

Dynamics, Dynamical Systems Theory, and Cognition:

A review of existing literature pertaining to the use of a dynamical approach in the scientific study of cognition and cognitive agents.

Joshua David McClurg-Genevese

OSU Department of Industrial, Interior, and Visual Communication Design
R. Brian Stone
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Introduction:

When investigating the varied aspects of cognition, and endeavoring to begin research into this very multi-disciplinary field of study, one is easily overwhelmed by the many theories attempting to explain how the mind works. The two currently at the forefront of cognitive science are the computational systems theory (CST) – which has been at the heart of much of the cognitive research performed for the past fifty years, and the dynamical systems theory (DST) – a much newer paradigm that is showing great promise.

Based on initial research that I have performed exploring these two theories, and a more thorough reading into both of them, I believe that the dynamical systems theory will prove to be the most accurate and relevant to my research as it progresses. This review of the literature surrounding the DST begins a more in-depth look into its methodologies and practices; how it is currently being used in the field, and what techniques I can use to implement it as a part of my thesis work.

Overview:

My initial research began with a comparison of the two theories (CST and DST) in an attempt to identify which methodology would prove to be the most effective when dealing with Web-based phenomenon. I used a sample Web-based task (purchasing a song from the iTunes Music Store) and through a series of usability studies tracked the users of the environment. I then attempted to explain the behavior witnessed in the users through the framework provided by each theory. It was a brief, qualitative exploration meant to help me define and identify the characteristics of both the computational systems theory and the dynamical systems theory, and to see which was more capable of explaining the phenomenon that the users exhibited.

At the conclusion of the initial paper, written to document the process and the findings of the research (McClurg-Genevese, 2003), a hypothesis was stated:

“The most accurate and reliable model for the analysis and prediction of behavioral patterns that emerge when dealing with a given Web-based phenomenon is one that is based on a dynamic, evolving, system that functions in real time and has at its core an aspect capable of symbolic knowledge representation.”

The findings of the research showed that the model of the dynamic systems theory seemed to be more capable in explaining Web-based phenomenon, but that further exploration of the concept of knowledge representation was necessary as it could not be surmised what alternative the DST offered to *symbolic* knowledge representation – a core precept of the

computational systems theory. Therefore, the final hypothesis was actually a combination of both theories.

However, despite the lack of evidence of a dynamic system having the capacity to allow for *symbolic* knowledge representation, it has been shown that the dynamic systems theory is capable of knowledge representation in a form more native to the theory; specifically, one that involves the representation of knowledge as point attractors of a system (Hopfield, 1982). Also, while the DST is capable of explaining cognition based on a computational model, the reverse is not always true. It has been shown that when dynamical models are employed, a computational explanation of cognition based on these models is difficult if not impossible (Giunti, 1995).

In addition, the framework established by a more connectionist approach to understanding cognition is yet another outlook that can be argued for in dealing with Web-based tasks. Connectionists model cognition through the use of neural networks, or clusters of smaller systems that are all connected together. Connectionist research seems to exist in a vague realm located somewhere between the computational and the dynamical approach – and it does not have much of an identity of its own. Thus far, most of the research done in this field has been regarded as either strongly computational or strongly dynamic depending on how the neural network is modeled.

In the end the choice is a rather philosophical one, for no theory of cognition has been proven to be the single most reliable model for understanding the nuances of cognition. Much more scientific research needs to be done before a conclusion is likely to be drawn. Therefore, the most that the researcher can do is choose the theory, and the respective framework, that best aligns itself with the subject matter he/she wishes to study.

I believe that the dynamical systems theory will prove to be not only more capable in modeling complex cognition, specifically as it pertains to Web-based phenomenon, but also more flexible in terms of adapting to new phenomenon as they arise and incorporating aspects of other theories as needed. Should the need for a hybrid approach be warranted, such as a dynamical framework with a computational component for knowledge representation, I feel the dynamical approach will be more supportive to such an endeavor. As such, the dynamic systems theory will be at the core of all future research.

