Thermodynamics and Cognition: Towards a Lawful Explanation of the Mind

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Abstract

An argument is developed to show that explanations of biological and physical systems can be unified via the second law of thermodynamics (SLT). The SLT's influence on the evolutionary history of life at the scale of the global Earth system justifies reunifying phenomena—i.e., mind and matter—whose separation dates back to Modern Western philosophy and still influences contemporary scientific investigations. From this perspective it appears that the necessity of ever-increasing entropy in nature may constrain the organization and behavior of living organisms and cognitive processes. Via an example of explaining memory at the scale of the brain-body-environment system, we recommend understanding cognition with respect to its role in increasing entropy in nature. This framework may lead to a fruitful understanding of cognition by appealing to the necessity of physical laws.

Keywords: action selection, cognition, entropy, memory, thermodynamics

Introduction

The classic dualism disjoining scientific descriptions of physical and biological systems rests on a perceived incommensurability. The division is rooted in Modern Western philosophy and has persisted contemporary science. Despite the ubiquitous constraints imposed on nature by the laws of physics, many domains of inquiry are indifferent to the general principles of these laws when investigating living organisms. In the cognitive sciences, dynamic systems theorists have made strides in bridging the two (e.g., Kelso, 1995; Thelen & Smith, 1994). Nevertheless, much of their work stops short of uniting accounts of cognition with a supreme law of physics like the second law of thermodynamics (SLT) (Varpula et al., 2013). If we instead approach cognizing organisms as physical systems, whose laws regulate all physical interaction within such systems, the constraints these laws impose on cognitive processes should be present and observable in organisms. Approaching the study of cognition from this perspective opens the door to promising lines of inquiry that may advance our understanding of the human mind.

The fecundity of bringing together the theoretical frameworks of physics and biology into a common sphere of theoretical and methodological practice is here explored by approaching the study of cognition with respect to the SLT. The case is made as follows: First, we reinforce the claim that the SLT predisposes the organizational and behavioral properties of all biological systems. Second, we argue that cognition, being a biological phenomenon, is likely to be invariably constrained by the SLT, which can be fruitfully understood as the quest for free-energy consumption in the least time. Third, we show that this approach to understanding cognition is readily amenable to the explication of two cognitive phenomena—memory and action selection—that enjoy a unique complementarity in nature in the context of the SLT by acting as an accelerating entropy production system.

The Biophysical Dichotomy

The dichotomy of biological and physical systems (*biophysical* henceforth) is rooted in Modern Western philosophy, particularly Descartes' mind-body dualism and Kant's autonomy of biology from physics (Swenson & Turvey, 1991). Since then, some researchers have attempted to develop domain specific laws of human behavior analogous to Newton's laws governing the heavenly bodies (cf. Stevens, 1957). However, psychology has experienced a steady decline in attempts to establish psychophysical laws that may provide explanations of cognitive phenomena. A study on psychology paper abstracts containing 'law' citations shows a decline from 22 references per 10,000 for entries occurring between 1900 to 1999, to 10 references per 10,000 for entries occurring in the decade to follow. Moreover, the latter works presented fewer attempts to formulate new laws, suggesting an increasing doubt regarding the lawfulness of cognitive processes (Teigen, 2002). Adding to this trend, Davidson (1995) further argued that explanations of the psychological—which understood in terms of propositional attitudes such as intentions, desires, and fears—is rational in nature, whereas the physical domain is chaotic and irrational in nature. Thus, he claims the two domains of description can develop rough correlations but will remain fundamentally incommensurable. It is important to note for present purposes that his argument appeals to minimal anecdotal empirical support, and is very much akin to the Hegelian arguments Chemero (2009) claims plagues immature sciences like cognitive science. An argument is "Hegelian" when apparently empirical propositions are false as a matter of logical necessity, such that certain frameworks for understanding the natural world are ruled out in advance. This is based on the notorious arguments Hegel made, following Plato, concerning the idea that the number of planets in our solar system is necessarily seven (Craig & Hoskin, 1992; Hegel, 1801/1987). Eventually, though, theories must be justified via appeal to empirical facts.

