Process and Mind: Exploring the Relationship Between Process Philosophy and the Nonlinear Dynamical Systems Science of Cognition

2016

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Abstract

This work examines the relationship between Alfred North Whitehead's process philosophy and the nonlinear dynamical systems framework for studying cognition. I argue that the nonlinear dynamical systems approach to cognitive science presupposes many key elements of his process philosophy. The process philosophical interpretation of nature posits events and the dynamic relations between events as the fundamental substrate of reality, as opposed to static physical substances. I present a brief history of the development of substance thought before describing Whitehead's characterization of nature as a process. In following, I will examine the both the computational and nonlinear dynamical systems frameworks for investigating cognition. I will show that the computational paradigm is subject to many of the same criticisms as substance. Conversely, I will show that nonlinear dynamical cognitive science avoids these criticisms and is congenial to Whitehead's philosophy insofar as it is suitable for describing emergent processes. To conclude, I suggest that the nonlinear dynamical cognitive science confirms and validates Whitehead's philosophy. Furthermore, I argue that process philosophy is an appropriate characterization of nature for guiding inquiry in cognitive science.

Keywords: cognition, metaphysics, mind, nonlinearity, process, system

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Chapter 1: Introduction

1.1 The Dilemma of Change

"Process" is a concept founded on the principle of change. Many principles in philosophy originated from simple questions. In the case of change, the question is: How is change possible? Attempts to explain change date as far back as the pre-Socratic philosophers (Lovejoy, 1906). If the history of philosophy is the history of its problems (Popper, 1963, p. 386), then we can begin to understand process by examining responses to the dilemma of change.

This endeavor ultimately leads into the history of the "substance" philosophy, whereby enduring material objects that exist independently from their environment are posited as the fundamental constituents of reality. Substance philosophy refers to any claim or presupposition that nature is comprised of permanent objects that have independent existence and properties. The mechanical physics developed during the 17th century presupposed a universe made of substances, and was largely influenced by the philosophical doctrines arguing for their existence. This resulted in well-established theories of matter that, aided by the invention of Calculus, enabled explanations and predictions of the trajectories and motion of many objects in nature. The presuppositions of the classical paradigm continued virtually unchallenged until Alfred North Whitehead generated his description of "process" philosophy during the early 20th century. Whitehead's philosophy dismisses several of the assumptions found in the doctrines of substance philosophy. Instead, he characterizes reality as a ceaseless process of becoming rather than permanent being in space and time.

Present-day process philosophers (e.g., Bickhard, 2008, 2009, 2011; Seibt, 1997, 2009; Stein, 2005) have continued to make the case against substance. Furthermore, they offer several key arguments in favor of process philosophy. Bickhard (2008) argues that many of our current scientific theories have benefited from moving away from traditional notions of substance. For example, the shift from phlogiston theory to the process of combustion for explaining fire. He also makes the case that our best scientific theories describe a quantum universe comprised of fields rather than elementary particles. Thus, there may be sufficient theoretical reason to dismiss the doctrine of substance, and doing so may also have pragmatic value for science insofar as it overturns standard conceptual and explanatory frameworks while encouraging the exploration of new questions and explanatory frameworks.

Process philosophy has yet to be given a great deal of attention in cognitive science. Meanwhile, traditional notions of substance have influenced philosophical debate (e.g., Kim, 1993) in cognitive science and other philosophical traditions, such as phenomenology (e.g., Gallagher & Sørensen, 2006) and logic (e.g., Turing, 1950), have guided inquiry in neuroscience and artificial intelligence, respectively. This work is intended to explore the similarities between the work of Whitehead, who has come to be known as the "champion" of process thought (Stein, 2004) and cognitive science. More specifically, it relates the application of nonlinear dynamical systems cognitive science and Whitehead's philosophy of organism. Along the way, some features of computational cognitive science will be examined from the context of Whitehead's philosophy.

The rest of this chapter is an examination of the philosophical responses offered to the question "How is change possible?" and how they facilitated the development of substance philosophy. It highlights how substance, aided by abstract mathematics, became the default theory for the ontological status of entities in nature. In Chapter 2 I will present an overview of Whitehead's philosophy of science and its subsequent evolution into process philosophy.

Chapters 1 and 2 should provide the conceptual background for relating substance and process thought to the various approaches for investigating cognition in Chapter 3. There I will show that the Nonlinear Dynamical Systems framework for studying cognition echoes several aspects of Whitehead's scientific philosophy and process philosophy. More importantly, it will be shown that nonlinear dynamical systems cognitive science and process philosophy are a matchless metaphysical and epistemological fit for explaining emergent phenomena investigated by cognitive scientists. To conclude, I argue that the congenial features between the two frameworks suggests that process philosophers and cognitive scientists ought to engage in a lively discussion in order to generate novel lines of inquiry.

1.2 Responses to the Dilemma of Change.

Active around 500 B.C.E., Heraclitus was among the first to offer a resolution to the question of change. Best known for the doctrine that one cannot step into the same river twice, Heraclitus' attempted to posit the process of change as the the fundamental essence of nature. A river is always in motion, and therefore is not the same river when stepped into a second time. It is always in flux and the flux as such is emphasized throughout his work. Heraclitus, "apprehended, and was the first to apprehend, the absolute as a process" (Patrick, 1888, p. 563). He can thus be considered a key figure in the development of process thought. However, it has been argued that Aristotle identified Heraclitus as a materialist monist (cf. Heidel, 1993). Indeed, a line from Heraclitus' fragments states, "as all things change to fire, and fire exhausted, falls back into things" (Haxton, 2011, p. 16). The passage appears to confirm that Heraclitus claimed fire was the material substance which all of nature could be derived from. However, when read in context with the second half of the passage, "the crops are sold, for money spent on food," it appears as though Heraclitus is calling our attention to a cyclical, non-static principle in nature—not to a material substratum. Heraclitus emphasized fire not for its role as the material substance from which all objects were derived, but because a flame appears as an enduring material object despite the regularity of its change. The flame highlights the constant flux within all of nature and tendency for man to attribute identity or permanence to objects undergoing constant change. Furthermore, Heraclitus' remark "if not stirred, the barley-brew decomposes" suggests that movement, or process, is necessary to maintain structures within nature (Popper, 1963, p. 388).

Heraclitus' position does not preclude permanence. Rather, both permanence and change are required for the material reality that is experienced. Mutually dependent opposites are necessary conditions for reality as we experience it, not static material substrates. This is all the more evident in the passage, "harmony needs low and high, as progeny needs man and woman" (Haxton, 2011, p. 17). Heraclitus' response to the question of change was to eliminate the need to explain how one object could change into another by characterizing nature as constant change, as a flux that precludes the type of permanence requiring explanation by the substance philosophies to follow. Nonetheless, several pre-Socratics continued to frame permanence as the target of their explanation.

1.3 The Origins of Substance

Parmenides' response to the question of change was to argue that change was not possible (Bickhard, 2011, p. 5). He argued that if object A was to change to object B, A must first disappear into nothingness and then reappear as B. This was impossible, Parmenides argued, because nothingness cannot exist, and therefore change is an illusion. In the case of Parmenides response to the dilemma of change, reason trumps the senses (the latter being mere deception).

The practice of granting privilege to a single epistemological method is repeated often throughout the history of philosophy of science. Nevertheless, attempts to resolve Parmenides' response to the question of change resulted in atomism and the theory of elements. Thus, answers to the question of change evolved into an explanation for the question, "What is nature made of?" Democritus' atomism is the belief that the universe is comprised of an infinite number of indivisible and unchanging entities that are invisible to the human eye. The Greek prefix "a" means "not," and the word "tomos" means "cut." When combined they form the Greek word *atomos*, which can be translated as "cannot be cut," as in they cannot be divided any further. Entities that cannot be divided any further were assumed to be the fundamental building blocks of reality. Democritus claimed that the differences in the shapes of the atoms, an independent property, determined the shape and properties of the objects we experience in nature when combined with other atoms. They are permanent objects, not coming into or out of existence, and all that is required for change is a simple reordering of their position in space. By positing a permanent and unchanging basic unit of nature, Democritus dealt a crucial blow to Parmenides' claims.

A competing theory arguing against Parmenides' claims was the theory of elements posited by Empedocles. The theory of elements posits four fundamental substances—earth, air, fire, and water—that, when combined, could construct all the objects in nature. Similar to atomism, rearranging the order of elements enabled change and the properties of an object acquired its properties based on the properties of the elements it was composed of. For example, water is wet and slippery because that is a property of the element of water itself, and the objects we encounter in nature that have their properties by virtue of the different combinations of the elements in them.

For both theories, nothing new comes into or out of existence, thus circumventing the paradox of nothingness proposed by Parmenides. It is entailed by both theories that the fundamental building blocks of nature are unchanging and that they possess a character intrinsically independent other entities. Therefore, the philosophies of Democritus and Empedocles were the first to fit the criteria of substance philosophy. Although they were among the first to develop the philosophies of substance, it was Aristotle's contribution that greased the wheels for its widespread acceptance.

Aristotle is one of the most influential thinkers in all of history (Hart, 1978). Several interpretations of his work suggest that his description of substance necessitates the independence of substances (e.g., Addis, 1972). In *The Categories,* Aristotle asserts that all beings can be distinctly classified in ten categories: substance, quantity, quality, relation, place, time, location, state, action, and affection. However, it is the first category, substance, that the rest of the categories depend on for predication. Aristotle claims, "everything except primary substance is either predicated of primary substances or is present in them, and if these last did not exist, it would be impossible for anything else to exist" (Aristotle quoted in Sellars, 1957, p. 688). The nine categories that are not substance are "present in" or "predicated of" the first category of substance. He continues, "by being 'present in a subject' I do not mean present as parts are in a whole, but being incapable of existence apart from the said subject" (Aristotle quoted by Edghill, 2009). Substance, for Aristotle, is the primary category on which the other nine secondary categories depend on for actualization, whereas substance has no such dependence. Substance is unique in that it is predictable of nothing and exists independently of its relationship to anything else in nature.

