Project Description

1. List of Participants

All of the following faculty participants are at Indiana University Bloomington. Abbreviations: COGSCI = Cognitive Science, CS = Computer Science, HPS = History and Philosophy of Science, INFO = Informatics, PBS = Psychological and Brain Sciences

Colin Allen: COGSCI, HPS
Randall Beer: COGSCI, CS, INFO
John Beggs: COGSCI, Physics
Geoffrey Bingham: COGSCI, PBS
Joshua Brown: COGSCI, PBS
Jerome Busemeyer: COGSCI, PBS
Robert Goldstone: COGSCI, PBS
Karin James: COGSCI, PBS
Thomas James: COGSCI, PBS
John Kruschke: COGSCI, PBS
Sharlene Newman: COGSCI, PBS
Luis Rocha: COGSCI, INFO
Matthias Scheutz: COGSCI, CS, INFO
Richard Shiffrin: COGSCI, PBS
Eliot Smith: COGSCI, PBS
Linda Smith: COGSCI, PBS
Olaf Sporns: COGSCI, PBS
Peter Todd: COGSCI, INFO, PBS
Larry Yaeger: COGSCI, INFO
Chen Yu: COGSCI, PBS

2. Vision, Goals and Thematic Basis

As is well known, the dominant methodology of science is reductionist in nature. This was clearly articulated by Descartes in 1628: In studying any phenomenon, simplify it to its essential components, dissecting away everything else. Reductionism is motivated by the belief that complicated systems are most fruitfully investigated at the lowest possible level. By reducing explanations to the smallest possible entities, the hope is that we will find entities that are simple enough to fully analyze and explain. The spectacular success of this methodology in modern science is undeniable. For example, it has led to unprecedented knowledge of the molecular components of living systems. Unfortunately, it has not led to a corresponding understanding of how large collections of such components operate *as systems*, giving biological organisms the unique properties that distinguish them from nonliving systems. Reductionist approaches have also led to sometimes disconnected disciplines of expertise, where advances at one level of analysis are unconnected to advances at another.

For these reasons, it is becoming increasingly clear in many areas of science that reduction must be complemented by synthesis. While reduction emphasizes decomposition and localization (Bechtel & Richardson, 1993), synthesis is focused on understanding how the organization of the interactions between these components give rise to the original phenomenon of interest (Keller, 2002). Thus, synthesis is more systemic in nature. Perhaps the best-known example of synthesis in modern science is the burgeoning field of systems biology. After more than 50 years of dissecting living systems into their molecular components, it has become increasingly clear that the challenge for biology in the 21st century is putting these pieces back together into organisms. Accordingly, synthesis requires a rather different skill set from reduction, with modeling and mathematical analysis playing central roles in understanding the complexity of interactions between large numbers of nonlinear dynamical components.

Aside from molecular biology, nowhere is this need for synthesis more apparent than in the behavioral and brain sciences. Converging lines of evidence from psychology, neuroscience, and robotics suggest that brain and mind are *embodied*, *situated*, and *dynamical* (Beer, 2000). The brain is a highly dynamic complex system (Freeman, 200l; Izhikevich, 2006; Rabinovich, Huerta & Laurent, 2008), naturally interfaced with the body through sensors and effectors. In turn, our bodies have their own intrinsic dynamics which serve as the spatiotemporal locus of our sensorimotor and cognitive identity, and provide the foundation for even our most abstract metaphors (Brooks, 1991; Thelen & Smith, 1994; Clark, 1997; Lakoff & Johnson, 1999; Pfeifer & Bongard, 2007). In addition, both the physical and social environment in which we live is highly structured by, and in turn structures, our cognition (Gibson, 1979; Suchman, 1987; Hutchins, 1995; Clancey, 1997; Clark, 2008). For example, we arrange our desk to offload memory and problem-solving demands, and cooperating groups of people can solve problems that no individual could. There can be no understanding of the nature of human intelligence – how it works, how it develops, and how it can be made – if one "dissects away" the clutter in our environments or the other intelligent agents with whom we are continually engaged. Finally, evidence is accumulating for the importance of continuous temporal processes and interactions across nested levels of analysis and nested time scales (Smith & Thelen, 1993; Kelso, 1995; Port & van Gelder, 1995; Spivey, 2007).