What is clear is that the biophysical chasm Descartes and Kant constructed is alive and well in the contemporary scientific and philosophical literature. Rowlands (1999) argues that the privilege researchers often grant to the processes going on inside the brain by computational models and neuroimaging are direct descendants of Cartesian internalism, a position that explicitly posits two differing substances—mind and matter. Additionally, some have argued (e.g., Anderson, 2014) that the dichotomy of mind and matter is responsible for subsequent attempts to locate where the mind occurs in the head, resulting in the development of phrenology and its continued influence in cognitive neuroscience (cf. Uttal, 2011). If cognitive scientists truly wish to achieve a scientifically virtuous theory of the human mind, then they may want to alter their trajectories away from the research paradigms established in part by the biophysical dichotomy and instead aim for commensuration. However, this line of thought is itself contingent on empirical evidence that justifies rescinding the biophysical dichotomy. If the empirical data serves to confirm Davidson's claims disjoining biology and physics, then there may be little hope of grounding cognitive processes in the laws of nature in physics. We argue here that by exploring the ramifications of the SLT on biological phenomena, the SLT can be established as a driving force behind the ontogenesis of living organisms at the scale of the global Earth system. This systems-based approach will merit minimizing the historical divisions of biological and physical systems and suggest that new explanations of cognitive process can be developed in cognitive science if it refocuses its inquiries towards the organism at various scales within the context of the fundamental laws of physics—namely, the SLT. If successful, this position will open the door to a promising thermodynamically lawful account of cognitive processes.

The Second Law, Entropy, and the Global Earth System

The SLT is distinct from many other laws of nature in that it can be interpreted not only as a law about laws but also a position on Aristotelian end-directed physics (Swenson & Turvey, 1991). As we shall see, not only does the SLT indicate that there is an end that all physical processes strive towards, but also that living organisms proceed along the same structured path. Understanding cognitive phenomena with respect to this law may lead to promising lines of inquiry and generate hypotheses. Such accounts could provide grounds for revising covering law-like models of explanations of cognitive phenomena (cf. Walmsley, 2008). Knowledge of the prior conditions of a system is combined with a law of nature (e.g., SLT) that, ceteris paribus, enables us to derive an explanation of the corresponding event that details what *had* to happen given the conditions. The promise of this model works symmetrically with prediction as it does explanation: We can combine knowledge of a future set of initial conditions with natural laws to accurately predict the conditions to follow. Explanations and predictions of this kind are grounded in the nomological necessity of laws of nature and not logical or metaphysical necessity. Though attempts to ground cognitive processes in physical laws have recently emerged with varying degrees of success (e.g., Kelso, 1995; Thelen & Smith, 1994), none have successfully appealed to nomic necessity for explanation. If we wish to have a comprehensive explanation of why specific cognitive phenomena exist and how they function, pursuing nomic necessity may be a good place to begin such a pursuit.

Note that we are not claiming that non-covering law explanations will not be sufficient or even ideal for certain phenomena. Rather, being placed within the context of laws of nature can strengthen even non-covering law explanations. We defend a general theoretical framework whereby cognitive phenomena can be understood in a manner similar to physical systems, namely, as continuous with the SLT.

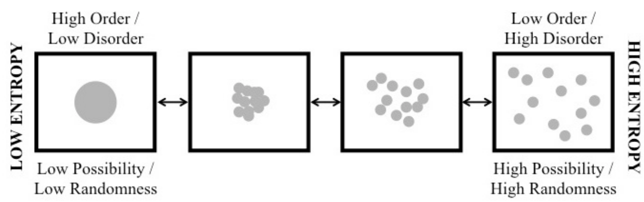

Figure 1: As the entropy of a system increases, it becomes less ordered/increases in disorder. As the entropy of a system decreases, it becomes more ordered/decreases in disorder.