Substance philosophies posit entities whose existence in nature is independent of anything outside of themselves. Aristotle appears to have extended this line of thought further, not unlike Democritus and Empedocles, by asserting that other properties are “incapable of existence apart from said subject” (Edghill, 2009). For the two pre-Socratics it was the shape of the atoms or the properties of the elements that determined the character of the objects experienced in nature. Thus, at the very heart of substance philosophy lie two core assumptions: First, that nature is comprised of an unchanging material substratum. This theme was developed as a means to circumvent Parmenides’ claim that change was an illusion if an object had to go into and out of existence to undergo change because change is possible by virtue of re-arranging the atoms in space over time. Second, the unchanging material building blocks of nature must depend on nothing other than themselves for their existence and their properties if they are to be predictable of nothing and qualify as substance.

For the ancient Greeks, thinking about or referring to something was akin to pointing it out (Bickard, 2011, p. 91). Attributing predication to substances in the manner detailed in Aristotle’s doctrine found a natural home in ancient Greek society. This habit by the ancient Greeks was immensely successful for it enabled them to communicate the identity of an object by pointing out its properties. Its successes rendered it an unlikely assumption about nature to challenge. As we will see, this would not be the last time the success of a theory led to its widespread acceptance. Nevertheless, these philosophies stand in stark contrast to Heraclitus’ emphasis on process. But it was the philosophies of substance, due in part to the profound influence of Aristotle throughout history, that stood the test of time.

1.4 Substance in Modern Science

Greek philosophies of substance became the basis for the scientific concept of matter. Furthermore, Descartes' mechanical philosophy lent additional force to the idea of substance, though he posited both physical and mental substances. What began as a contentious philosophical conjecture eventually evolved into common sense—similar to ancient Greek substance philosophy. Subsequently, the success of mathematical thought in the 17^{th} century set the stage for the mathematically minded centuries to follow. Scientists developed the atomic theory of matter, treating objects in nature as point particles spread throughout geometric space at discrete instants of time. It was as if the scientific revolution "were some vivid dream of Plato and Pythagoras" (Whitehead, 1926, p. 33). These developments provided scientists with what was the ultimate goal of Newton and his contemporaries: the tremendous power to predict and explain the motion of objects through points in space and time. Moreover, it led to a relatively unparalleled period of engineering and technological advances that confirmed and validated the nascent sciences. In many cases it was common to find an entity stripped of all characteristics except its location in space and time. The passage of nature through time became "conceived as being merely the fortunes of matter in its adventure through space" (Whitehead, 1920).

The Cartesian doctrine postulated that the mind, in addition to matter, could be assimilated into the category of substance. The mental realm had entities—mental states—with unique properties. Thus nature consists of two kinds of fundamental substances subject to predication. On this view, the brain, along with the rest of nature, operated on mechanical principles and the mind operated on principles of reason.

The mechanical approach Descartes developed became an adequate replacement for Aristotelian physics at the time. Descartes subscribed to the theory of elements—earth, air, fire, and water—which could be distinguished by their characteristic sizes, shapes, positions, and motion. Matter was comprised of these elements, but unlike the atom, they were infinitely divisible and constituted space itself. The motion of matter, he claimed, was governed by three laws of motion and a law of impact that were guided by the will of God. His aim was to explain the realm of the physical in terms of purely material and mechanical process. But the realm of the mental was distinct. It was governed solely by human reason. Adding force to this theory of the mental realm was a contemporary of Descartes, Thomas Hobbes, who believed that the laborious calculations required to derive nascent scientific knowledge was an explicit model of the mental realm, whereby thought was carried out by rule-governed transformation of symbols in the head (Van Gelder, 1998). For Hobbes, reason was computation, "and to compute is to collect the sum of many things added together at the same time, or to know the remainder when one thing has been taken from another" (Hobbes quoted in Duncan, 2009).

The works of both men have had a profound impact on the Western world's understanding of the mind. Their impact on contemporary cognitive science are discussed in the forthcoming sections. The present task is to examine the heightened impact that substance philosophy had on the developments in modern science. By the 18th century it is was widely accepted that nature was comprised of fundamental objects with extension in space at an instantaneous moment of time. In order to develop clockwork-like explanations for the movement of these objects, Newton and Leibniz independently created one of the most successful mathematical frameworks to date: calculus.

In calculus, the concept of a "limit" enabled scientists to calculate the speed of an object at an instantaneous moment in time. However, speed can only be calculated if there is a change of location, thus the speed of any object at a durationless instant is by definition zero (Kraus, 1998, p. 12). Making this calculation required knowledge of a second point, infinitesimally close to the original point, used to calculate the change in distance during the smallest imaginable duration of time. This is the limit, a pragmatic mathematical abstraction that enables the calculation of a particle in space as infinitesimally close to an instant as is needed for our calculations. Scientists could use calculus to understand, predict, and explain the movement and reorganization of the particles compositing the entities revealed to our senses. They had seemingly mastered describing the change posited by Democritus.

The scientific revolution reintroduced the atomic theory of matter in light of these developments. Advances in abstract mathematics and an entrenched commitment to the notion of substance allowed scientists to understand the mechanisms underlying the movement of objects. Though at first it was merely a mathematical entity whose primary qualities were quantified as aspects of Euclidean space, the atomic theory evolved into an attempt to understand the structures of these substances—the consequence of which is the enterprise of chemistry (Whitehead, 1926). As Democritus claimed, atoms have their own shapes and properties, and chemistry successfully endeavored to reveal them.

It would be difficult to overstate the success this doctrine has had for engineering and technology. The subsequent discovery of the electron became the ultimate triumph for the evolution of ancient notions of substance. It was virtually inconceivable at the time to doubt that nature was comprised of interacting atoms that possessed independent properties at points in space and time. The scientific revolution's response to the question "What is the world made of?" was infinitely small particles, thus reaffirming the pre-Socratic response to the question of change, namely, that is was the consequences of the reorganization of enduring substances in space through time.

Many of the first attempts to explain change in nature lead to common-sense doctrines of substance that have influenced the history of philosophical and scientific thought. The traditional notions of substance remain influential to this day. In the following chapter, I will examine Whitehead's scientific philosophy that was highly critical of these substance-based habits of thought and present his extensive metaphysical framework he believed could account for these shortcomings.

Chapter 2: Whitehead's Philosophy of Science and Process Philosophy.

2.1 Process Philosophy

Alfred North Whitehead echoes Heraclitus' emphasis on the flux of nature, claiming it is the, "one generalization around which we must weave our philosophical system" (Whitehead, 1978, p. 208). Moreover, his scientific philosophy was critical of traditional substance based habits of thought, due in large part by the intractable philosophical problems they engendered (i.e., the discontinuity of space, time, and matter; a lack of justification for inductive reasoning; and the dualist categorization of nature). In describing his comprehensive metaphysical schema in *Process and Reality*, he framed it as an, "endeavor to frame a coherent, logical, necessary system of general ideas in terms of which every element of our experience can be interpreted" (Whitehead, 1928, p. 3). The privilege Whitehead grants to the reality of our experience of nature is apparent in this passage. However, he is careful to avoid, and is often critical of, subjective idealism. Rather, he affirms that our sense awareness is the awareness of something else and insists that the character of immediate experience serve as the foundation for scientists and philosophers to build their descriptions of reality on (Whitehead, 1927/1978, p. 157).

In the wake of his mathematical work, Whitehead offers a description of reality where material substances are no longer fundamental. In their place he posits "events," which are experienced in the unity of our immediate experience and are situated within and coinciding with other events, as the fundamental elements of nature. In exiling the enduring material world from his concept of nature, though, Whitehead exposes his philosophy to Parmenides' charge that change must be an illusion. Whitehead moves to characterize nature as a "process of becoming," or a "creative advance," whereby events in the present inherit their character from the past while actively bringing about the future.

In this chapter I will outline a brief historical account of Whitehead's philosophy of science. Of central focus will be his objections to the traditional doctrine of substance, the dualistic account of reality, and concerns regarding causation and induction. I will then present his process philosophy, which Whitehead refers to as the philosophy of organism, and how generalizing from the features of immediate experience enabled him to generate an interpretation of reality that was not subject to these criticisms.

2.2 Whitehead's Philosophy of Science

Whitehead introduced his philosophy of science due to concerns with the traditional materialist habit of thought. He describes it as, "one long misconception of the metaphysical status of natural entities" (Whitehead, 1920). Dissatisfied with the geometric description of nature that consists of three mutually exclusive classes of entities (space, time, and matter), he argues that the principle of Occam's razor motivates reducing the classes of entities posited (Whitehead, 1906). He endeavored to develop potential mathematical methods for expressing space, time, and matter in terms of a single relation (Lowe, 1962, p. 160). The desire to unify space, time, and matter into a unified framework would fully come to fruition in metaphysical form when he published *Process and Reality* (PR). Prior to that, however, he directs his criticisms of science in *The Concept of Nature* (CN) towards two distinct, but related, scientific and philosophical habits of thought: the fallacy of misplaced concreteness, and the bifurcation of nature.

2.2.1 The Fallacy of Misplaced Concreteness.

Whitehead (1920, 1926, 1927/1978) was weary of abandoning what is experienced by "sense-awareness" in favor of notions that are arrived at via the act of abstraction. The practice of using calculus to slice nature into durationless instants of time exemplifies this line of thought. Though not opposed to the use of abstract thought, nor to its application, he aimed to remind researchers that they ought to avoid characterizing objects in nature in the same manner as the entities posited in abstraction (Whitehead, 1920). If one concludes that an abstract entity exists in nature in such a way, they commit what he calls 'the fallacy of misplaced concreteness.' He fervently attributes this fallacy to the scientific doctrine of physics that posits the existence of volumeless points of matter at durationless instants in time as fundamental (Whitehead, 1920, 1926, 1978).

A mathematician before turning his attention to philosophy, Whitehead understood that the physics of his time was couched in the language of mathematics. Noting that the notion of simple location at a durationless instant in time has always satisfied scientists' need to explain, predict, or create, Whitehead stressed that, "mathematics is thought moving in the sphere of complete abstraction from any particular instance of what it is talking about" and yet, "the paradox is now fully established that the utmost abstractions are the true weapons with which to control our concrete thought" (Whitehead, 1926, p. 27). For men of science to understand fundamental substances it became necessary to look at lower levels of nature than what was revealed to their immediate experience and doing so created a scientific habit of thought built on a foundation of abstractions. To illustrate the fallacy in its completed form, Whitehead turns to quantum theory.