Situated, embodied and dynamical ideas are having an increasing impact across cognitive science, leading to important breakthroughs not only in psychology, anthropology, linguistics and neuroscience, but even philosophy and artificial intelligence. Based on studies such as an analysis of expert performance in the video game Tetris, Kirsch (1995) argued that we actively organize the space around us in ways that simplify perception, choice and reasoning. Suchman (1987) traced breakdowns in communication between people and a photocopier help system to mistaken assumptions by the designers about the nature of action, demonstrating that action is contingent upon the actual situation as it unfolds. Based on his studies of the navigation team of a large naval vessel, Hutchins (1995) showed how cognition can sometimes be a socially constituted process, carried out by groups of people interacting rather than a single individual. Considerations such as these have led some philosophers to propose a radical new "extended mind" hypothesis, in which objects in the environment literally function as part of an agent's mind (Clark & Chalmers, 1998; Clark, 2008). Landy and Goldstone (2007) explored how even formal mathematical reasoning is grounded in our ability to perceive and to make physical transformations to notational structures, leading to the development of a grounded algebraic tutoring system for middle school students. Tognoli and colleagues found that coordinated behavior among individuals was associated with specific patterns of neural dynamics, demonstrating that social interactions affected the neural states of participants (Tognoli et al., 2007). Using data collected from robots, Lungarella and Sporns (2006) demonstrated how sensorimotor interaction and body morphology induce statistical regularities in neural dynamics. Needham, Barrett and Peterman (2002) demonstrated the importance of embodiment to the developmental process by fitting 2- to 5-month-old infants with Velcro-covered 'sticky mittens'. These mittens enabled the infants to grab objects merely by swiping at them, enabling them to precociously coordinate vision and reaching. Infants who were given 2 weeks of experiences with 'sticky' mittens subsequently showed more sophisticated object exploration and recognition even with the mittens off. Smith and colleagues (see Smith, 2004, for overview) have similarly shown the cascading consequences and co-developmental relations among toddlers' actions on objects, their visual processing of shape information, and their understanding and attention to object functions (and affordances). Spivey (2007) has provided an extensive review of how temporally continuous processes permeate mental processes when we probe just below the surface appearance of discreteness. By dynamically analyzing recurrent connectionist networks trained to predict subsequent words in sentences drawn from a corpus of 10,000 sentences, Elman (1995) explored how the build-up of state in the network dynamics served to provide the context for resolving long-distance dependencies such as number agreement. Phattanasri, Chiel and Beer (2007) showed how associative learning-like behavior can evolve when a dynamical neural circuit is situated in a changing environment, even in the absence of synaptic plasticity. Brooks (1991) demonstrated that taking a situated and embodied perspective could revolutionize the design of robots, leading to a major new approach now known as "behavior-based robotics" (Arkin, 1998).

All of these developments suggest a new perspective in which behavior and cognition are seen as arising from the dynamical interaction between a nervous system, body and environment (which includes other agents) and can only be fully understood within this broader context (Beer, 1995; Figure 1). From this perspective, behavior and cognition are conceptualized as arising from the closed-loop interaction of a nervous system with the body

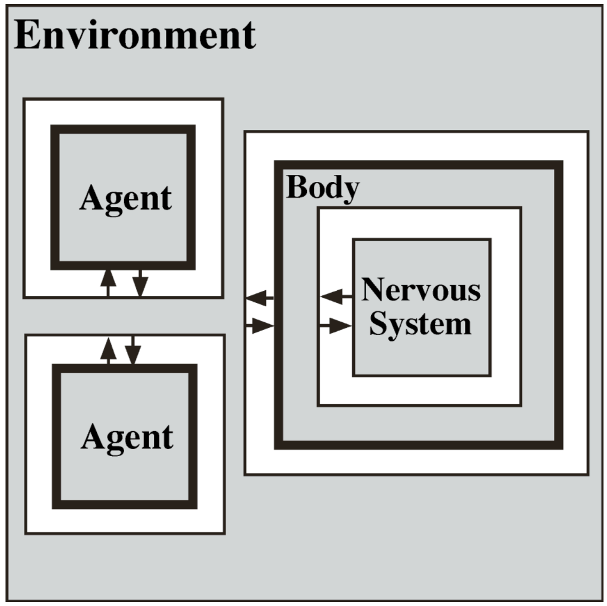

Figure 1

and environment in which it is embedded, rather than as the sole product of any one component of this coupled system, such as the brain. Certainly from an evolutionary perspective, it is the behavior of the complete system that is selected for or against, not the individual components. It might seem that taking such a coupled perspective would make an already very difficult problem simply intractable. Studying any one component of a brain-body-environment system is difficult enough, but studying all three components and their interactions simultaneously in any animal is simply beyond our current experimental capabilities, let alone our ability to understand theoretically. However, we are **not** suggesting that the entire brain, body and environment of an agent must be fully characterized before any progress can be made. Rather, the trick is to work with simplifications that cut across the traditional brain-body and agent-environment boundaries instead of along them, as disciplinary approaches normally do.

Such an integrated approach requires bringing together many important theoretical threads from across the cognitive, behavioral and brain sciences. Cognitive science and neuroscience have largely been bounded by the human skin, failing to take advantage of the way that feedback through the environment of an agent's own actions actively structures the sensory information that it receives. On the other hand, ecological psychologists who emphasize the mutuality of organisms and their environments have often failed to address the neural support for perceiving and acting. Many areas of cognitive science, psychology and neuroscience have been slow to embrace the mathematical tools offered by complex systems theory in general and dynamical systems theory in particular as a way to come to grips with the fundamental nonlinearity of the interactions occurring across temporal and spatial scales. Finally, if physical embodiment and situatedness in an actual environment are to play essential roles, then computer modeling must be augmented by robotic models of real systems interacting with real environments. Of course, such theoretical and modeling efforts must be developed hand-in-hand with experimental studies of human subjects, with constant feedback between modeling and theoretical work on the one hand and experimental analysis on the other.