The objectives of this review are: to enhance the theoretical framework upon which I will continue my research, to become more familiar with the field of dynamics in general, and to become more aware of the research currently being done with dynamic cognitive systems in the field of cognitive science. As such, this literature review will look at the dynamic systems theory from three different perspectives: 1) A more in-depth, and current, look at the theory itself, 2) an introductory look at the field of dynamics, and 3) a review of what research is currently being done using the dynamical systems theory.

Discussion:

The following is a list of the works reviewed as part of this paper and a brief summary of their content:

1. **van Gelder, T. J. (1998) The dynamical hypothesis in cognitive science. *Behavioral and Brain Sciences*, 21, 1-14.**

This work is a detailed explanation of the dynamical hypothesis (DH), arguably the foundational idea in discussing the use of the dynamical systems theory in the study of cognition.

This paper begins by comparing the dynamical hypothesis to the computational hypothesis (CH) in cognitive science and sketches out some examples of work being

done using the DH. It continues by talking about systems in general and causal organization, and then compares and contrasts digital computers and dynamical systems stating some key ideas in distinguishing dynamical models from other ones.

The author goes on to describe in detail the dynamical hypothesis and the two sub-hypotheses that comprise the DH: the nature hypothesis and the knowledge hypothesis. The discussion then turns to what truly makes up the dynamical methodology and how it is implemented. Dynamical models, dynamical tools, and the dynamical perspective are highlighted as being the core components of a dynamical approach to cognitive science.

Finally the paper discusses the conditions favoring the dynamical hypothesis as well as the criticisms and objections to it.

This paper alone could be the cornerstone for my research as it lays out a definitive stance on the dynamical approach to cognitive science, what its strengths and weaknesses are, how it compares to the other major theory of cognition (computational) and most importantly how to then utilize the dynamical approach in research.

2. **van Gelder, T. (1999) Revisiting the Dynamical Hypothesis. Preprint No. 2/99, University of Melbourne, Department of Philosophy.**

This paper is a more contemporary version of the one above (van Gelder, 1998) with revised and updated facts and examples of current research (which are all included in this review), a revisiting of the dynamical hypothesis and the two sub-hypotheses: the nature hypothesis and the knowledge hypothesis, and a defense of the DH against the most recent criticisms.

3. **van Gelder, T. J. (1998) Disentangling dynamics, computation, and cognition. *Behavioral and Brain Sciences*, 21, 40-7.**

This entire paper is a defense of the dynamical hypothesis in response to commentaries on “The Dynamical Hypothesis in Cognitive Science” (van Gelder, 1998). It begins by looking at the definitions of a dynamical system, and a quantitative system, and how this compares and contrasts with formal computational systems. It then goes on to discuss the objections to the formulation of the dynamical hypothesis, its vying for status as a Law of Qualitative Structure, and its ontological vs. epistemological nature. It continues with a defense of the use of dynamics as a model for cognition, its placement in the levels of cognition (that it can be used at any level where dynamic systems are instantiated), and finishes by addressing some of the more general objections to the hypothesis – such as its inability to be falsifiable and its anti-representational approach to cognition.

4. **van Gelder, T. J. (1999) Defending the dynamical hypothesis. In W. Tschacher & J.-P. Dauwalder ed., *Dynamics, Synergetics, Autonomous Agents: Nonlinear Systems Approaches to Cognitive Psychology and Cognitive Science*. Singapore: World Scientific, 13-28.**

Another defense of the dynamical hypothesis that reiterates some of the common objections based on commentaries and past writings. It answers each in turn and provides a brief overview of the position of the dynamical approach in the field of cognitive science.

Issues addressed include objections to its placement in the levels of cognition, its comparison to the computational theory of cognition, and the basic structure of the

dynamical approach.

5. **van Gelder, T. J., & Port, R. (1995) *It's About Time: An Overview of the Dynamical Approach to Cognition*. In R. Port & T. van Gelder ed., *Mind as Motion: Explorations in the Dynamics of Cognition*. Cambridge MA: MIT Press.**

This paper lays the foundation for why a dynamical approach is not only a relevant but also an accurate approach for the understanding of cognition and cognitive agents. It begins by looking at cognition as a whole and positing that “Cognitive processes and their context unfold continuously and simultaneously in real time.” (van Gelder, 1995). It goes on to look at the field of dynamics in general and how, over the past century, it has been used to help explain much of the natural world around us with extreme accuracy. It asks for the adoption of a dynamical approach to cognitive science.