An electron is measured as it appears in a series of discrete positions in space, not a continuous path through space (Whitehead, 1926, p. 39). This exemplifies the lack of endurance for objects in time and space, different from the view that had been established in Europe since the development of substance philosophy. Whitehead decries the practice of calculating the average position of an electron from its discrete appearances, and then claiming knowledge of the precise location of an enduring object in a volumeless point in space at an instant of time, as a fallacy. The electron does not appear to travel through space nor does it exist at an instant, and instead requires a durative period with which to manifest itself.

Scientists errored when they imposed their tried and true metaphysical assumptions of substance into their interpretations of scientific data. Whitehead argues that the quantum data, in addition to our immediate experience, suggests they do away with the traditional view of matter, and that there is no need to posit a new substance in its place. Instead, the electron should be understood as being like a musical tone produced by vibrations in air molecules. Whitehead insists that the goal of scientists and philosophers was to reveal the "ingredients" that go into a "vibratory organism" (Whitehead, 1926, p. 40).

The use of the term 'organism' is significant here. Darwin's theory of evolution was very much alive in the minds of the Western world in the early 20th Century and it greatly influenced Whitehead's thinking (Lowe, 1962, p. 223). Whitehead, along with one of his most influential colleagues, Samuel Alexander, were part of a loosely formed movement known as emergent evolutionism (Goldstein, 1999). The central hypothesis of the movement was that entirely new properties, such as life and mind, could be caused by static and unchanging material substances. Whitehead's fully developed metaphysical schema, which he so aptly dubbed the philosophy of organism, rehabilitated the traditional view of causality in a manner (as a process of becoming) that would not preclude emergent phenomena. His position on causality is alluded to in his second criticism of the materialist habit of thought: the bifurcation of nature.

2.2.2 The Bifurcation of Nature.

Whitehead's criticism of the bifurcation of nature was directed at the persistent habit of philosophers and scientists to divide nature into two categories of existence: the "causal nature" posited by scientific theories and the "apparent nature" apprehended in sense-awareness (Whitehead, 1920). Causal nature is the inertial transmission of substances through space that may come into contact with the body, and apparent nature is the sensation of heat, sight, or smell experienced by the mind. Whitehead states that there is insufficient justification to state that both the molecules conjectured by scientific theory and the greenness of the grass apprehended in awareness are elements of different categories of nature. Furthermore, there is no reason to assign ontological superiority, "in nature to material inertia over colour or sound" (Whitehead, 1920). Instead, he argues that nature apprehended in awareness and the causal nature based on theory are both elements *within* nature. He summarizes the objection to the theories of bifurcation as follows:

> In the first place it seeks for the cause of the knowledge of the thing known instead of seeking for the character of the thing known: secondly it assumes a knowledge of time in itself apart from the events related in time: thirdly it assumes a knowledge of space in itself apart from the events related in space. (Whitehead, 1920)

Instead of bifurcating nature into two categories of existence, Whitehead asks what characteristics of causal nature ought to be shared by apparent nature. The seed for this critique was planted in his (1906) memoir that argued against a theory of nature in which space, time, and matter are understood as mutually exclusive. Such an account provides no correlation between these classes of entities, which creates havoc for our understanding of causation and the practice of induction. That is, there exists, "no physical relation between nature at one instant and nature at another instant" (Whitehead quoted in Lowe, 1962, p. 199). What he is beginning to allude to is that, rather than causal nature simply *being in* space and time, causation is the result of spatially and temporally related "events."

The bifurcation theories leave Whitehead unsatisfied with the account of causality that is couched in the doctrines of substance insofar as they fail to align what is observed with the concept of a material world of enduring substance. Our awareness of nature is that of situated events perceived through duration, and thus the objects of inquiry for natural science are states of change (Lowe, 1962, p. 200). Events are Whitehead's answer to the inadequacies of substance philosophy and he sought to show that they could do justice to the interconnectedness of nature. This contrasts with Descartes' description of substances that, "require nothing but themselves in order to exist" (Descartes quoted in Whitehead, 1978, p. 179).

2.2.3 The Ontology of Events

Events are inherently durative in Whitehead's philosophy. This was the natural conclusion for him given the character of reality presented to immediate experience. He describes events using an analogy of Russian nesting dolls, whereby a series of increasingly smaller dolls rest within a series of larger dolls (Whitehead, 1920). This is the first step in characterizing nature in a manner that precludes mutually exclusive classes of entities. Therefore, the analogy of the Russian nesting dolls applies to both the spatial location of events and their temporal durations. All events are extended in both time and space, that is, events extend over events in time and over events in space. Space, time, and matter are here construed as a single relation. The nested doll analogy is easier to illustrate by appeal to spatial events. For example, the event of a biological cell is nested within the event of a human organ that is nested within the event of a human body. For the durative aspect of events, the assassination of John F. Kennedy is an event that is temporally extended over the event of the gun firing, and the firing of the gun is an event that extends over the mere pulling of the trigger. Events extending over concurrent events is a concept Whitehead refers to as the "principle of extension" (Whitehead, 1920).

The analogy of the Russian nested doll is doubly important because we must understand that every event is comprised of events and is a constituent of other events. They are interrelated, unlike enduring substances, and they do not exist in isolation. Rather, events always presuppose something within themselves, and they themselves are presuppositions in concurrent events (Whitehead, 1926, p. 88). As Rowe (1962) puts it, we are, "aware that inside the cupboard there are events whose space-relations complete the space-relations of the things fully seen (the exterior of the cupboard, other objects seen in the room)" (p. 204). Thus, Whitehead details a unity within nature that is inherent to enduring events, and unity as such would lack coherence if developed within the traditional theories of substance. He characterizes the unity of events in the following passage.

> That which endures is limited, obstructive, intolerant, infecting its environment with its own aspects. But it is not self-sufficient. The aspects of all things enter into its very nature. It is only itself as drawing together into its own limitation the larger whole in which it finds itself. Conversely it is only itself by lending its aspects to this same environment in which it finds itself (Whitehead, 1926, p. 89)

This passage serves to highlight one of the key differences distinguishing process philosophy from substance philosophy. Substance philosophy posits enduring unchanging entities with unique properties that are independent of external influence. For this ancient doctrine, change is brought about by the simple reorganization of substances in space that is caused by external forces influencing their interactions. On the other hand, having done away with the traditional notion of enduring material objects *being in* space and time, Whitehead is beginning to present an ontology of durative events revealed directly to immediate experience that are created by the internal constitution of a multitude of events, while also being limited by the larger whole of events in which it finds itself. A metaphysical framework accounting for the creation and dissolution of these events and their direct perception in immediate experience is described by his philosophy of organism.

2.3 The Philosophy of Organism

The general hypothesis underlying Whitehead's metaphysical schema is that the structure of reality is analogous to the structure of every organism, and that the structure of an organism is analogous to an occasion of experience. The principle of transitivity then suggests that reality should have the character of that which is presented in immediate experience. In PR, experience is described as, "the self-enjoyment of being one among many, and of being one arising out of the composition of many" (Whitehead, 1927/1978, p. 145). The task for Whitehead then—if he is to unify space, time, and matter into a single coherent relation—is to conceive of nature in such a way that it can be understood as a single unity, while accounting for its actualization "by many" and "among many." His answer was that the whole of nature arises from the creative advance of "eternal objects" as they are realized into "actual entities."

2.3.1 The Creative Advance

The creative advance is the "ingression" of "eternal objects" into actual occasions within nature. Whitehead writes extensively on ingression, but for present purposes it can be understood as the realization of potential entities. The eternal object is the concept developed by Whitehead that refers to entities with the potential to be actualized. They are pure potentialities. While they have many similarities to Platonic and Aristotelian forms, they are distinct in that they are not independent or superior to changing things (Lowe, 1962, p. 27). Eternal objects have several unique features that distinguish them from objects encountered in experience as well: First, they are infinite in quantity. Second, they are eternal. Like substances posited by previous theories, they can be thought of as enduring, except that they are not *in* space or time. As pure potentialities, they do not exist in the spatial and temporal relation presented to immediate experience. Instead, they are presupposed by it. That is, an event realized in nature presupposes existence of a prior potential for its actualization. Eternal objects as described here are a necessary presupposition for reality construed as a continuous creative advance. They are ingredients in the "process of becoming."

The principle of pure potential entails a presupposition of its own: actualized existence in nature. An "actual entity" is an eternal object that has been actualized into nature. Each actual entity has for itself a "private side" and "public side," and are characterized by Whitehead as "drops of experience, complex and interdependent" (Whitehead, 1978, p. 18). A drop of experience inherits, and is thus constituted by, knowledge of the prior occasion as it fades into the past. This is Whitehead's attempt to weave the experience of memory into his conception of nature. Their public side is what can be felt by the concurrent community of actual entities. The totality of actual entities that are actualized simultaneously form the continuum of actual entities. Whitehead refers to this totality as the "actual occasion." An actual entity's feeling of both the immediate past and the concurrent community of events is a fundamental fact of nature in his philosophy. It is the "value" of that occasion. They constitute the immediate fact available for "prehension" by an actual entity so as to realize its actualization.

Prehensions can be understood as the entity's feeling, or grasp, of the information made available to it by the public side of concurrent actual entities. This characterization is noteworthy because human experience of the subjective self and the objective world has historically led to multiple dualisms. This move highlights Whitehead's desire to position each element of human experience as a fact of nature rather than dividing it into multiple categories of existence. He states, "the sole concrete facts, in terms of which actualities can be analyzed, are prehensions [of objects by subjects]; and every prehension has its public side and its private side" (Whitehead, 1929, p. 290). The private subject and the public object are fundamental facts of reality presented to immediate experience. Preference is not to be given to one over the other as is often done throughout the history of philosophy.

2.3.2 Process Philosophy

At this point we can begin to unpack the characterization of Whitehead's philosophy as that of process. In his scientific philosophy he rejected the plausibility of the traditional notions of substance and the subsequent dualisms that naturally arise from them. In addition to the vibratory nature of quantum theory, Whitehead notes that atoms can decay or be altered by chemistry (Whitehead, 1926). Thus, the doctrines of substance failed in their attempt to capture structures that never take a break from nature. Having dismissed substances, Whitehead sought to reveal the undeniably invariant and enduring elements of reality. In the previous section I described two of these elements: eternal objects and actual occasions. The two concepts inherently presuppose each other. Eternal objects, being pure potentials, could not have the character of potentiality if actual entities did not also exist; and actual entities could not exist if their potential did not exist. The third invariant element found in nature is also presupposed by eternal objects and actual entities, while at the same time presupposing them. That element is the *process* of becoming.