This emerging new perspective in the cognitive, behavioral and brain sciences requires a new kind of training experience for graduate students.

The central vision for this proposal is to bring together cognitive science faculty at Indiana University doing cutting-edge research at the neural, behavioral, and social levels using both experimental and modeling approaches to develop a unique training program in the dynamics of brain-body-environment systems. Just as symbolic and connectionist cognitive science require proficiency in computation and linear algebra, respectively, in order for students to contribute to research in situated, embodied and dynamical cognitive science, they need to become familiar with the concepts and tools of dynamical systems theory, the mathematical language of change. In addition, they need to learn to think across multiple spatial and temporal scales, so they can understand how phenomena at one level arise from the interactions between components at another level. They also need to learn how to make use of robots as a new modeling medium for embodied cognitive science. Finally, students need to become comfortable with analyzing behavior and cognition across the brain-body and agent-environment boundaries. We believe that the theoretical language of dynamical systems and the perspective of coupled brain-body-environment systems have the potential to serve as a unifying framework for advancing our understanding of intelligent systems.

The training program is new and innovative in that it will explicitly provide students a unique set of skills that will enable them to both conduct experimental studies and build mathematical, computational and robotic models that bridge different levels of analysis, including neural, behavioral, and social. It will add value by weaving into a single graduate training program four research and training programs of considerable strength and in so doing will build the self-sustaining infrastructure of training necessary to train a new kind of scientist. We anticipate that the impact of training cognitive science students with this unique set of skills will be significant. Much progress in Cognitive Science has been made by isolating components and systems. But many fundamental integrative questions have been left unanswered by this approach. Lack of progress on such questions is due in part to the difficulty of the skills needed to understand intelligence as an emergent property of a complex dynamic system, but it is also due in part to traditional disciplinary boundaries within cognitive science. It is often said that such boundaries can only really disappear from a scientific field when a new generation of scientists who have no personal commitment to those boundaries begin to think outside the boxes of their teachers. The proposed training program will train a new kind of scientist who will have the combination of experimental and theoretical skills to take embodiment, situatedness and dynamics seriously across multiple levels of analysis. These new scientists, in turn, will transform not only our understanding of intelligence, but also the very way Cognitive Science is done.

<u>The specific objectives of our training program are</u>:

(1) to provide trainees with the theoretical and mathematical tools necessary to understand behavior across nested levels of time and space;

(2) to provide trainees with the experimental and methodological tools to study cognition across the brain-behavior, agent-environment, and agent-agent boundaries;

(3) to build a training infrastructure based on continuing interactions and collaboration across leading scientists who use different methods to study related phenomena at different levels of analysis ;

(4) to develop a model training program whose structure of collaborative multi-leveled and multi-method research may serve as a transformative program capable of transcending boundaries of disciplinary culture;

(5) to recruit, train and place in top research institutions a cohort of students who though originally diverse in their starting disciplines become able to think across the brain-body-environment boundaries;

(6) to increase the participation of underrepresented groups in cutting-edge science – by recruiting those individuals to this program and providing the support necessary for success in the program and beyond;

(7) to systematically evaluate our success in meeting these objectives and to continually adjust the components of the program in response to those evaluations;

3. Major Research Efforts

Taking a coupled brain-body-environment perspective seriously raises special challenges for the cognitive, behavioral and brain sciences. Meeting these challenges requires an unusual combination of expertise. Subsets of the research threads that comprise this training proposal certainly exist at other institutions. However, we believe that Indiana University is uniquely positioned to tackle these challenges in a coherent and unified way, with its world-renowned cognitive science program, its outstanding department of psychological and brain sciences, its track record in mathematical psychology, its strength in complex systems, and its new robotics program. In this section we first briefly review research of the faculty participating in this proposal, all of whom are members of the Cognitive Science Program at IU. We then describe three examples of the kinds of new collaborative projects that the IGERT would make possible.

3.1 Current Research Efforts

The proposed training program will build on four areas of research excellence at Indiana University, with the goal of providing training in the skills necessary to unify and work across levels. The proposed research focus is drawn from a subset of the full cognitive science faculty, and represents a new emphasis for the program. Each of these component research areas is primarily focused at one or an adjacent pair of brain, behavior, and social levels of analysis, and they each employ a combination of experimental and theoretical approaches. The proposed training program will both expose students to ongoing cutting-edge interdisciplinary research within each of these areas, and encourage the integrative study of behavioral and cognitive phenomena across these levels.