The author talks about natural systems as dynamical systems, the idea of concrete systems, state space, and phase space and how dynamic systems are governed by differential equations. It then makes a parallel from natural systems to natural cognitive systems as dynamical systems. It discusses quantitative modeling, the temporal aspects of a dynamic system, continuity, multiple time scales, self-organization, and emergence as part of a natural cognitive system.

He then goes on to discuss the place of the dynamical approach in the field of cognitive science and how it compares to computational theory and connectionist theory, neural processes and chaos theory.

He finishes with a historical sketch of the dynamical approach.

6. **Abraham, R., and Shaw, C. (1982) *Dynamics – The Geometry of Behavior, Part 1: Periodic Behavior*. Santa Cruz, CA: Ariel Press.**

This is the second volume in a five volume series of books on the geometric illustration of dynamics. It deals with some of the underlying, basic, concepts in the field of dynamics and explains them by using geometric simulations and visual mappings.

In order for me to be able to make full use of the dynamic systems theory I am going to need to acquire a working knowledge of the field of dynamics as the former is based on the latter. The implementation of some of the concepts is slightly different in the study of cognition, but the underlying ideas are the same – as are the methods used in the mapping of a system (whether physical or cognitive).

This book superbly illustrates concepts such as: state space and phase portraits, trajectories and behavior, time series, velocity, vector fields, limit points, attractors, basins, separatrices and a myriad of other tools and techniques used to describe and accurately map dynamic systems. By attaining a working knowledge of not only what dynamics is but also how to illustrate and map dynamic systems I will be able to produce research that is both qualitative and quantitative.

7. **Norton, A. (1995) *Dynamics: An Introduction*. In R. Port & T. van Gelder ed., *Mind as Motion: Explorations in the Dynamics of Cognition*. Cambridge MA: MIT Press.**

This is another general discussion on the foundational concepts in the field of dynamics. It is meant as an overview of the basic concepts and how they impact the study of cognition. This work is in contrast to the above example (Abraham and

Shaw, 1982) of geometric illustration and mapping of dynamic systems in that this paper focuses largely on the mathematics behind the mappings where as the former work focuses more on the illustration of a system.

An understanding of both is required to make use of the dynamic systems theory and so I wanted an example of each in this initial review.

8. **Bingham, G. P. (1995) Dynamics and the Problem of Visual Event Recognition. In R. Port & T. van Gelder ed., *Mind as Motion: Explorations in the Dynamics of Cognition*. Cambridge MA: MIT Press.**

This paper deals with the inherent problems of visual event recognition: surface motions, rigid objects, kinematics, etc. and posits a more dynamical approach to sensory stimulation focusing on consistent, universal, circumstances such as gravitational force and time as they naturally exist outside of the event to be recognized. The hypothesis is that there exists, as an inherent part of sensory stimulation, information that can enable a visual system to identify the event without the need for advanced symbolic manipulation on the part of the cognitive agent.

9. **Busemeyer, J. R., & Townsend, J. T. (1995) Dynamic Representation of Decision-Making. In R. Port & T. van Gelder ed., *Mind as Motion: Explorations in the Dynamics of Cognition*. Cambridge MA: MIT Press.**

This paper discusses the concept of the decision field theory (DFT), which is a dynamical, probabilistic framework for the modeling of decision-making. It is an attempt at a quantitative modeling of the psychological processes involved in decision-making through the use of preference states and the evolution of these states over time – modeled by differential equations.

10. **Giunti, M. (1995) Dynamical Models of Cognition. In R. Port & T. van Gelder ed., *Mind as Motion: Explorations in the Dynamics of Cognition*. Cambridge MA: MIT Press.**

Giunti discusses the concept of dynamical models in cognition by first defining what is really meant by dynamical and computational and what the inherent difference is between dynamics, the physical system and the dynamic systems theory, and the abstract mathematical models of a cognitive system as it relates to dynamical and computational methodologies.