Pure potentials and their subsequent actualizations presuppose a procedure by which the potential can be actualized. Thus, nature is not comprised of static enduring substances. Nature *is* a process. The process is that of becoming. It is a ceaseless creative advance whereby eternal objects are transmuted into actual entities by their prehensions of the immediate fact that is the rest of nature in that moment. All that is within nature is an evolving continuum of actual occasions, and the actual entities of the occasion adapt to it like organisms in their environment. The drops of experience are the units in nature that constitute events and the relationships between them (which are also events). Nature so construed unifies space, time, and matter into a single coherent organism whereby all of the elements of the system presuppose each other.

Whitehead's account of process philosophy is antithetical to the arguments made by Parmenides. Not only is change not an illusion (illusions being very much real in Whitehead's philosophy, insofar as they are found *within* nature), but nature at any moment *is* the effect of a ceaseless process that features coming into and going out of existence. "The reality is the process," Whitehead (1926, p. 90) claims. The process of ceaseless becoming drives the passage of time forward. Permanence may appear, but it does so as the result of repeated patterns of continuous becoming that are reinforced by the prior occasions and constrained by community of actual entities which every actual entity finds a member of. *Being* is the consequence of patterns of *becoming*.

There are three key features of human experience that Whitehead includes in his process philosophy that are worth restating. First is that there are many real things: events, potentials, experiences, feelings, processes, etc. There is little wishing away of contradictory concepts in the quest for simplicity or some other ideal. Second, the multiplicity of all things are connected with one another. For example, without the information made available by a community of actual entities (actual occasions) or the past that preceded them, the realization of an actual entity would not have the essence that it otherwise would have had. In that sense, an actual entity is connected to all of space and time. Third, process is, "the most evident characteristic of our experience" (Whitehead, 1938, p. 109). Therefore, any theory of nature cannot justifiably preclude the reality of process, the flux, from its descriptions of it.

There is a fourth feature that has not been explicitly pointed out but is necessary to present insofar as it major implications for the traditional notions of causality. The feature is the "effectivity of aims." That is, the realization of an actual entity is the consequence of its aim to experience that occasion. Aims are an undeniable element of human experience. Whitehead writes, "the conduct of human affairs is entirely dominated by our recognition of foresight determining purpose, and purpose issuing conduct" (Whitehead quoted in Christian, 1959, p. 219). In rendering aims effective, Whitehead is able to justify beliefs that nature at one moment of time can influence nature at the next, due to intentionality being a feature of sense-awareness. Thus, the justification for induction is an apparent fact of reality, so long as causation is not construed as the interaction of particle *in* space or *in* time. Rather, space and time are the relations caused by the aims of actual entities as they are prehended in nature. Causation occurs through the continuous ingression of actual entities from eternal objects into the immediate occasion, and it would be incoherent with respect to Whitehead's philosophy to assert that causation occurs between unrelated entities traveling through time and space.

For Whitehead, what began as a project to generate a new geometry for space, time, and matter lead to the development of a monumental metaphysical schema. This required a novel interpretation of reality that didn't fall victim to the traditional materialist habits of thought. He rejected the ancient doctrines of substances and in their place positioned events as the objects in nature worthy of predication. According to his philosophy of organism, events are the outcome of a ceaseless ingression of eternal objects into a community of actual entities in nature. Whitehead referred to this as a 'creative advance' or the 'process of becoming.' He built this characterization of nature by using the features of reality experienced in sense-awareness as a starting point. In doing so, Whitehead synthesized his mathematical, scientific, and metaphysical philosophies into a coherent, logical, and necessary system for interpreting nature.

In the next chapter I will present a brief account of several developments in cognitive science that lead to the application of dynamical systems theory to study cognition. The following chapter will juxtapose these developments and dynamical cognitive science to the development of Whitehead's philosophy and his description of nature.

Chapter 3: From Computationalism to Dynamicism

3.1 Computationalism

The crux of the mainstream (classical) approach to studying cognition is the hypothesis that cognitive agents are computational agents. This is sometimes referred to as the computational hypothesis (Newell and Simon, 1976). The computational paradigm has dominated cognitive science for decades and has been highly productive, generating many insights into the nature of human cognition (for a thorough review, see Miller, 2003). The computational hypothesis comes in strong and weak forms. The weak claim is that cognitive agents can be *understood* as digital computers. The successes of the paradigm presented by Miller (2003) suggests that this is at least approximately true. The strong claim, rooted in the earliest work in cognitive science, suggests cognitive agents *are* computers.

In the early days of cognitive science, Newell and Simon (1976) published a paper describing the concept of a "physical symbol system," a concept that became a foundational principle on which computational cognitive science was built. A physical symbol system is, "a physical device that contains a set of interpretable and combinable items (symbols) and a set of processes that can operate on the items (copying, conjoining, creating, and destroying them according to instructions)" (Clark, 2013, p. 30). Newell and Simon go on to claim that such systems are both necessary *and* sufficient conditions for intelligent action. A system's intelligence was thought to be measured by its ability to achieve a predefined goal by computing a linear series of steps (Newell & Simon, 1976, p. 114).

The claim that physical symbol systems were both necessary and sufficient conditions for intelligent action exerted a large influence on scientists and philosophers studying the mind. Human cognition was thought to exemplify intelligent action. Thus, it was inferred that, if physical symbol systems were both necessary and sufficient for intelligent action, the human mind *is* such as system. At the time, a special kind of physical symbol system was all the buzz: the digital computer.

Computation was formally developed by Alan Turing (1936). The first digital computers, like those influenced by John von Neumann's designs, were the "bedrock machinery" that instantiated Turing's notion of computation (Clark, 2013). These early machines could compute answers to challenging questions via computations governed by a set of physical symbols (which, at the time, were nothing more than holes punched in tape). They were designed to run independently according to a set of predefined instructions (a program) carried out over a linear series of discrete symbol structures. Haugeland (1981) describes a well-programmed computer, "like a chess set that sits there and plays chess by itself, without any intervention from the player…" (p. 10).

Influenced by Newell and Simon's physical symbol system, classical cognitive scientists assumed the mechanisms by which intelligent tasks were carried out by humans was computational. The mind, then, was thought to be a program operating over a series of symbolic structures. Thus, the aim of the classical approach was to investigate the programing and symbols governing the mind's behavior (Shapiro, 2011, p. 14). Sensory organs were posited as first step of the computational process. Impoverished signals from the environment are transmitted from sensory organs, through the nervous system, and into the brain where they are enriched so that they may be manipulated computationally. At this step enriched signals become inputs ready to be processed. That is, the impoverished sensory signals are transformed into the system's symbols, taking the form of representations of the external world. The human memory system, analogous to the memory system of a computer, stored knowledge and could be retrieved when called upon to allow the mind to make inferences, decisions, judgements, action and more. This is the output component of the system and signals the final step in the computational sequence.

3.2 Representationalism

Given that one of the core claims of the classical paradigm is that representations are required for computation (Fodor, 1983), any controversy regarding the existence of representations or mental states is a controversy for computational cognitive science. Consequently, the ontological status of representations has been a hotly debated topic (cf. Chemero, 2009; Clark, 2013; Shapiro, 2010). Much of this debate revolves around the causal nature of mental representations. If mental representations can be observed and tested in a lab, then they have the type of causal powers that can be observed with scientific instruments. In that case, it would be difficult to deny they are real, and therefore must have the power to influence cognitive behavior. Unfortunately, direct observations of a cognitive agent's subjective mental representations continue to elude scientists. Consequently, proponents of the computational hypothesis were forced to find alternative arguments to account for the ontological status of these entities.

Some prominent philosophers from the computational camp have stated that mental representations are theoretical entities (e.g., Fodor, 1983). For example, scientists, despite being unable to observe them directly, posited atoms in their theories to explain the cause of behavior of their instruments during experiments. Accordingly, mental representations are, "vindicated and their proposed properties are confirmed by the success of explanations that call upon them" (Chemero, 2009, p. 50). Essentially, mental representations have often been successfully appealed to in order to explanation various types of behavior. For example, a child cries after falling from their bicycle because they experienced the mental state of being in pain. However, the philosophical objections did not stop there. Chemero (2009) argued that the more fundamental task for the theories of representation is to explain how objects outside the agent could come to exist as representations inside the head. However, rather than taking on this daunting task, some researchers began to develop theoretical and methodological practices to examine cognition without appealing to representation.

3.2.1 Non-Representationalism

One of the first cognitive frameworks that did not appeal to representation was developed by James J. Gibson (1979). Rather than posit theoretical entities inside the head, Gibson argued that cognition was carried out through an organism's active engagement with the environment. The main claim was that an organism's perception of the environment was direct, a claim exemplified in the following passage.

> Perceiving is an achievement of the individual, not an appearance in the theater of his consciousness. It is a keeping-in-touch with the world, an experiencing of things, rather than a having of experiences. It involves awareness-of instead of just awareness. It may be awareness of something in the environment of something in the observer or both at once, but there is no content of awareness independent of that of which one is aware. (Gibson, 1979, pp. 239-240).

Gibson applied this concept of “direct perception” to his explanations of behavior in what would eventually become the core hypothesis of ecological psychology (Turvey et al., 1981). This approach leaves the properties of the external environment where they are (instead of in the head) and interprets perception in a way that, “allows natural laws, relating occurent properties to both animal and environment dispositions, to replace cognitive rules, relating concepts and representations” (Turvey et al., 1981, p. 292). Among the finest examples demonstrating Gibson’s theory of direct perception is the visual cliff experiment (Gibson & Walk, 1960). In this experiment, both preterm and at-term infants are placed on an apparatus with a four-foot drop off. A Plexiglas panel strong enough to support the weight of the infants is placed over drop off to ensure their safety. The use of very young infants is significant. At their age it was thought that they would not have acquired the knowledge to compute depth perception. Thus, an infant that avoids crawling onto the faux cliff would be the exemplify an effect, caused by the direct perception of depth—not an inference computed using representations. The infants are then placed on the apparatus and the mothers are instructed to call for them or present a toy from the other side of the faux cliff. Several infants crossed but were hesitant, and many refused to cross at all. Moreover, some of the infants that refused to cross the edge did so despite having knowledge of the solid glass after patting it.