The SLT states that within a closed physical system *entropy* can only increase over time (Boltzmann, 1886/1974; Brissaud, 2005). Entropy is the measure of disorder in a physical system. It is important to understand that when the total amount of order in the system is low, its entropy is high, and vice versa (Figure 1). Physicists generally agree that the only truly closed system known to exist is the universe itself. Thus, the universe is in the process of transitioning from a higher-ordered state to a lower-ordered state. At first glance it would seem the SLT supports the biophysical dichotomy, for it would entail that complex, higher-ordered living systems could not emerge in an open system that is lawfully trending towards disorder without violating the SLT. Dennett's (1995) interpretation takes this line of thought a step further into the domain of biology by defining living systems as those in nature that defy the SLT. However, this approach fails by re-emphasizing that the universe is the only closed system known to exist: It entails that biological systems cannot be closed systems and, consequently, accounts of their description (like Dennett's) cannot presume otherwise. Such interpretations naively disengage the highly ordered biological system from the environment by treating it as unique with respect to the SLT, only taking into account the order produced explicitly within the system itself.

Contemporary treatments of living systems in isolation from their environments seem to have supplemented beliefs in the biophysical dichotomy that began long ago. However, von Bertalanffy (1950) demonstrated that in open systems such as living organisms, order must arise (decreasing entropy) whenever the opportunity presents itself, and at the same time the total net entropy in nature is increased via some process whereby it is released into the local environment. The SLT equation balances itself out once a multi-scale system perspective is taken into account and higher-ordered biological systems are understood as physically open systems within the closed universe system. If the net entropy produced in nature by the evolution of complex organisms is positive, then the SLT suggests that the proper construal of biological systems as physical systems dynamically situated within their environment must be taken. Evidence for this net increase in entropy at the scale of the global Earth system is suggested by empirical data with respect to the evolutionary history of life on Earth. From this a nascent perspective for understanding biology, and subsequently cognition, emerges.

Schrodinger (1945) argued that for a living thing to exist it must never cease contributing to the total entropy of the universe. Moreover, Swenson and Turvey (1991) established that the global Earth system reveals an increase in biospheric entropy during the development and growth of living matter over geological time. Primal life on Earth was likely to have been largely anaerobic, or without a supply of oxygen and biological compounds to metabolize like present day life. The emergence of the first photosynthetic bacteria linked life directly to the sun. Through an extraordinary development in the history of the planet, the anaerobic organisms were unable to split electrons from Earth's vast water supply for energy. Proto-Cyanobacteria were the first to do otherwise. This was accomplished by making use of the virtually endless supply of photons from the sun to split the electrons within the water molecules. This process resulted in the release of O_2 into the atmosphere. Combined with a vast supply of water and sunlight, this led to the rapid oxidation of the primal Earth atmosphere, a process that equates to a rapid increase in entropy. Since this process began, the global Earth system has generated an exponential increase of entropy production. The aforementioned Pre-Phanerozoic era, where the first photosynthetic organisms employed sunlight to release the O_2 molecules from water, significantly increased the terrestrial levels of entropy. The resulting high concentration of atmospheric O_2 provided a unique opportunity for generating additional entropy. It was then that nascent life forms metabolized the newly formed organic matter and O_2. This resulted in an even greater increase of entropy production along with increasingly higher ordered forms of life. This trend continues to this day. Thus, from the moment life began on Earth the production of entropy by progressively higher ordered biological systems was largely responsible for an exponential increase in net entropy in nature over time. The vantage point that views biological systems as situated thermodynamically within nature advances our claim that the SLT demonstrates an intrinsically homogenous biological and physical universe.

Entropy and the Free Energy Principle

, The SLT has multiple coherent interpretations. One interpretation—the law of maximum entropy production—suggests that entropy maximization and field potential minimization are expressions of the same symmetry (Swenson, 1997; Swenson & Turvey, 1991). When all available energy is evenly distributed throughout a system and there are no remaining local field potentials, then entropy is maximized and the system is at equilibrium. The system will remain at equilibrium (maximum entropy) unless acted upon by an external non-equilibrium system with free energy to consume. The SLT is also referred to as the principle of least action (Annila, 2010, Kaila & Annila, 2015). If the system is at equilibrium and there are no local free energy pools, no action can be taken. But when a non-equilibrium system is within proximity to affect a system at equilibrium—which is always the case for any open system—the equilibrium system reacts efficiently by consuming any readily available free energy with the least amount of action possible. Thus, according to several mutually consistent interpretations of the SLT, a low-entropy system must consume free energy by reducing local field potentials with the least amount of action if it is to remain consistent with the SLT and contribute a net increase of entropy in nature. As noted earlier, this increase occurs somewhere along the system's physical boundaries. This interpretation of the SLT has been referred to as the *free energy principle* (Friston, 2010) and it manifests in many processes in nature.