He then goes on to prove that while it is possible to understand computational models of cognition dynamically, it is not possible to understand dynamic models of cognition computationally and therefore the dynamical approach should be the one utilized when investigating cognition.

Lastly he discusses the concept of instantiation, and how by understanding a mathematical model of a behavior (some aspect of change) instantiated by a dynamic system we can better understand the dynamic system itself.

11. **Port, R., Cummins, F., & McAuley, J. D. (1995) Naïve Time, Temporal Patterns, and Human Audition. In R. Port & T. van Gelder ed., *Mind as Motion: Explorations in the Dynamics of Cognition*. Cambridge MA: MIT Press.**

This paper deals with the way in which natural cognitive agents (humans or animals) hear words and sound. It suggests that there are two ways in which temporal information is understood: serial order and durational information and that the latter is a more accurate approximation of how natural cognitive agents perceive sound.

The authors argue that serial order relies on a time/space buffer that simply does not exist in natural systems and that a more durational aspect to understanding this information should be considered. They suggest that perception of auditory traces and signals occurs naturally, over time and they illustrate this idea through the use of an oscillator.

12. **Thelen, E. (1995) Time-Scale Dynamics and the Development of an Embodied Cognition. In R. Port & T. van Gelder ed., *Mind as Motion: Explorations in the Dynamics of Cognition*. Cambridge MA: MIT Press.**

This work discusses research into the nature of cognitive development in infants and how, through a series of tasks such as reaching for an object or kicking at a mobile, insight can be gained into the behavioral patterns that can emerge in children. And how these patterns are part of a larger model of self-organization.

The author uses dynamic modeling to explore and explain the gradual, self-evolving, nature of embedded cognition and shows how development happens over varying time scales. She illustrates how the change that occurs at one time scale can shape the changes that occur at other time scales.

Key Ideas:

There are a few key ideas that have been garnered as part of this initial review (and past research) that are beginning to establish a conceptual framework that is needed to begin solid research.

A. The nature of dynamical systems:

There are many different definitions of dynamical systems (everything from the study of forces to a simple change in time), and it is important to state what we are talking about when we say we are endeavoring to understand them. A distinguishing feature of dynamical systems in cognitive science is that their values are numerical, and that because of this quality they could be considered to be quantitative systems – that is a system in which there are distances in state or time such that these distances can affect the behavior of the system (van Gelder, 1998).

In addition, van Gelder states the following as being at the core of understanding what we mean when we say a dynamical system in cognitive science:

1. Quantitative in state – A system is quantitative in state when there is a metric over the state such that behavior is systematically measured by that metric (van Gelder, 1998).
2. Quantitative state/time interdependence – A system is quantitative in time when there is a metric over the time set. The behavior of the system is such that amounts of change in the state are systematically related to amounts of elapsed time (van Gelder, 1998).
3. Rate dependence – Systems such that their rates of change are dependent on current rates of change within the system (van Gelder, 1998).

In addition, there is often a rule expressed as a part of a dynamical system that specifies the distance-dependent changes of a system (often referred to as the rule of evolution). Under normal circumstances, a system is taken to be dynamical to the extent that it is quantitative in one of the above senses (van Gelder, 1998).

B. The dynamical hypothesis:

“The dynamical hypothesis (DH) is the unifying essence of dynamical approaches to cognition. It is encapsulated in the simple slogan, *cognitive agents are dynamical systems*” (van Gelder, 1998).

The dynamical hypothesis is comprised of two parts: an ontological and an epistemological component each addressing key pieces of the hypothesis as a whole.

1. *The Nature Hypothesis:*
The nature hypothesis tells us what cognitive agents are by specifying the relationship they bear to dynamical systems. The heart of this relationship is not identity, but instantiation. Cognitive agents are not themselves systems, but rather objects whose properties can form, and instantiate, systems (van Gelder, 1998).
2. *The Knowledge Hypothesis:*
The knowledge hypothesis is a claim about how we should go about understanding dynamical systems and argues for the use of three key elements: dynamical models, dynamical tools, and a broadly dynamical perspective (van Gelder, 1998).