This experiment supports the core criticism of the representational account of cognition from the ecological camp. The infant’s decisions were caused by the direct perception of depth, not from the properties of representations generated by the mind. Gibson’s theory of direct perception suggests that the environment contains adequate information for perception and action, thus positing theoretical entities is superfluous. This positions direct perception of the environment as the cause of action.

To illustrate the difference, consider an example of behavior caused by the representational account of cognition. Imagine you're driving to work after a violent storm the night before. As you drive, you experience the mental representation of a tree that was blown down and is now laying across the road. In the next moment you experience a representation signaling danger, followed by a representation signaling to brake. For the classical approach, the cause of you breaking was a representation of the possible outcome had you collided with the fallen tree. It suggests that you are not aware of the fallen tree itself, but are aware only of your mental representations and that you can only only infer from them what action to take. This is in stark contrast with the non-representational approach of the ecological psychologists, whereby perception of the external environment is direct and therefore constitutes the cause of cognitive behavior.

The debate over representation continued to motivate researchers to seek out alternative ways to explain cognitive behavior. In addition to ecological psychology, several competitor approaches have been developed. Today, however, the largest theoretical chasm exists between computational cognitive science and dynamical cognitive science (Van Gelder, 1998).

3.3 Dynamicism

Dynamical cognitive science is an alternate framework for investigating cognition. One of the core claims from this approach is that cognitive agents *are* dynamical systems (Van Gelder, 1998), that is, they are systems that change over time. Dynamical cognitive scientists employ the broad theoretical framework of dynamical systems theory (DST) to describe laws governing the behavior of complex systems. Hume's dream of a mathematical understanding of the laws governing the mind, akin to laws governing the physical world, is somewhat realized by this framework.

DST is a branch of pure mathematics developed by Poincaré (1890) to provide a *qualitative* description of celestial mechanics. It is considered a qualitative framework due to its reliance on differential equations to generate geometrical and topological models (in phase space or state space) depicting all the possible states for all times and initial conditions at once (Thompson, 2007, p. 40). Differential equations are used when the system being described undergoes continuous change. Difference equations would be used if the system was changed in discrete steps. One of the key features of differential equations is that they may require knowledge of variables from more than one system in order to be modeled. Such systems are said to be dynamically coupled (Beer, 1995).

An example of a simple dynamical system is the pendulum. A pendulum mass repeatedly swings from side to side over time, and its position is relative to its speed. The pendulum slows down the closer it gets to the apex of its swing, and is moving fastest toward the bottom where the pendulum would rest if it weren't in motion. The location of the pendulum could be calculated given knowledge of its speed and vice versa. Nonetheless, qualitative models may be the preferred method of description because it visualizes all the possible states the pendulum could be in as a function of time. A common model used to represent dynamical systems is the phase portrait. Phase portraits can present the trajectory of all the possible states a system can pass through in the system's phase space. A phase portrait for a pendulum is depicted in Figure 1. The horizontal X-axis depicts the position of the pendulum and the vertical Y-axis depicts its speed. The arrows define a vector field depicting the flow of the system.

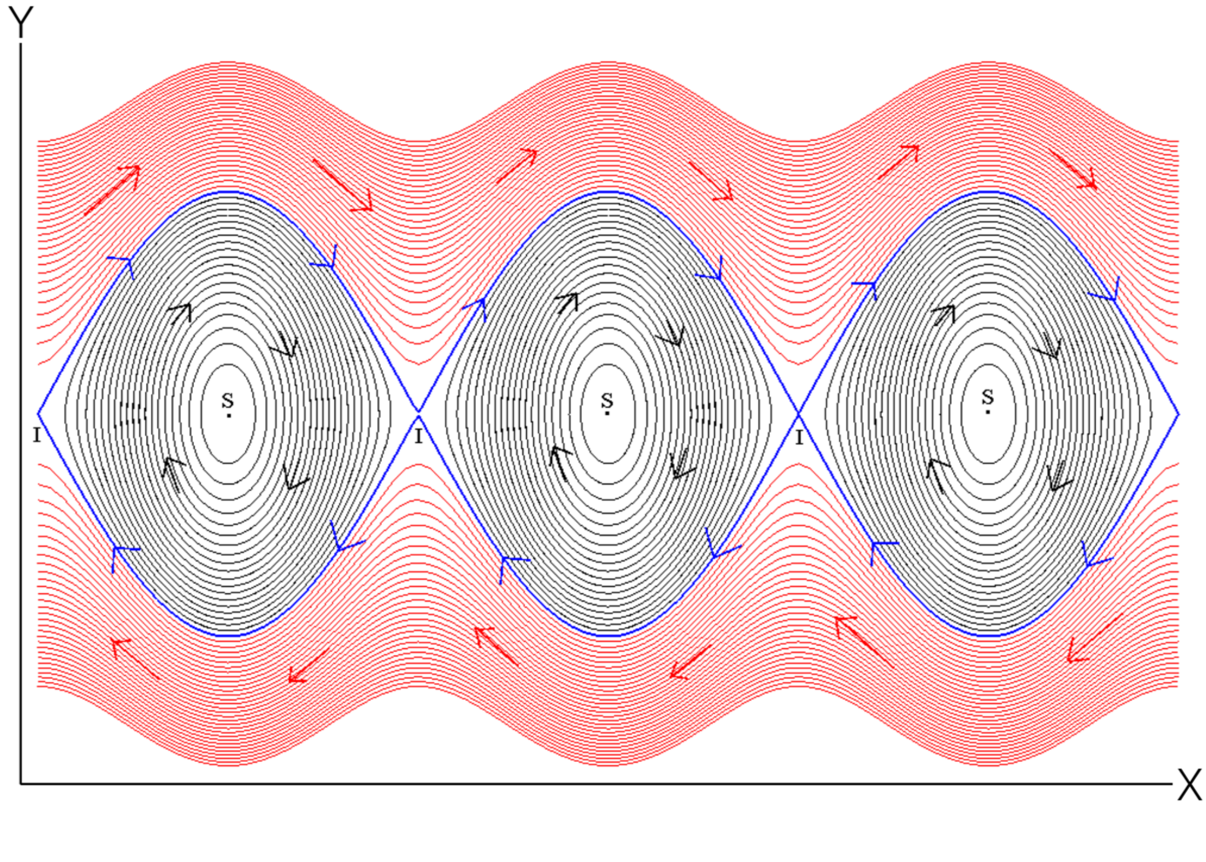

Figure 1. Phase portrait of pendulum motion. The X-axis depicts the pendulum's position and the Y-axis depicts its speed. (Modified creative commons image. Retrieved June 7, 2016 from https://commons.wikimedia.org/wiki/File:PenduleEspaceDesPhases.png)

DST is not restricted to depicting the behavior of simple pendulum motion. It has been applied to natural phenomena at various levels of description, from quantum mechanics all the way up to cosmology (Van Gelder, 1998, p.11). Dynamical systems theorists assume that the mind and the body are a part of the same natural world. Therefore, DST is an appropriate tool for describing the various types of cognitive behavior that occur at various levels of analysis (i.e., neural dynamics and motor coordination), a feature that the representational framework had difficulty accounting for. According to Fusella (2013), “DST views all psychological processes and capacities as dynamic systems which are best described as complex, non-linear, self-organizing and emergent” (p. 1).

The emphasis on complex, non-linear, self-organizing, and emergent phenomena (which are inherently related in a manner to be described later) distinguishes dynamical cognitive science from other alternatives. Kelso (1995) was among the first dynamical cognitive scientists motivated to study behavior according to one of these processes, namely, self-organization. Self-organization refers to spontaneous pattern formations that arise without a central control mechanism guiding behavior. That is, “the system organizes itself, but there is no ‘self,’ no agent inside the system doing the organizing” (Kelso, 1995, p. 8). Examples include the structures built by social animals (i.e., beehives) and flocking behavior formed by flocks of birds or schools of fish.

In one of the landmark experiments establishing DST as a viable alternative to the classical framework, Haken and colleagues (1985) developed a dynamical model (HKB Model) describing the spontaneous change in rhythmic finger motion found in novel experimental observations. Subjects were instructed to oscillate their index fingers back and forth with the same frequency as a metronome. It was found that subjects performing this task can regularly reproduce two stable patterns (see Figure 2). First, the in-phase pattern, whereby both fingers move in the same direction at the same speed, and second, the anti-phase pattern, whereby both fingers move in the opposite directions at the same speed. Both patterns are depicted below in Figure 2.

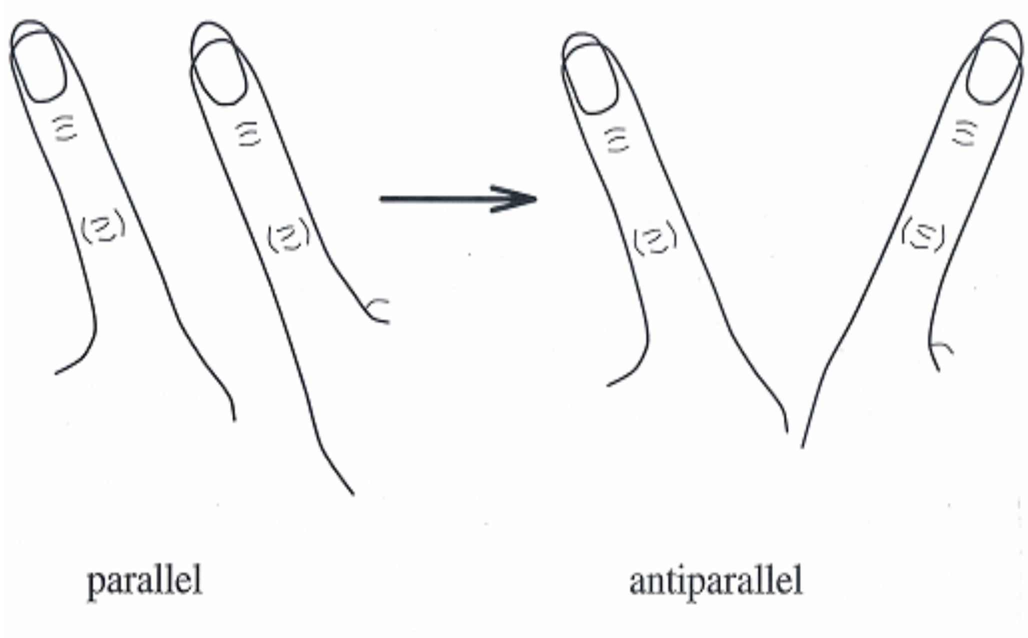

Figure 2. In-phase and anti-phase (parallel and antiparallel) finger movement patterns. (Creative Commons Attribution-ShareAlike 3.0 License. Retrieved June 7, 2016 from https://en.wikipedia.org/wiki/File:Self-Organization_in_Brain_Fig1.png).