<u>Brain Dynamics and Connectivity</u>: Five research groups currently participate in this research area, which centers on the complex dynamics of neurons and brain areas and how their interactions are influenced by and shape behavior. The **Beggs** laboratory's main research focus is on emergent properties of living neural networks, particularly cortical neuronal cultures and slices (Hsu et al., 2007). Based on multielectrode recordings of neuronal activity, the lab has developed and applied computational techniques to elucidate network patterns of information transmission and processing. The **Brown** laboratory investigates how humans monitor and adjust their behavior as they evaluate potential outcomes associated with available alternatives in decision-making (Brown et al., 2005). The lab uses a combination of computational neural modeling, fMRI and cognitive psychology methodologies. The laboratory of **Thomas James** investigates the neural mechanisms of multi-sensory object recognition (James et al., 2005). Using fMRI methods, he is particularly interested in how the brain integrates across inputs from different sensory systems in order to interpret a potentially ambiguous environment. The **Newman** laboratory studies the neural basis of sentence comprehension and problem-solving (Newman et al., 2005). Using fMRI approaches, the lab measures differences in functional connectivity across individuals to obtain a better characterization of the neural network that supports cognition. The **Sporns** lab studies brain connectivity and dynamics in both simulated and empirically derived brain networks using a blend of computational tools from dynamical systems theory, graph theory, and information theory (Sporns et al., 2004). Research focuses on how brain dynamics is shaped by interactions with the environment and by the topology of neural connections. Together, this group of researchers will provide trainees with a strong foundation in experimental and theoretical tools for studying the properties of brain connectivity and dynamics and their role in behavior and cognition.

<u>Self-Organization of Individual Behavior</u>: Six groups currently participate in this research area, which investigates how behavior and cognition arise from the closed-loop interaction between an agent and its environment. The **Bingham** laboratory focuses on the information and dynamics of human perception/action tasks through a combination of experimental and

dynamical modeling methods (Mon-Williams et al., 2007). Their work include studies of perceptual coupling in bimanual coordination, visual event recognition, spatial perception, visually-guided reaching-to-grasp and long-distance throwing. The **Beer** laboratory uses evolutionary algorithms to evolve nervous systems for model agents and then uses the tools of dynamical systems theory to analyze the resulting brain-body-environment interactions (Beer, 2003). Behaviors that have been studied include walking, visually-guided reaching, categorical perception and selective attention. The **Busemeyer** laboratory develops dynamical models of decision-making using decision field theory (Busmeyer & Johnson, 2006). The **Scheutz** laboratory focuses on how humans and robots can interact in natural and effective ways (Scheutz et al., 2007). This work includes both experimental studies of people's perceptions and mental models of robots and computational studies of architectural principles and algorithms for robots. The **Yaeger** lab builds computational models of evolving agents to study the relationship between neural architectures and behavioral performance in an environment (Yaeger et al, 2006). Neural connectivity is shaped by evolutionary constraints and the resulting complexity of neural structures and dynamics is observed as a function of changes in environment and fitness. Finally, **Allen** studies the philosophical underpinnings of explanations of human and nonhuman animal behavior (Allen, 2006). He is particularly interested in what grounds attributions of goal-directedness and intentionality, and the differing perspectives brought to these issues by psychologists and biologists, as well as the nature of concepts and ways of modeling conceptual structures computationally. Together, this group of researchers will provide trainees with a strong foundation in experimental and theoretical tools for studying how behavior and cognition of individual agents arises from the interaction between that agent's nervous system, body and environment.

Processes of Change: The five laboratories studying processes of change investigate how an individual's own activity creates long-term change in the system and its intrinsic dynamics, as well as the cascading consequences of this change. This group includes the experimental analysis of learning and developmental change as well as computational modeling and mathematical analysis of such change. **Karin James**' laboratory focuses on the effects of sensory-motor activity on the development of visuomotor processes, including the role of action in the development of the visual system (James et al., 2006). The work, which uses both behavioral and fMRI methods with children as young as 4 years of age, is especially interested in how the motor and visual systems in the brain are interconnected and how their development is affected by multi-modal experience. **Kruschke** (2006) and **Shiffrin** (Mueller et al., 2006) study computational and formal models of learning, especially as they apply to changes in attention. **Linda Smith**'s laboratory focuses on the mechanisms of change in infants' and toddlers' learning about objects with special emphasis on the interactions of perception, action, and language (Smith, 2005b). The key idea concerns how moment-to-moment activity creates long term change that then creates new opportunities for (and constraints on) future learning. Theoretical approaches include dynamic field models and connectionist models. **Yu**'s laboratory examines how language learning is grounded in sensorimotor interaction and uses computational modeling and behavioral studies of infants (Yu et al., 2005). In addition this work (in collaboration with Smith) also examines the dynamic coupling of parent-toddler behavior in naturalistic settings and as related to object name learning using measures of head movements, hand movements, and using head cameras. Together this group of researchers will provide trainees with a strong foundation in experimental and theoretical tools for studying how processes of change contribute to the dynamics of brain-body-environment interactions.