Rainwater flowing down a dry mountain riverbed readily illustrates the free energy principle (Figure 2A). Water does not merely flow in a straight line down the main body of the riverbed. Rather, the water flow branches off into any available side streams as the water follows the path of least resistance down the riverbed. Multiple paths minimize the constraints otherwise imposed on the water flow if it had been confined only to a straight line down the main body of the riverbed, thereby ensuring field potential minimization and maximum entropy increase in the fastest possible time. The riverbed analogy serves as an easy to grasp instantiation of the free energy principle in nature by demonstrating a familiar physical system's quest to maximize free energy consumption in the least amount of time. Given the ubiquity of the SLT throughout nature, it is unsurprising that the instantiation of the free energy principle is evident in cognitive processes as well (e.g., Friston, 2010; Friston & Stephan, 2007).

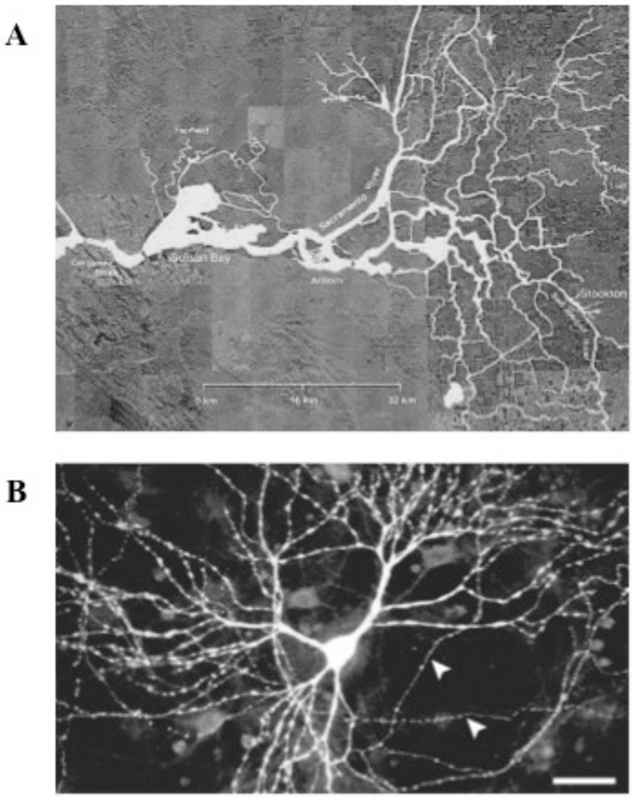

Figure 2: Increased energy flow results in increased speed of flow. (A) River flow of California's Sacramento-San Joaquin River delta (modified from Trump, 2004). (B) Expression of TRPV1, a receptor protein, in cultured hippocampal neurons (Zemelman et al., 2003). The hippocampus and receptor proteins such as TRPV1 are associated with memory formation in the brain (e.g., Gibson et al. 2008).

It may come as no surprise that animals have to move to eat, and that they need to eat to move (Varpula et al., 2013). A living organism's need to consume free energy to move and live entails that these cognitive perception-action cycles at the scale of the organism-environment system (Favela & Chemero, 2016) are constrained by the SLT. At the scale of the brain, the cortical mechanisms for action selection can be understood as a manifestation of this principle because it facilitates what actions an organism selects to stay alive and contributes to the net increase in biospheric entropy. Thus, for the animal, an action may be considered advantageous if it leads to maximized consumption of free energy in the least amount of time. Moreover, action selection is invariably constrained by an organism's memory. Memory is a cognitive phenomenon that can be understood as participating in extending nature's entropy increasing efficacy into the future.