Haken and colleagues then asked participants to match the speed of their finger movement with the increasing frequency of a metronome. They discovered that, as the speed increased, the rhythmic behavior reached a threshold, a “critical” value, where subjects performing the anti-phase pattern spontaneously transition to the in-phase pattern. They also found an additional threshold where the sped-up, in-phase pattern could transition back to the anti-phase pattern as the metronome frequency decreased.

While observing finger wagging behavior may seem inconsequential, it demonstrated that motor behavior could be explained without appealing to representations. Instead, the behavior is described in the language of dynamical systems, which appeals to “control” and “order” parameters to describe the system (Van Rooij & Favela, 2016). An order parameter can be thought of as the dependent variable of the system whose behavior is the target of measurement in an experiment. Control parameters can be thought of as the independent variables of the system guiding its behavior.

The order parameter in this experiment refers to the phase relationship of the finger movement—the relative phase. The relative phase is selected as the order parameter due to the system's nonlinearity, a feature that entails new quantities beyond the activity of the individual components be accounted for in order to understand self-organized behavior (Kelso, 1995, p. 52). The changing frequency of movement that induces the change in relative phase is the control parameter. When the behavior changes once a critical threshold is reached, the system undergoes a 'phase transition,' a term often used to refer to a phenomenon where the pattern of a system reaches a critical value and spontaneously reorganizes into a new pattern of activity. These types of transitions are often indicative of a system that features nonlinear interactions.

3.3.1 Nonlinear Dynamical Systems

The methods for nonlinear dynamical systems (NDS) are a subset of tools from DST. In contrast to the equations used to model linear systems, nonlinear equations are "functions in which the value of the output is not directly proportional to the sum of the inputs" (Thompson, 2007, p. 39). Some cognitive scientists, philosophers, and psychologists have claimed that behavior exhibited by NDS are more than the mere sum of their parts, or, that they are *emergent* properties (cf., Bickhard, 2011; Goldstein, 1999; Van Orden, 2011). Like DST, NDS also uses differential equations. What distinguishes NDS is that solutions result from calculations other than sums, such as exponential and multiplicative calculations.

A helpful way to understand nonlinear systems is to contrast them with linear systems. To say that the relations between components of a system are linear is to imply that there is a proportional relationship of *cause* and *effect,* or, “the causal links of the system form something more complicated than a single chain, for example a system with feedback loops” (MacKay, 2008). Furthermore, the inputs and outputs of a linear system will generally be proportional. For example, if an automobile gets 20 miles per gallon of gas, and one gallon of gas is put in it, then it will be able to travel 20 miles until more gas is needed. If you put five gallons in, then you will be able to travel 100 miles before more gas is needed. The input (one gallon of gas) is always proportional to the output (20 miles of travel).

Now imagine if putting one gallon of gas enabled 20 miles of travel but then when a second gallon is added you are able to travel 200 miles. In this case, the input is no longer proportional to the output. The exponential increase in output relative to the input implies nonlinearity. Depending on the condition of a system, small changes to a single component in the system could have a tremendous influence on the overall behavior of the system. If we reconsider the phase transitions featured in the HKB Model, the spontaneous transition to a new pattern of behavior occurs despite a linear increase in speed. The speed increase has little to no effect at most frequencies, but at a critical threshold an entire new pattern of activity arises.

While some differential equations can be solved analytically using mathematical formulas, the behavior of nonlinear systems, due in part by the disproportionality of their inputs and outputs, are virtually impossible to predict (Thompson, 2007, pp. 39-40). These systems cannot be reduced to the interaction of their component parts. Therefore, *qualitative* dynamical modeling is necessary for describing the novel, or emergent, properties exhibited as the system changes over time.

3.3.2 Emergence

There have been numerous attempts to classify emergence (cf. Deguet et al., 2006). However, Thompson (2007) generates a definition that is intended to capture the characteristics of emergence that NDS scientists have in mind when describing self-organizing behavior. Thompson's definition states that a, "network, N, of interrelated components exhibits an emergent process, E, with emergent properties, P…" if it is able to satisfy these three propositions (p. 418): First, that emergent processes occur in systems where dynamically coupled components have nonlinear interactions. Second, the system features *circular* or *reciprocal causality*. Third, the features of the system are irreducibly relational, that is, they exhibit *relational holism*. Thompson adds,

> Although the term *emergent property* is widespread, I prefer *emergent process*. Strictly speaking, it does not make sense to say that a property emerges, but only that it comes to be realized, instantiated, or exemplified in a process or entity that emerges in time. Emergence is a temporal process… (2007, p. 418, italics in original).

I have already detailed several of the key features of the nonlinearity posited in the first proposition. However, the second and third propositions, that an emergent process must exhibit circular causality and be irreducibly relational, need to be examined further.

Circular causality describes a system that features both "top-down" and "bottom-up" causation. The idea behind bottom-up causation is that the local interactions of the system's components are responsible for generating the activity of the system at the global level. Conversely, top-down causation is the idea that higher level (i.e., global) processes constrain the activity of the system at the level of its individual components. This type of causation can be understood as ongoing and continuous due to the activity at the local level constraining activity at the global level which in turn constrains activity at the local level.

The word ‘constrain’ is used in this context to refer to the, “relational properties that the parts possess in virtue of their being integrated or unified (not aggregated) into a systemic network” (Thompson, 2007, p. 424). Thus, relational holism is closely related to the notion of circular causality. The ontological assumption behind holism is that certain wholes possess properties that are not exhaustively determined by the intrinsic properties of its fundamental parts. Instead, these properties are thought to be irreducibly relational. Thus, relational holism construes relations as the most basic unit of the system, and the components of the system do not have an independent or nonrelational status (p. 428). In such a system, the change of some properties will be the effect caused by a change in the system’s relations.

While both the classical and dynamical paradigms for investigating cognition offer a wealth of insight into the nature of the human mind, they are decidedly distinct. The classical paradigm claims the mind is like a computer and that human behavior can be explained in terms of internal representations of the external world. However, there is no agreed upon explanation of how an object from the external environment could come to be represented in the mind. This has lead cognitive scientists to apply alternative nonrepresentational frameworks like DST. The nonlinear element of dynamical cognitive science has enabled researchers to examine novel behavior, i.e. phase transitions and emergent processes, in cognitive agents. Due to the linear and discrete nature of computational processing, the nonlinear and continuous features of human cognition may have otherwise never been revealed. Nevertheless, the extent to which dynamical cognitive science is appropriate for examining cognition remains an open empirical question and, like the classical paradigm, will likely be the subject of extensive philosophical debate.

The following chapter will examine the relationship between Whitehead's philosophy and the developments in cognitive science presented here. It will be shown that the computational paradigm posits entities that have a similar character to the doctrines of substance that Whitehead rejects. Additionally, I detail how dynamical cognitive science can be seen as an empirical framework that is congenial to the description of nature presented in Whitehead's philosophy.

Chapter 4: Process Philosophy and Cognitive Science

4.1 Two Varieties of Process

Whitehead explicitly criticized traditional notions of substance, where change is thought to occur due to the spatial reorganization of fundamental independent substances. In place of substance, he argued that nature was a ceaseless process of becoming that generated the durative events experienced in sense-awareness. According to the manner by which cognitive change is accounted for, I will show that dynamical cognitive science is comparable to process philosophy, and classical cognitive science is comparable to substance philosophy. If this claim is true, change described in classical cognitive science will have the character of substance, and will consequently be subject to several of Whitehead's criticisms. Conversely, change in dynamical cognitive science will not have the character of substance, and instead must characterize cognition as a process that reflects Whitehead's philosophy.

4.1.1 Classical Cognitive Change

The classical paradigm of cognitive science held the view that cognitive behavior was the result of computations occurring inside the head (Van Gelder, 1998). While actual computation is a process, it is a process of rearranging symbols. Both computational and dynamical cognitive sciences are concerned with process of rearrangement, but it is the character of their processes and the objects being rearranged that distinguishes them. For example, Newell and Simon (1976), claiming that a physical symbol system has both necessary and sufficient conditions for intelligent action, describe the objects of such a system in the following passage:

> A physical symbol system consists of a set of entities, called symbols, which are physical patterns that can occur as components of another type of entity called an expression (or symbol structure). Thus, a symbol structure is composed of a number of instances (or tokens) of symbols related in some physical way (such as one token being next to another). At any instant of time the system will contain a collection of these symbol structures. (p. 116)

The cosmetic similarities between this description and theories of substance may be obvious. If not, simply replace every instance of the word 'symbol' with 'atom,' and 'system' with 'object.' The result is: an atomic structure is composed of a number of instances of atoms related in some physical way (such as one being next to another); at any instant of time the object will contain a collection of these atomic structures.

This description of the objects in cognitive processes is strikingly similar to the pre-Socratic theories of substance. The construal of a system whereby entities are ordered *in* space at a durationless *instant* of time and combine to form physical structures is not consistent with Whitehead's synthesis of space, time, and matter into a single relation. Moreover, symbols and representations, insofar as they are characterized in classical cognitive science, are *independent* entities. Their properties at one instant are not dependent on any relationship to concurrent entities at that instant. Rather, they are the result of a linear series of discrete instants whereby the structure of the symbol alone at that instant constitutes its properties. Employing terms like 'instants' and 'states' are commonplace in the classical cognitive science literature. It is not clear if the paradigm's notion of discrete mental states was intended to be durative or not. Nonetheless, the usage of the terms such as 'state' and 'instant' suggests that they are referring to an unchanging slice of time, not durative and ever changing events. In Whitehead's philosophy, there are no durationless instants in time and nothing is unchanging. Similar to how the abstract concept of a “limit” illegitimately lead scientists to posit a volumeless point at a durationless instant of time as a bare entity, “which is simply an abstraction necessary for the method of thought, into the metaphysical substratum of these factors in nature” (Whitehead, 1920), the concept of the “mental state” appears to have lead classical cognitive scientists to posit their own bare entity.