C. The dynamical approach to cognition:

To date, I have been talking about the dynamical systems theory as if it were unto itself the entirety of a dynamical approach to studying cognition. In reality, I have come to realize that

the DST is only a small part of a much broader dynamical mind set. Tim van Gelder has outlined the approach as such:

“A thoroughly dynamical perspective on cognition has three major components: a dynamical model, use of the intellectual tools of dynamics, and adopting a broadly dynamical perspective” (van Gelder, 1999).

1. *The dynamical model:*

The dynamical model is an abstract mathematical model that describes some aspect of change (behavior) instantiated by a dynamical system. The behavior of the model (as defined by differential equations) is compared with empirical data on the cognitive performance of human subjects (van Gelder, 1999).

2. *The intellectual tools of dynamics:*

In addition to computer simulation of dynamical models, the tools of dynamics include dynamical modeling and the dynamical systems theory. The former is a branch of applied mathematics that endeavors to understand some natural phenomenon using abstract dynamical models. The latter is a branch of pure mathematics with a focus on understanding nonlinear dynamical systems (van Gelder, 1999).

3. *The dynamical perspective:*

A dynamical perspective is one in which cognition is seen as the emergent outcome of the ongoing interaction of sets of coupled quantitative variables. Cognitive performances are illustrated as continual movement in a geometric space, where the interesting structure is found over time. Interaction with the world is a matter of simultaneous mutual shaping of the aspects of a system (van Gelder, 1999).

The dynamical approach, taken as a whole, forms a very powerful framework for research into cognitive performance. It allows for both qualitative and quantitative research and is very aptly suited for the analysis of human-computer interaction. Specifically, when dealing with Web-based phenomenon the temporal aspects of the approach – the simple fact that time is built into the system as a concrete variable and that it has the ability to affect the behavior of the system – could potentially be extremely valuable in trying to understand how best to help enhance the concepts of user-centered design for the medium.

D. The geometric modeling of dynamic systems:

The field of dynamics is overwhelmingly robust and the idea of having to construct advanced theoretical mathematical models that accurately describe the behavior of a cognitive system is unto itself a task probably worthy of an advanced academic degree. And I cannot hope to attain a full, comprehensive, understanding of the field in the time it takes me to complete mine.

Yet, in order to use a fully dynamical approach to cognition I will need to be able to provide a working model of the system I am studying, and in the dynamical approach to cognition such a model takes on the form of a differential equation.

As part of my research I will need to construct a working mathematical model that posits an accurate description of a behavior instantiated by the cognitive system I am studying. The mathematical model will be at the core of the user testing and indeed will be the basis for empirical comparison. It will be simulated in a geometric space, which can then be used to show the patterns of behavior through time-series illustrations.

Conclusion:

In this paper I state the current direction of my research and why I feel that the dynamical approach to cognition is the appropriate choice to make considering the subject matter I wish to study. I state the objectives of the review; provide a brief summary of the topics covered in each of the works selected, and callout key ideas garnered from the readings.

The dynamical approach to cognition involves a clear articulating of the definition of a dynamical system so as to provide an intuitive path to its understanding, and its relationship to the field of cognitive science. Such an approach articulates that what is being studied is not necessarily the natural cognitive agent but rather the systems that such an agent instantiates.

Through the creation of abstract mathematical models that attempt to accurately describe the change caused by the aspects of a system (behavior), one can better understand the system itself and subsequently the cognitive agent that instantiated the system. Such mathematical models take on the form of differential equations that provide empirical comparison for quantitative analysis and can be illustrated through geometric renderings of state spaces and time sequences.

Finally, this is undertaken with a belief that all things evolve in real time and that all aspects of a given system affect, and can be affected by, all other aspects of the same system. The behavior of such a system can be affected by outside forces that act as parameters upon the system and affect the rule of evolution – a guiding, deterministic, principle that describes expected behavior. The result is a naturally, co-evolving, collaboration of cognitive processes that unfold over time.

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