A Multi-Scale Entropy Production System: Affordance Selection and Memory

Neurophysiological data suggests that neural activity within the brain is produced in a manner consistent with the free energy principle (Friston & Stephan, 2007). More specifically, any neuron or neuronal assembly that can change will do so in an effort to consume free energy in the least amount of time. Like rainwater flowing down a mountainside, as an activation signal traverses a neural pathway, it takes the path of least resistance and reduces energy field potentials within the brain as fast as possible (Figure 2). In the case of action selection, neurophysiological data suggests that multiple simultaneous opportunities for action are selected and specified in parallel (Cisek, 2007). This "affordance competition hypothesis" is different from the classical cognitivist perspective where action was thought to be selected first and specified after. Instead, neural activity in the brain produces bodily action once a neurological signal is received from the motor cortex, and the neurological signal that the motor cortex transmits will be the signal that survives the action selection competition carried out in the brain in accordance with the free energy principle. But an organism's free energy consumption is not restricted to the intracranial processes. Rather, in order to survive, the brain needs its free energy consumption process to adapt in a way that can guide the organism through dynamic environments. Unless an organism is situated in a static and threat-less environment with unlimited access to free energy, to survive it will need a memory system that reorganizes the morphology of the brain to enable adaptation to external circumstances. In addition to action selection, memory can be explicated in the context of the SLT.

New memories are made—at least in part—by the brain establishing new or strengthening old neural connections. The mechanism that enables this morphodynamic process in the brain is Hebbian learning. Hebbian learning can be summed up as "neurons that fire together, wire together" (Keysers & Perrett, 2004). The pathways that activated neural signals traverse throughout the nervous system are strengthened, subsequently providing a means of increasing the likelihood and efficiency that whatever environmental stimulus generated the initial neural activation will follow a similar path if reencountered in the future (Figure 2B). Again, the mountain riverbed analogy is helpful here. The more frequently water flow traverses a specific path down the riverbed, the more likely it is to erode and deepen the river. While river erosion and memory formation are wildly different processes, the erosion will serve to increase the likelihood that a similar path will be taken again during the next rainfall, which is akin to how Hebbian learning in the brain facilitates an increased likelihood that neural signals will traverse similar paths in the future. The process of memory formation via Hebbian learning enables an organism to facilitate an increasingly efficient means of dissipating field potentials from local free energy pools with its actions. Thus, combined with a Hebbian learning process, the free energy that traverses an organism's nervous system simultaneously constructs a feedback process that increases the likelihood that it will select similar field potential minimizing actions in the future. From this perspective, memory can be vaguely understood as a physical feedback mechanism within an organism that enables the past to influence the present. Both implicit and explicit memory can be characterized by this description and is therefore indifferent to the different types of memory often instantiated in living organisms.

Memory is thus unique with respect to the SLT on the grounds that it permits the exploitation of temporal circumstances to increase nature's entropic efficacy. The SLT not only ensures all physical systems—including living organisms—consume free energy pools the moment they are within spatial proximity to be consumed, but if the system is organized with an effective memory system it will enable that system to forgo immediate free energy consumption in order to consume greater amounts into the future. The SLT ensures maximum entropy production in real time with respect to local field potentials. This is evident in cortical mechanisms for action selection. By grounding memory in the SLT we have an exclusive account of nature organizing itself in a way that removes spatial constraints imposed on entropy production. Non-autonomous and memory-less systems are restricted to entropy production only when they encounter free energy within spatial proximity of the system's boundaries. In the case of living physical systems endowed with memory, they are able to forgo immediate field potential minimization that presents itself locally within spatial proximity and instead extends nature's entropy, thereby increasing efficacy forward in time thanks to greater amounts of free energy consumption in the future.

The consequence of this unique cognitive phenomenon is that aspects of human culture—including education, socializing, career and financial planning, and science, all of which require memory to function—allow for sacrifices of immediate field potential consumption for an increased net consumption at a non-local point in time. This suggests that not only are there likely to be additional cognitive processes constrained by the SLT, but that additional phenomena from the domain of the social sciences can potentially be understood from this perspective.

