident in hindsight, but it is a game-changer for the entire field of knowledge.

In short, the physical properties of waves allow for the combining of multiple streams in one channel (multiplexing) and guiding separate streams through different channels (demultiplexing). We know about this possibility in artificial communication technologies. It remains to look at the natural technologies of the brain from this perspective. TTT provides a detailed account of the neural pathways' physiology that reflects the wave physics of their communication function and explains their external and internal structure (Tregub, 2021e). The physical bridge closes the explanatory gap and solves the riddle of neural pathways divergence and convergence. The same physical bridge allows TTT to solve the problem of binding from an encoding point of view.

Standard neuroscience theories regard neural activity as identical discrete spikes. This "digital code" assumption that has been the foundation of all spiking neuron models (rate code or temporal code) leads to another dead-end. We have not succeeded in deciphering the brain code for a simple reason: these models contradict the reality of the brain functioning in terms of informational density, speed and efficiency (Rieke, 1999). Moreover, neurons actually do not produce spikes as discrete "digits." They are only depicted like this in the research reports to fit reality into the theoretical models. "The spike is added manually for aesthetic purposes and to fool the reader into believing that this is a spiking neuron … All spikes are implicitly assumed to be identical in size and duration … However, using the model might be a waste of time" (Izhikevich, 2007).

Neurons produce waves. If we increase the resolution on the time scale, then the spike will show its true nature: a change of the membrane potential is a continuous oscillatory process that differs in duration and waveform. It is exactly the graded potentials that provide high capacity and efficiency of the code. Unfortunately, they have been ignored and wiped out of the analysis for decades. No wonder we didn't get anywhere. We need to get back from the dead-end, forget about wasted time and look for another way so as not to waste any more time. Sooner or later, this will happen. Better sooner than later. But for that, we need to change the conceptual paradigm. Here wave physics again provides us with the guiding light.

Signals of the environment are waves with certain amplitudes, frequencies, and the development of phases in time. Thus, the neural code has to be a complex multidimensional structure. It cannot be less complex than the signals that it encodes. Spiking neuron models reduce it to a minimal set of parameters (average tempo or sequence of spikes). Also, the neural code cannot be slower than the signals that it encodes. Otherwise, we would not be discussing the neural code. Spiking neuron models are about such a slow encoding process that no living system would survive if it used such a code. The brain is not a "Turing machine" that reads symbols from a strip of tape. The timeline of the computations in the brain is too fast and a "strip of tape" that the standard models try to create from a sequence of identical spikes is too slow. This leads to another riddle: how can slow neurons encode the world so fast? There is no answer to this mystery within the spiking neuron paradigm.

Only waves are capable of creating the observable capacity, speed, and multi-level complexity of the real neural code. Waves form and read information not sequentially bit by bit but from all participants of a specific wave pattern simultaneously within the reference wave's clock frequency which can be rather fast. This solves the riddle of how representations

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with all the intricate details of the parameter space are formed and reproduced almost instantly. It means that the computational time window of the brain is a lot faster than the activity of a theoretical spiking neuron that would need to produce and read the average speed of spikes or successive spike patterns along a linear chain. Of course, the successive patterns of oscillations carry the informational load too, but it is a lot "heavier" than in spiking models as each individual oscillation has its own meaning within the code.

Proceeding from this new physical outlook on the physiology of the technological chain of the neural circuits that encode the signals of the world and produce the unified reality model, TTT offers a Symphonic Neural Code (SNC) hypothesis. It not only reflects the reality of the complex waveform of each impulse but explains its meaning within the overall computational process. Each activation/deactivation of a neuron, being a discrete unit of the code, contains internal parameters as a continuous oscillatory process. The combination of such information-rich oscillations produces a representation as a wave pattern. Thus, computationally the neural code is analog-digital-analog. The model provides a detailed physical, mathematical and technological description that explains the informational, temporal and energy efficiency of the brain (Tregub, 2021d,e).

Many researchers compare the brain with an orchestra and call neural circuits ensembles. Taking this metaphor to the level of physical analogy, the SNC hypothesis regards each action potential as a note of the music of the brain that has individual characteristics of the waveform (period, amplitude, phase portrait). The information density of each note and each pause (resting potential) is very high. Thus, complex information can be encoded in a short activation/pause sequence and even within a single cycle. Due to this, the system as a whole has tremendous computing power, efficiency and speed.

And last but not least, the physics of the wave interactions based on cross-frequency and phase coupling naturally solve both aspects of the binding problem. Just like in music where many sounds with a variety of parameters combine into a harmonious symphony while retaining their identity, billions of neurons tune in to each other to play the music of the Mind. The activity of a given neuron with a precise spatial-temporal organisation of each note and pause allows it to be part of the overall brain symphony with its melodies (frequency patterns), rhythms (phase patterns) and harmonies (the simultaneous existence of different patterns).

TTT has an explanatory range that encompasses all the issues of signal processing starting from initial reception and encoding, transmission and storage to decoding and integrating into a coherent reality model. The overall process is the interaction of varying neuronal oscillations via synchronization. The term is used not in the sense of simultaneous events of identical spikes (synchrony as unison) but speaks about the complex mechanism of cross-frequency coupling, which creates a harmonic structure while preserving the individual characteristics of each representation as a wave pattern. The coupling of different wave patterns provides the brain with the ability to solve the BP2. It also allows for maintaining the uniqueness of each pattern solving the BP1. Thus, the same physical mechanism deals with both aspects of the binding problem.

This binding-by-harmony solution means that the elements of the brain ensemble can synchronize instantly and participate in complex, differentiated and integrated representations as wave patterns creating a coherent model of reality and an integral Self. TTT describes fine details of the physiological implementation of the physical binding mechanism and uncovers subtle nuances of brain polyphony and polyrhythm. It offers a detailed description of the functional roles of different frequencies of the brain and provides a physically grounded taxonomy of neural oscillations based on harmonic scale (Tregub, 2021f). It also describes how the breakdown of the binding mechanism leads to the disintegration of Self and splitting of the reality model associated with some mental disorders (Tregub, 2021g,h).

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