Self-Organization of Group Behavior: Cognitive scientists traditionally have focused on the behavior of single individuals thinking and perceiving on their own. However, interacting groups of people also create emergent organizations at a higher level than the individual. Four groups focus on the dynamics of collective behavior, how people influence one another, and how groups organize themselves over evolutionary, historical, and briefer time-scales. **Goldstone**'s laboratory has developed an internet-based experimental platform that allows groups of people to interact with each other in real time on networked computers. They study the competitive foraging for resources by individuals inhabiting an environment consisting largely of other individuals foraging for the same resources, the dissemination of innovations in social networks, group coordination, and how groups create rules that then govern their patterns of organization (Goldstone et al., 2008). Also interested in how groups search for information, **Rocha**'s laboratory explores how social foraging is accomplished online, by examining patterns of web-based information exchanges and social interactions (Rocha et al., 2005). They develop information retrieval and recommendation algorithms that infer thematically coherent communities in online resources, and predict future social relationships. **Eliot Smith**'s research involves both human experimentation and agent-based modeling and focuses on when, why, and how people turn to using information provided by others in preference to using information that they obtain individually from the environment (Mason et al., 2007). The interplay of several motivations for conforming or copying shapes collective outcomes as groups self-organize, whether converging to uniformity of opinions and behavior or maintaining diversity. **Todd**'s work focuses on how people can make appropriate decisions in adaptively important domains, such as mate choice and food choice, by using simple heuristics that are shaped to fit the structures of information available in the environment (Todd et al., 2007). Often, the decision environment is composed of other individuals, as when people are searching sequentially for mates who must also choose them in return.

3.2 Three Examples of New Collaborations Enabled by the IGERT

The central research goal of the proposed training program is to bring together faculty and students from the existing research groups at Indiana University to tackle projects that cross brain-body and agent-environment boundaries and that combine empirical studies with computer and robotic models and mathematical analysis. Here we describe three examples of the kinds of new collaborations that the proposed IGERT would facilitate. In all cases, the faculty expertise and interest already exist. The only missing component required for these collaborative projects to move forward is the training and funding for students with the necessary interdisciplinary perspective and skills required to carry out this research. Note that these examples are intended to be representatives only and by no means exhaust the range of possibilities.

<u>Information-Theoretic and Dynamical Analyses of Brain-Body-Environment Systems</u>: There are fundamental theoretical questions about how best to understand brain-body-environment systems. Two distinct bodies of mathematics, information theory and dynamical systems theory, have been brought to bear on the analysis of such complex systems. Although the philosophical commitments of informational and dynamical approaches to cognitive science are often thought to be at odds, the underlying mathematical tools are quite compatible. Information theory fundamentally concerns the statistical structure of one or more random variables, and the central notion in information theory, entropy, quantifies the "surprise" associated with measuring a particular outcome. On the other hand, dynamical systems theory studies the geometrical and topological structure of the space of possible trajectories of systems that change over time, as well has how this structure varies with parameters. We propose to study how informational measures change over time and flow in model brain-body-environment systems, as well as how information structure relates to the dynamics and coupling of the underlying components. In addition , we are interested in exploring how the dynamics of an agent's own actions self-structure the information it can obtain from its environment. **Beer** and **Yaeger** have extensive experience in the evolution of model brain-body-environment systems, ranging from sensorimotor behavior such as walking and minimally-cognitive behavior such as categorical perception and selective attention (Beer, 2008) to the collective behavior of large populations of agents in Polyworld (Yaeger, 1994), while **Sporns** specializes in graph theoretic and information theoretic characterizations of complexity in brain structure and dynamics (Lungarella & Sporns, 2006; Sporns, Honey & Kötter, 2007). In addition, Beer has carried out extensive dynamical analyses of evolved agents (Beer, 2003) and Sporns and Yaeger have begun to apply information theoretic measures of complexity to Polyworld

(Yaeger & Sporns, 2006; Yaeger, Griffith & Sporns, 2008). This group will combine information theoretic and dynamical analyses of evolved model agents in order to develop a solid theoretical foundation for the analysis of brain-body-environment systems. In addition, they will work with **Bingham** to test the applicability of these tools to perception/action tasks in humans. As an initial step in this direction, Beer has begun to evolve models of the kinds of tasks studied in Ecological Psychology, including the perception of passability affordances and visually-guided interception.

Integrating Neural, Behavioral and Robotic Approaches to Understand How Brain-Body-Environment Systems Change Through Their Own Activity: Perhaps the most fundamental question in all of science is the origin of new forms. This question of new forms is particularly daunting in the case of intelligence: How does an organism that cannot walk become one that can? Where do words and ideas of space, time, number, etc. come from? Developmental process (both in body and in mind) is very much a case of increasing complexity, of making more and something new from something less. We seek a new understanding of brain-body-environment systems *change themselves* though their own multimodal activities in tasks and the role of other agents in fostering this change. **L. Smith** (2002; 2005a) has extensive experience in the study of toddlers and children's real-time learning and has shown, for example, that their manual actions on objects, which create the dynamic first person views, drives dramatic changes in visual object recognition. **K. James** (2006, submitted) is conducting state-of-the art studies of neural development and the interactions of the visual and motor systems in driving change. She studies how children's and adults multi-modal experiences drive change in coupled neural systems, for example, how writing and seeing the forms one writes create changes in brain response (as measured in imaging studies) in motor and visual areas and in the functional connections between these systems. Smith and James (Pereira et al, 2007) are already collaborating on studies of motor driven perceptual learning in toddlers. **Scheutz** (Scheutz et al, 2007) uses humanoid robots to understand multimodal processes and learning by an agent as it explores it world. **Yu** and Smith (Yu et al, 2007, Pereira et al, 2008) are placing head cameras and movement sensors on toddlers as they engage in toy play, tracking in real time the dynamics of the sensory-motor experience. One new result that they have discovered is that toddlers – through their manual actions – limit their views to one object at time. Given a cluttered field, toddlers manually bring the object of interest close to their eyes, essentially occluding other objects, a whole-bodied approach to attention that may make segregating and learning about objects easier. This group is poised to combine neural, behavioral, and robotic approaches to study activity-driven learning, how sensory and motor systems in the service of some real world task create new functional systems. This is a unique opportunity for conducting parallel experiments in biological and artificial systems in order to work toward a deeper understanding of developmental process.