Memory formation is necessary for virtually all living organisms that rely on their personal autonomy to move their bodies through their environment. It enables them to select appropriate action—in the interest of avoiding risk and seeking nourishment—so that they may continue to survive in the wild. In the context of the global Earth system detailed above, the combination of action selection and memory in living organisms compliment one another in a way that results in unique and increasingly viable entropy production system in nature.

Concluding Remarks

Having motivated a rejection of the assumption that biological and physical systems are separate and incommensurable within scientific explanation, we have presented accounts of cognitive processes with respect to the SLT and its symmetry with the free energy principle. This suggests that cognitive, biological, and physical phenomena can be examined and understood in some of the same ways. Further investigations into this matter may ultimately show that memory exists and is organized in a manner that is necessary for nature to continue increasing its entropy within the constraints of the global Earth system. Additional researchers have begun to notice the connection at additional scales and link it to other processes like sleep, perceptual sensation, learning, notions of self, task performance, single cell recordings, and neural information flow in neuroimaging (e.g., Collell & Fauquet, 2015; Dimitrov, Lazar, & Victor, 2011; Varpula, Annila, & Beck, 2013). This framework diminishes the risk of epistemological shortcomings that result from the influence of Modern Western philosophy in contemporary studies of the mind (for discussions of such shortcomings see Anderson, 2014; Assecondi, Bagshaw, & Ostwald, 2014; Chemero, 2009; Clark, 2008; Sporns, 2012; Uttal, 2011).

For a comprehensive and fruitful understanding of the mind, researchers will benefit from not only broadening the scopes of their domains to take into account the brain-body-environment system, but also by examining the constraints imposed on living organisms by the SLT—and perhaps other laws. Moreover, such an approach looks to be a promising line of inquiry for building a *bottom-up* understanding of the mind. "Bottom-up" is used here to refer to a framework that is grounded in the laws of nature that ascend into higher order processes. Motivating this model is an appeal to the conditions for covering law models of explanation, which derives hypotheses from sets of premises that contain at minimum one law of nature. If the premises turn out to be true (e.g., empirical evidence), then there is strong assurance that the explanation will entail nomological necessity, namely, whatever happened *had to* happen.

This approach presupposes the commensurability of our theories and explanations of both biological and physical systems. We defended this presupposition by highlighting the guiding role entropy production has played over the history of the global Earth system. Rescinding the biophysical dichotomy that has held much scientific practice captive requires a non-dualistic approach to understanding the mind. Cognitive systems ought to be examined as biological systems, and biological systems as physical systems that are thermodynamically situated within their environments. From there, we can draw from the copious amounts of knowledge that exists in the domains of cognitive science, physics, biology, neuroscience, and philosophy to continue developing a comprehensive, lawful understanding of the mind.

References

Annila, A. (2010). All in action. *Entropy, 12*, 2333-2358.

Anderson, M. L. (2014). *After phrenology: Neural reuse and the interactive brain.* Cambridge, MA: MIT Press.

Assecondi, S., Ostwald, D., & Bagshaw, A. P. (2014). Reliability of information-based integration of EEG and fMRI data: A simulation study. *Neural computation, 27*, 281-305.

Boltzmann, L. (1886/1974). The second law of thermodynamics. In D. McGuinness (Ed.), *Theoretical Physics and Philosophical Problems: Selected Writings* (pp. 12-32). Boston, MA: D. Reidel Publishing Company.

Brissaud, J. B. (2005). The meanings of entropy. *Entropy, 7*, 68-96.

Chemero, A. (2009). *Radical embodied cognitive science*. Cambridge, MA: MIT Press.

Cisek, P. (2007). Cortical mechanisms of action selection: The affordance competition hypothesis. *Philosophical Transactions of the Royal Society, 362*, 1585-1599.

Clark, A. (2008). *Supersizing the mind: Embodiment, action, and cognitive extension.* New York, NY: Oxford University Press.

Collell, G., & Fauquet, J. (2015). Brain activity and cognition: A connection from thermodynamics and information theory. *Frontiers in Psychology, 6*, 1-11, doi: 10.3389fpsyg.2015.00818.