4.1.2. Dynamical Cognitive Change

The phase portrait depicting simple pendulum motion indicates that DST portrays nature in the durative form that is characteristic of Whitehead’s notion of events. Moreover, a pendulum that is mathematically modeled using differential equations, rather than difference equations, will feature continuous rather than discrete change over time. This is consistent with Whitehead’s bold claim that, “one all-pervasive fact is the passage of things, one to another. This passage is not a mere linear procession of discrete entities” (Whitehead, 1926, p. 88). DST appears headed in the direction of a process philosophical description. Unlike computation, which processes symbols in discrete steps, a model of a dynamical system features a, “smooth manifold with a vector field” (Chater & Hahn, 1998, p. 633) This property entails that the transitions between state spaces are continuous rather than discrete. However, it could be argued that the mass of the pendulum is shown as an *enduring* volumeless *point* traveling *in* space as a function of time. Thus, the use of mathematical abstractions by dynamicists may render them subject to Whitehead’s criticism of the fallacy of misplaced concreteness. I concede that this criticism may be applied to DST in general, but the task at hand is to examine DST as it is used in cognitive science.

The HKB model demonstrated that the changing order parameter in the system was the *relative* phase of the finger motion. The object undergoing change is inherently relational, not an independent entity. Van Gelder (1998) writes, "dynamicists tend to think of systems as operating in parallel, that is, all aspects changing *interdependently* at the same time" (p. 621, emphasis added). While this relation could be presented as a point in geometric space, dynamical cognitive scientists have yet to claim it is a concrete entity with the same geometric properties as a point.

In addition to the durative and interdependent properties featured in the HKB model, some dynamicists have described dynamical systems in a way that reflects Whitehead's principle of extension. The principle of extension, according to Whitehead, suggests that all events are related to each other, in both space and time, in a manner analogous to a Russian nesting doll extending over a multitude of smaller dolls. Events in space can be thought of as being spatially extended over a multitude of events in space, like the event of a biological system extending over the event that is one of its organ systems. In dynamical systems verbiage, "any given object will usually instantiate a great many systems," and, "cognitive agents 'are,' in this sense, not some particular dynamical system but as many systems as are needed…" (Van Gelder, 1998, pp. 617-619). Rather than claim that dynamical agents are comprised of fundamental particles, they are thought to consist of a multitude of systems in a way that echoes the principle of extension.

4.2 Representation as Bifurcation

The representational view is deeply rooted in dualistic thought (Rowlands, 1999). In describing the bifurcation of nature, Whitehead makes several explicit references to representational theories of perception throughout the history of philosophy. Speaking on Descartes, he writes, "his unquestioned acceptance of the subject-predicate dogma forced him into a representational theory of perception" (Whitehead, 1978, p. 49). Additionally, though he notes Locke had discovered that the mind was unity arising from the realization of ideas into a fact of nature, he still presupposed the dualistic view that, "minds are one kind of particulars, and natural entities are another kind..." (p. 54). Locke even makes an explicit reference to representation in the passage, "and, like pictures of them there, represent only those individuals" (Locke quoted by Whitehead, 1978, p. 54). Whitehead's criticism of the representational theories is that the all of the attempts to vindicate the representation in the mind of external facts is by appealing to some "animal-faith" (God).

The classical view in cognitive science that the mind carries out algorithmic processes on properties of representations inside the head is the bifurcation of nature in its most elaborate form. According to the representational theory, the appearance of color is caused by an enrichment process of the impoverished signal. For example, we do not see the things that enter the eye (photons), rather, the things we see are colors. Whitehead calls these "psychic additions" by the mind. There exists no agreed upon explanation for the processes generating these psychic additions. Despite this difficulty, the representational view persisted. Whitehead thinks that the obstacle of developing an adequate explanation for the psychic additions *is* the cause of the theory's persistence. He writes:

> The reason why the bifurcation of nature is always creeping back into scientific philosophy is the extreme difficulty of exhibiting the perceived redness and warmth of the fire in one system of relations with the agitated molecules of carbon and oxygen, with the radiant energy from them, and with the various functionings of the material body (Whitehead, 1920).

The main criticism by Whitehead regarding the bifurcation of nature theories of science is that they grant privilege to causal nature, and thus apparent nature is viewed as nothing more than an "effluent" of causal nature. The reality of our immediate perceptual experiences are abandoned in favor of theory. He responded by developing a concept of nature where both the causal and apparent nature were interpreted as within nature. This move reflects one of the core assumptions of dynamical cognitive science.

Recall that dynamical cognitive scientists claim that cognitive agents are dynamical systems. Yet it has been argued that *all* systems in nature are dynamical systems (cf. Van Gelder, 1999). Therefore, dynamical cognitive scientists attempt to explain and understand cognitive agents and the natural world under the same theoretical framework. Nature is not bifurcated into two categories of existence. However, it could be argued that dynamical cognitive scientists simply *ignore* the need to explain apparent nature, and it does not follow that they do not carry out their studies under the assumption that two categories of nature exist. But work on motor behavior has a long history of dynamical thinking from within the field of ecological psychology, where perception is claimed to be direct (Beer, 2000). The notion of direct perception finds a metaphysical home in the philosophy of organism, where Whitehead makes explicit reference to the directedness of human perception several times. Recall that actual entities, which have both a private and public side, prehend the community of concurrent actual entities (the actual occasion) during its ingression into nature. Because space, time, and matter is construed as a single unified relation, any object in nature will feel or grasp the "value" of its immediate environment. There is no need for the molecules and photons in the air to undergo an enrichment process in the brain because to be actualized in nature *is* to experience the immediate environment.

Another important factor is that actual entities have aims, or the desire to satisfy their creative advance. The incorporation of aims into his philosophy was due in part by the experience of human intentionality. According to some dynamical cognitive scientists, “intentionality is central to subjective experience and permeates all human activities,” and it suggests, “a capacity to bring behavior into existence, to cause behavior” (Van Orden et al., 2011, pp. 639-640). Van Orden and colleagues sketch an account of intentionality according to the principles of NDS. A full treatment of their explanation of intentionality is outside the scope of this work, but they summarize it best in their proposal that, “intentions affect behavior as constraints, not causes. Intentions as constraints are temporary dynamical structures, soft assembled from interdependent components…” (p. 667).

4.3 The Creation of Novelty

The most compelling similarity between process philosophy and nonlinear dynamical cognitive science is the manner in which they account for the cause of novelty in nature. According to the philosophy of organism, novelty is a brute fact of the process of becoming. In DST terms, novelty is the result of emergence. The character of an emergent processes is similar to the character of the “creative advances” described in Whitehead’s work.

The notion of self-organization was influential in the development of dynamical cognitive science. Self-organization is a term used to refer to the spontaneous emergence of novel patterns in nature despite there being no central control unit directing its behavior. Instead, the nonlinear interactions of the system are able synchronize into new patterns with the influence of some central control mechanism. Whitehead has a similar view regarding behavior, going on to say, “a good many actions do not seem to be due to the unifying control…” (Whitehead, 1978, p. 108).

For example, jellyfish seem to be harmonized cells, and when cut in two, “their parts go on performing their functions independently” (p. 108). In differentiating his view from the view that the mind *informs* the body, he states the the living body is, “a coordination of high-grade actual occasion; but in a living body of a low type the occasions are much nearer to a democracy” (p. 108).

The circular causation detailed by Thompson (2007) has similar features to the philosophy of organism such as an actual entity being determined by the actual occasion they are situated within. Furthermore, events feature the principle of extension. Every event extends over a multitude of events. The principle of extension suggests that an actual entity may extend over, and thus be determined “bottom-up” by, a multitude of internal actual entities. The same actual entity may also be determined “top-down” by the immediate occasion extending over it. Goldstein (1999) describes the appearance of emergent properties, “as integrated wholes that tend to maintain some sense of identity over time. This coherence spans and correlates the separate lower-level components into a higher-level unity” (p. 50).

A key feature to be derived from the principle of extension is that intrinsic individuation is impossible. Rather, nature is construed as a continuum of events extending over one another. Goldstein (1999) reflects the continuity characterized by Whitehead in his portrayal of scientific explanations of emergence.

> In respect to its use in scientific explanation, the construct of emergence is appealed to when the dynamics of a system seem better understood by focusing on across-system organization rather than on the parts or properties of parts alone. Yet, appeals to emergence follow more of a continuum than a discrete jump from part to whole (p. 50).

This passages appeal to system organization rather than its components also alludes to the fact that an emergent process should exhibit relational holism. Much of Whitehead's philosophy was motivated by replacing the traditional materialist views with one that synthesized space, time, and matter into a single relation. Nature, so construed, is one holistic interdependent relation in Whitehead's philosophy. Indeed, he goes on to characterize the human body as a "complex structure" and immediate experience as, "the harmonized relations of the parts of the body constitute this wealth of inheritance into a harmony of contrasts issuing into the intensity of experience" (Whitehead, 1927/1978, p. 109).

There are various additional criticisms of substance philosophy's ability to account for novel phenomena. For one, it is not clear how a reconfiguration of substance can yield a truly novel object (Bickhard, 2011). For example, the elements posited by Empedocles cannot combine to form a new substance. A similar example is echoed by Hume, (1776/2012) namely, that we cannot derive norms from facts. How can an *ought* arise from what *is* within nature. This issue exemplified by the classical cognitive paradigm, where novelty is understood as, "a simple combination of existing structures, juxtaposed or added together in representations," or, "novelty must preexist in some way before the novel behavior is realized" (Van Orden et al., 2011, p. 640).

Despite these criticism, analytic ontology still follows a traditional research paradigm that is couched in terms of, "concrete, countable, particular (i.e., uniquely located) individuals" (Seibt, 2009, p. 481). That is, the objections to the causation characterized in emergent processes presupposes the substance metaphysics that is not coherent with process philosophy. Seibt (2009) also notes how several other core problems of ontology (i.e. the problem of individuation, the problem of persistence, and the problem of universals) are consequences of substance philosophy that can be circumvented by abandoning such presuppositions. Seibt also notes that one of Whitehead's biggest influences, Samuel Alexander, argued that emergence requires a process ontology.