Diffusion of Innovation Across Evolving Social Networks: Cognitive science has focused on the behavior of single individuals because our own introspection provides us with motivation and perspective at this level. However, in a literal sense, we are all participating in entities greater than ourselves. Self-organized collectives of people create emergent, group-level patterns that are rarely the goal of any individual. One important case of this is the diffusion of innovations in social networks, striking because humans are uniquely adept at adopting, and extending, one another's innovations. Any organism that is capable of imitating its peers must decide when and how much to imitate others' solutions versus explore one's own solutions, and these decisions influence how well the group as a whole learns to solve problems, coordinate, and cooperate. We will engage in a collaborative project that explores feedback loops of social imitation and individual exploration. We will employ mathematical models of individual and collective search behavior by **Brown**, **Kruschke**, and **Todd** (Brown, Reynolds, & Braver, 2007; Kalish, Lewandowsky, & Kruschke, 2004; Todd & Gigerenzer, 2007) to generate empirical predictions on group innovation diffusion. We will compare these predictions to experiments with human groups using Internet systems that we have developed that allow groups of 20-200 people to interact with each other in real time on networked computers, using a collective behavior platform developed by **Goldstone** (Goldstone, Roberts, & Gureckis, 2008), employing social experimentation methodologies employed by **E. Smith** (Smith & Semin, 2007), and compared to models using model-fitting techniques developed by **Busemeyer** (Busemeyer, Jessup, Johnson, & Townsend, 2006). Simultaneously, **Allen** and **Rocha** will compare these laboratory results with large corpora of Internet data on the popularity of web sites, website-to-website link distributions, and the diffusion of ideas/terminology/opinions over blogs (Allen, Buckner, & Niepert, 2008; Rocha, 2001). Finally, **Beggs** will employ evolutionary modeling techniques to account for how these social networks change over time, and determine what kinds of networks and inter-agent communications are ideal for different kinds of problems (Beggs, 2007). Critically, the models will generate hypotheses that are compared to laboratory and real-world data sets, the results of which, in turn, will be used to inform and revise the models.

4. Education and Training

A comprehensive training program must integrate coursework, community-building programs, research experiences, teaching experiences, professional development, and dissemination of results. In this section, we briefly describe each of the major components of our proposed training program, their motivation, and how they fit together.

Degree Programs: We will build our training program around the Cognitive Science Program at Indiana University. This program offers both a stand-alone Ph.D. degree in Cognitive Science and a joint Ph.D. with a variety of departments, including Psychological and Brain Sciences, Computer Science and Informatics. The stand-alone degree program in Cognitive Science was initiated in 2005. In contrast, the joint Ph.D. program in Cognitive Science began in 1989 and has been extremely popular, graduating hundreds of students over the past 19 years. This structure allows us to rely on all students having at least the following six core courses: *Mathematics & Logic in Cognitive Science*, *Programming Methods in Cognitive Science*, *Philosophical Foundations of Cognitive Science*, *Models in Cognitive Science*, *The Brain and Cognition*, and *The Cognitive Science Colloquium Series*. By building our IGERT training program on this core, we can address one of the most common problems of interdisciplinary training programs: preparing students with widely varying backgrounds for advanced graduate training in an interdisciplinary research area.

IGERT-Specific Course Requirements: Beyond the course work required by each student's major, the IGERT training program will add the following requirements:

1) All IGERT students must take the new 3 credit hour course *Situated, Embodied and Dynamical Approaches to Cognitive Science* (described in more detail below) during their first year in the program.
2) All IGERT students must take the new 1 credit hour *Professional Development Seminar* (described in more detail below). This course will typically be taken during their second year in the program, since we believe that students will be sufficiently far along in their graduate training and research to derive the most benefit from this seminar at that point.
3) All IGERT students must take two additional 3 credit hour courses from a list of approved electives at some point during their course of study. Typical electives include the following courses: *Behavior-Based Robotics*, *Introduction to Dynamical Systems*, *Developmental Processes in Perception, Action and Cognition* (a new course described below), *Brain Dynamics* (another new course described below), *Evolution and Analysis of Brain-Body-Environment Systems*, *Biological and Artificial Neural Networks*, *Perception/Action*, *Complex Adaptive Systems in the Social Sciences*, *Introduction to Complex Systems*, *Neural Networks as Models of Cognition*, *Biologically-Inspired Computing*, and *Artificial Life as an Approach to Artificial Intelligence*.
4) All IGERT students must participate in a new IGERT Colloquium Series (described in more detail below).