Craig, E., & Hoskin, M. (1992). Hegel and the seven planets. *Journal for the History of Astronomy*, *23*, 208-2010.

Davidson, D. (1995). Could there be a science of rationality? *International Journal of Philosophical Studies*, *3*, 1-16.

Dennett, D. C. (1995). *Darwin's dangerous idea: Evolution and the meanings of life.* New York: Simon and Schuster.

Dimitrov, A. G., Lazar, A. A., & Victor, J. D. (2011). Information theory in neuroscience. *Journal of Computational Neuroscience*, *30*, 1-5.

Favela, L. H., & Chemero, A. (2016). The animal-environment system. In Y. Coelllo & M. H. Fischer (Eds.), *Foundations of Embodied Cognition: Volume 1: Perceptual and Emotional Embodiment* (pp. 59-74). New York, NY: Routledge.

Friston, K. J., & Stephan, K. E. (2007). Free-energy and the brain. *Synthese*, *159*, 417-458.

Friston, K. (2010). The free-energy principle: a unified brain theory? *Nature Reviews Neuroscience*, *11*, 127-138.

Gibson, H. E., Edwards, J. G., Page, R. S., Van Hook, M. J., &, Kauer, J. A. (2008). TRPV1 channels mediate long-term depression at synapses on hippocampal interneurons. *Neuron*, *57*, 746–59.

Hegel, G. W. F. (1801/1987). Philosophical dissertation on the orbits of the planets (1801), preceded by the 12 theses defended on August 27, 1801. P. Adler (trans.). *Graduate Faculty Philosophy Journal*, *12*, 269- 309.

Kaila, V. R. I., & Annila, A. (2015). Natural selection for least action. *Proceedings of the Royal Society A*, *464*, 3055-3070. doi: 10.1098/rspa.2008.0178

Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, MA: MIT Press.

Keysers, C., & Perrett, D. I. (2004). Demystifying social cognition: A Hebbian perspective. *Trends in Cognitive Sciences, 8*, 501-507.

Rowlands, M. (1999). *The body in mind: Understanding cognitive processes*. Cambridge, MA: Cambridge University Press.

Schrodinger, E. (1945) *What is life?* New York: Macmillan

Sporns, O. (2012). *Discovering the human connectome*. Cambridge, MA: MIT press.

Stevens, S. S. (1957). On the psychophysical law. *Psychological review, 64*, 153-181.

Swenson, R. (1997). Autocatakinetics, evolution, and the law of maximum entropy production: A principled foundation towards the study of human ecology. *Advances in Human Ecology*, *6*, 1-48.

Swenson, R., & Turvey, M. T. (1991). Thermodynamic reasons for perception action cycles. *Ecological Psychology*, *3*, 317-348.

Teigen, K. H. (2002). One hundred years of laws in psychology. *The American Journal of Psychology, 115*, 103-118.

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action.* Cambridge, MA: MIT Press.

Trump, M. (2004). Sacramento–San Joaquin River Delta. *Wikipedia*, photograph. Retrieved January 29, 2015 from http://en.wikipedia.org/wiki/Image:Wpdms_usgs_photo_sacramento_delta_2.jpg. GNU Free Documentation License.

Varpula, S., Annila, A., & Beck, C. (2013). Thoughts about thinking: Cognition according to the second law of thermodynamics. *Advanced Studies in Biology*, *5*, 135-149.

Uttal, W. R. (2011). *Mind and brain: A critical appraisal of cognitive neuroscience*. Cambridge, MA: MIT Press.

Von Bertalanffy, L. (1950). The theory of open systems in physics and biology. *Science, 111,* 23-29.

Walmsley, J. (2008). Explanation in dynamical cognitive science. *Minds & Machines*, *18*, 331-348.

Zemelman, B. V., Nesnas, N., Lee, G. A., & Miesenböck, G. (2003). Photochemical gating of heterologous ion channels: Remote control over genetically designated populations of neurons. *PNAS*, *100*, 1352-1357. Image retrieved January 29, 2016 from http://www.pnas.org/content/100/3/1352/F2.large.jpg