Chapter 5: Conclusion

5.1 Implications for Cognitive Science and Process Philosophy

If epistemological truth can serve as evidence for metaphysical truth (cf. Chemero, 2009, 67), then NDS vindicates process philosophy's characterization of nature. Some researchers have noticed the applicability of process philosophical concepts to fields such a chemistry (e.g., Stein, 2004), physics (e.g., Griffin, 1986), and complexity science (e.g., Bickhard, 2011). Though substance philosophy has served as the philosophical backdrop for centuries with varying degrees of success, it nonetheless reinforces the notion that philosophical concepts can be fruitfully employed to guide scientific research. Thus, process philosophy could be viewed favorably as an alternative interpretation of nature that may guide inquiry.

To what extent process philosophy can guide cognitive science research remains an open question. Nevertheless, the similarities between Whitehead's philosophy and NDS are plentiful and should encourage process philosophers and cognitive scientists to engage in a lively discussion. For cognitive scientists, Whitehead's philosophy presents a novel default conceptualization of nature for researchers investigating cognitive behavior. This is especially true for emergent processes, where a great deal of philosophical debate has taken place but has done so from the perspective of the traditional materialist habit of thought (e.g., Kim, 1993; O'Connor, 1994). Moreover, Whitehead (1920) himself claims that the goal of any philosophy of science is to develop ontologies. Perhaps a formal event ontology based on Whitehead's principle of extension could produce a befitting philosophical account of emergence that is consistent with the latest empirical developments.

Cognitive science is unique in that it is largely an interdisciplinary endeavor, drawing on knowledge from biology, computer science, neuroscience, phenomenology, philosophy, and more. There may be significant developments from the field that could facilitate the development of process philosophy. For example, it is clear in Whitehead's work that, insofar as he sought out the invariant features of experience, he is doing phenomenological analysis. Phenomenology was a relatively new method of analysis at the time. Husserl had published *Logical Investigations* by the time of Whitehead's writings, but *Cartesian Meditations* was not published until two years after *Process and Reality*. Two other prominent phenomenologists, Jean-Paul Sartre and Maurice Merleau-Ponty, would not publish their major works until over a decade later. Therefore, in addition to NDS, there may be a variety of phenomenological insights available for process philosophers to incorporate into their descriptions of nature.

Process philosophy may be especially useful to researchers who favor the embodied, enactive, and extended view of cognition (e.g., Anderson, 2014; Chemero, 2009; Rowlands, 1999; Thompson, 2007). According to these approached the brain is dynamically coupled to the body which is dynamically coupled to the environment. Embodied cognition does not divide nature into mind and matter, and instead positions them as one large interactive system. Whitehead intended for his philosophy of organism to be used as an instrument for analyzing nature, and since the embodied mind is within nature, the philosophy of organism may be a fecundate approach for analyzing it.

The extent to which process philosophy and cognitive science can mutually benefit one another remains an open question. The presuppositions of substance philosophy may continue to be a fruitful guide to investigating cognition, but several issues in cognitive science (e.g., the boundaries of cognition and the mind-body problem) remain contentious areas of disagreement that may benefit from a fresh perspective. Whether or not alternative metaphysical frameworks will provide the explanatory contexts needed to answer many important questions can only be known if the philosophical and scientific community explores these possibilities.

Moralez, 2016

References

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

Aristotle. Categories. (2009). In E. M. Edghill, *The Internet Classics Archive*. Retrieved June 04, 2016, from http://classics.mit.edu/Aristotle/categories.1.1.html

Beer, R. D. (1995). A dynamical systems perspective on agent-environment interaction. *Artificial Intelligence*, *72*, 173-215.

Beer, R. D. (2000). Dynamical approaches to cognitive science. Trends in cognitive sciences, *4*, 91-99.

Bickhard, M. H. (2008). Issues in process metaphysics. *Ecological Psychology*, *20*, 252-256.

Bickhard, M. H. (2009). Interactivism: a manifesto. *New Ideas in Psychology*, *27*, 85-95.

Bickhard, M. H. (2011). Systems and process metaphysics. In C. Hooker (Ed.), *Philosophy of Complex Systems* (pp. 91-103). Oxford, UK: Elsevier.

Chater, N., & Hahn, U. (1998). What is the dynamical hypothesis? *Behavioral and Brain Sciences*, *21*, 633-634.

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

Christian, W.A. (1967). *An Interpretation of Whitehead's Metaphysics*. New Haven, CN: Yale University Press.

Clark, A. (2013). *Mindware: An introduction to the philosophy of cognitive science*. Oxford, UK: Oxford University Press, Inc.

Deguet, J., Demazeau, Y., & Magnin, L. (2006). Elements about the emergence issue: A survey of emergence definitions. *ComPlexUs*, *3*, 24-31.

Duncan, S. (2009). Thomas Hobbes. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Summer 2013 Edition). Retrieved June 02, 2016, from http://plato.stanford.edu/entries/hobbes/

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*. Cambridge, MA: MIT press.

Fusella, P. V. (2013). Dynamic Systems Theory in Cognitive Science: Major Elements, Applications, and Debates Surrounding a Revolutionary Meta-Theory. *Dynamical Psychology*. Retrieved June 7, 2016 from http://dynapsyc.org/2013/Fusella.pdf

Gallagher, S., & Sørensen, J. B. (2006). Experimenting with phenomenology. *Consciousness and cognition*, *15*, 119-134.

Gibson, E. J., & Walk, R. D. (1960). The "visual cliff." *Scientific American*, *202*, 67-71.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston, MA: Houghton Mifflin

Goldstein, J. (1999). Emergence as a construct: History and issues. *Emergence*, *1*, 49-72.

Griffin, D. R. (1986). *Physics and the ultimate significance of time: Bohm, Prigogine, and process philosophy.* Albany, NY: SUNY Press.

Hart, M. H. (1978). *The 100: A ranking of the most influential persons in history*. New York, NY: Citadel Press.

Haxton, B. (2001). Fragments of Heraclitus. *New England Review*, *22*, 15–19.

Haken, H., Kelso, J. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, *51*, 347-356.

Haugeland, J. (1978). The nature and plausibility of cognitivism. *Behavioral and Brain Sciences*, *1*, 215-226.

Hume, D. (1776/2012). *A treatise of human nature*. Mineola, NY: Courier Corporation.

Kelso, J. S. (1997). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, MA: MIT press.

Kim, J. (1993). *Supervenience and mind: Selected philosophical essays*. Cambridge, UK: Cambridge University Press.

Kraus, E. M. (1998). *The metaphysics of experience: a companion to Whitehead's Process and reality*. Bronx, NY: Fordham University Press.

Lovejoy, A. D. (1907). Review of Qualitative Change in Pre-Socratic Philosophy. *Classical Philology*, *2*, 490-490.

Lowe, V. (1962). *Understanding Whitehead*. Baltimore, MD: Johns Hopkins University Press.

Miller, G. A. (2003). The cognitive revolution: a historical perspective. *Trends in Cognitive Sciences*, *7*, 141.

Newell, A., & Simon, H. A. (1976). Computer science as empirical inquiry: Symbols and search. *Communications of the ACM*, *19*, 113-126.

O'Connor, T. (1994). Emergent properties. *American Philosophical Quarterly*, *31*, 91-104.

Patrick, G. T. W. (1888). A further study of Heraclitus. *The American Journal of Psychology*, *1*, 557-690.

Poincaré, H. (1890). Sur le problème des trois corps et les équations de la dynamique. Acta mathematica, *13*, 3-270.

Popper, K. R. (1963). Kirk on Heraclitus, and on fire as the cause of balance. *Mind*, *72*, 386-392.

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

Seibt, J. (1997). Existence in time: From substance to process. In J. Faye et al. (Ed.), *Perspectives on Time* (pp. 143-182). New York, NY: Springer Netherlands.

Seibt, J. (2009). Forms of emergent interaction in general process theory. *Synthese*, *166*, 479-512.

Sellars, W. (1957). I. Substance and Form in Aristotle. *The Journal of Philosophy*, *54*, 688-699.

Shapiro, L. (2010). *Embodied cognition*. Abingdon, UK: Routledge.

Stein, R. L. (2004). Towards a process philosophy of chemistry. *International Journal for Philosophy of Chemistry*, *10*, 5-22.

Thompson, E. (2007). *Mind in life: Biology, phenomenology, and the sciences of mind*. Cambridge, MA: Harvard University Press.

Turing, A. M. (1950). Computing machinery and intelligence. *Mind*, *59*, 433-460.

Van Gelder, T. (1998). The dynamical hypothesis in cognitive science. *Behavioral and brain sciences*, *21*, 615-628.

Van Gelder, T. J. (1999). Defending the dynamical hypothesis. Dynamics, synergetics, autonomous agents: *Nonlinear systems approaches to cognitive psychology and cognitive science*, *8*, 1-16.

Van Orden, G. C., Kloos, H., & Wallot, S. (2011). Living in the pink: intentionality, wellbeing, and complexity. In C. Hooker (Ed.), *Philosophy of Complex Systems* (pp. 629-675). Oxford, UK: Elsevier.

Van Rooij, M. M. J. W., & Favela, L. H. (2016). A nonlinear dynamical systems theory perspective on dual-processing accounts of decision-making under uncertainty. In A. Papafragou, D. Grodner, D. Mirman, & J. Trueswell (Eds.), *Proceedings of the 38th*

Annual Conference of the Cognitive Science Society. Philadelphia, PA: Cognitive Science Society.

Whitehead, A. N. (1906). On mathematical concepts of the material world. *Philosophical Transactions of the Royal Society of London*, *205*, 465-525

Whitehead, A. N. (1920). *The concept of nature*. Courier Corporation.

Whitehead, A. N. (1926). *Science and the modern world*. Cambridge, MA: Cambridge University Press.

Whitehead, A. N. (1978). *Process and reality*. (1978 reprint) New York, NY: The Free Press

Whitehead, A. N. (1938). *Modes of thought*. New York, NY: Simon and Schuster.