Development of New Courses: In support of the educational goals of our training program, we intend to develop the following new graduate courses:

Situated, Embodied and Dynamical Approaches to Cognitive Science (Beer; 3 credit hours): This will be a new core course required for all IGERT students. It will provide a broad introduction to the growing importance of the concepts of situatedness, embodiment and dynamics in cognitive science. The course will cover both the key conceptual content and the historical development of these ideas. In addition, it will survey classic work in this area. Examples will be drawn from each of the main research thrusts of our proposal (Brain Dynamics and Connectivity, Self-Organization of Individual Behavior, Processes of Change, and Self-Organization of Group Behavior).

Developmental Processes in Perception, Action and Cognition (L. Smith; 3 credit hours): This will be a new elective course. This course will consider behavioral and neural evidence from human and nonhuman development on the role of perception and action in creating developmental pathways and also higher level cognitive processes, and also the use of these advances in knowledge in the development of robotic systems. Specific issues that will be considered will be the role of multimodality, imitation, closed perception-action loops, and exploration in developmental process. The course will have three main components: reading and discussing classic and new papers in the field; being trained in experimental methods in the study of development; and planning and conducting (as a class project) a study of perceptual and/or action learning in infants and/or robots.

Brain Dynamics (Sporns; 3 credit hours): This will be a new elective course. The course will address how the brain is structured as a complex network, how it functions as an integrated dynamic system, and how the brain interacts with body and environment. The course will provide an overview of major research issues in these areas and introduce students to classic as well as modern theoretical, computational, and empirical literature. Specific course topics will include major components of nervous systems and their evolutionary history, network architecture of the mammalian brain, modeling and observation of spontaneous and evoked brain dynamics, brain dynamics and its role in cognition and behavior, information theory and the interface of brain, body and environment in neurorobotics. A part of the class will consist of lecture and discussion, and another part will be devoted to student presentations of research literature. Another portion of the class will involve simulation and analysis of computational models of brain dynamics in Matlab, including student projects.

Professional Development Seminar (Goldstone; 1 credit hour): This will be a new seminar course required of all IGERT students. The goal of this seminar is to engage the full panoply of issues facing the new faculty members that our students will become. Topics to be addressed include the ethical conduct of research, proposal writing and review, critical reading of the scientific literature, paper writing and reviewing, presentation skills, teaching, international perspectives, challenges facing underrepresented groups in science and issues in cross-disciplinary collaboration. The seminar will be organized as a series of presentations and discussions led by IGERT faculty, IGERT students, and invited guests both from within and outside the university. Whenever possible, the seminar topics will be integrated with other ongoing activities in the IGERT program. For example, presentations on proposal writing would occur as students are beginning to formulate their proposals due at the end of their second year projects. As a second example, a discussion of the challenges facing underrepresented groups in science would be scheduled in preparation for our summer recruiting program for underrepresented groups (see Section 7 of this proposal).

Extended Colloquium Series: An essential part of any training program is a vigorous colloquium series that exposes IGERT students and faculty to the very best researchers, as well as familiarizes these visitors with the work going on within the IGERT. However, we believe that the traditional colloquium format provides insufficient opportunities for students to interact with visiting researchers. Instead, we propose an extended interaction between IGERT students and external speakers. To make this possible, speakers will be expected to stay for at least two full days. During this time, they will not only give a formal talk and visit related research labs, but they will also participate in a variety of activities specifically targeted at IGERT students. For example, time will be reserved after the formal talk for students to engage the speaker in more detailed discussion. In order to prepare students for this discussion, the extended seminar series will feature a critical discussion of one of the speaker's papers (suggested by the speaker themselves and lead by the faculty host for that speaker) during the week before their visit. In addition, students will have an opportunity to discuss broader issues with the speaker (e.g., where they see their field going in the future or their views on organizing a presentation to an interdisciplinary group). This could take place during a lunch hosted by the students. Not only will this extended colloquium series expose students to the best current research in situated, embodied and dynamical cognitive science, but it will also expand their postdoctoral and employment options by giving them opportunities to forge personal connections with top researchers.

First Year Experience: Before they arrive on campus, students will be matched with an initial mentor based on their background and preliminary research interests. In order to build a sense of community, all IGERT students will be housed initially within adjacent space in Cognitive Science. We will organize a series of informal social events, beginning with a welcome party when the students first arrive, in order to develop a sense of community within the group. During their first year, IGERT students will take a combination of courses required by their major and courses specifically targeting the topics of this training grant as described above. At some time during the year, each laboratory participating in the IGERT will hold an open house in order to make new IGERT students aware of the research going on within that laboratory. New IGERT students will also take part in the Professional Development Seminar and Extended Colloquium Series (described above). Finally, each student will begin a preliminary research experience with one of the faculty members participating in the IGERT.

Summer Research Internship: During the summer between their first and second years, IGERT students will participate in an IGERT-supported research internship. In some cases, these internships will take place in the research labs of IGERT faculty at IU. However, whenever possible, students will be encouraged to visit another institution, giving them an opportunity to broaden their experience and to develop skills and perspectives that they can bring back to IU to enrich the IGERT program. Support will also be made available for international internships, and students will be strongly encouraged to explore this option (see Section 9). This international option will give students an opportunity to experience the culture of science in other countries, and to learn the sometimes quite different perspectives and approaches these scientists take. In addition to broadening the research experiences of IGERT students, external internships will strengthen existing connections between IU and these other institutions, as well as form the foundation for new connections. In order to facilitate these research internships, we will partner with specific top-quality institutions in the US and abroad. Letters of commitment from five domestic institutions (*Gary Cottrell* at UCSD, *Michael Spivey* at UC Merced, *William Warren* at Brown University, *Cynthia Breazeal* at MIT, and *Luis Bettencourt* at the Los Alamos National Laboratory) and four international institutions (*Inman Harvey*, *Ezequiel DiPaolo* and *Phil Husbands* at the Center for Computational Neuroscience and Robotics at the University of Sussex in the United Kingdom, *Jun Tani* at the Behavior and Dynamic Cognition Lab at the

RIKEN Brain Science Institute in Japan, *Gregor Schöner* at the Institut für Neuroinformatik at Bochum University in Germany, and *Dirk Helbing* at ETH Zurich in Switzerland) to provide internships for our students are attached to this proposal. These internships will not only provide our students with broader research experiences in top-notch research groups outside of Indiana University, but they will also expand the postdoctoral and employment opportunities available to our students after graduation from the program.

<u>Second Year Research Project</u>: During their second year in the program, as IGERT students continue to take courses, they will also begin a year-long research project grounded in their preliminary research in their first year and their summer research internship experience. These projects will be co-supervised by two IGERT faculty, either from different approaches within a research area (e.g., experimental psychology and computational modeling) or from different research areas (e.g., Brain Dynamics and Connectivity and Self-Organization of Individual Behavior). Although not required, it is anticipated that this second year research project will often form the basis of a student's dissertation work. Some IGERT money will be made available on a competitive basis for students to apply for internal financial support for these projects (e.g., for a small piece of required equipment or software). The main deliverable for the second year project will be a grant proposal written in either NSF or NIH format for which the student's research provides the preliminary data. At the very least, this experience will give students practice writing a grant proposal. In some cases, these proposals may form the basis of a dissertation proposal or even a submitted grant. The students will also present their research as part of an internal annual IGERT research showcase meeting (see below).

<u>Teaching Experience</u>: We believe that teaching experience is an essential component of any graduate training program, not only to prepare students to teach their own courses as future faculty members, but also to build their skills in organizing their knowledge and in explaining complex concepts to diverse audiences. Unfortunately, there is a large gap between the TA experience of typical graduate programs (which often involves only grading, running a recitation section or perhaps giving a few guest lectures) and completely running your own course. Accordingly, we propose a novel teaching experience for our IGERT trainees that will help them to bridge this gap. In particular, we propose that a group of IGERT students team-teach an undergraduate course in the general area of situated, embodied and dynamical approaches to cognition under the supervision of an IGERT faculty member. With help from the faculty advisor, the students will need to collectively design the course, deciding on the material to be covered, how it will be organized, and who will present what. Each student will then be responsible for a 2-4 week section of the course, giving lectures and preparing and grading an assignment covering the material from that section.

<u>Annual Research Showcase</u>: Near the end of each academic year, we will hold an internal IGERT research showcase meeting. This meeting will consist of posters by IGERT students about their research. Not only will this meeting give all IGERT participants, as well as the larger Indiana University and Bloomington communities, a chance to familiarize themselves with all of the research being conducted within the IGERT program, but it will also give the IGERT students an opportunity to practice their presentation skills. In addition, we will schedule one of the external colloquia to coincide with this meeting, with the outside visitor serving as both a keynote speaker as well as one of the judges for a best poster award.

<u>IGERT Affiliates</u>: In addition to IGERT fellows, our program will also include IGERT Affiliates. These are students who are not being directly supported by the training grant, but whose research is closely related. Affiliates will be able to participate in all IGERT activities, including the extended meeting time with colloquium speakers, the Annual Research Showcase, and all social events. IGERT Affiliates can be nominated by any participating IGERT faculty member. The IGERT Affiliates Program will allow us to broaden the impact and participation of our training program beyond the set of students that we can directly support.

<u>Dissemination Plans</u>: Perhaps the most important method of dissemination is publication of IGERT research in refereed forums. As students progress through the program, they will be

expected to submit papers describing their research. More broadly, we will maintain a website for the training program that will not only serve as an internal focal point for the program itself, but also as a rich source of information for the external world. This site will include application materials, audio and video podcasts of selected lectures, a schedule of courses, colloquia and other IGERT events, links to curricular materials and software developed as part of the program, and a bibliography of papers published by IGERT students and faculty.