Center for Large-Scale Integrated Optimization and Networks (CLION)- Science of Resilient Networks for Crisis Response, Prediction & Decision Support

A. The Grand Challenge

Current mathematical approaches are limited in their ability to rigorously model complex interactions in large-scale networks as required to enable resilient network structures that support optimal response to rapidly changing conditions. Von Neumann computer architectures have governed the processing structure and related hardware and software of computing machines since their advent in the 1940s. Although increasingly complex algorithms, circuitry, and data collection and integration techniques have been developed that permit significant improvements in implementation, these do not resolve the fundamental limits of the architecture in terms of computing time and resources. We hence experience the paradoxical situation of being able to sense various events without having the capability of processing them efficiently to support robust decision-making. These limits pose particular challenges in complex, dynamically changing scenarios requiring robust and rapid decision-support to produce optimal results, such as in the case of natural or man-made crises. In these scenarios, decisions must be made rapidly based on the combination of often hundreds of thousands of sensory channels, presenting formidable challenges due to the combinatorial explosion of possible interactions between diverse sensoria.

B. Vision and Goals

The Center for Large-Scale Integrated Optimization and Networks (CLION) for Crisis Response, Prediction and Decision Support seeks to resolve current theoretical and technological challenges associated with network optimization problems involving crisis response situations in complex, large-scale systems with rapidly changing operational conditions. By studying various manifestations of resilience in physical, biological, and social systems, we will develop new mathematical approaches to address challenges of flexible reconfiguration of large-scale networks of interacting diverse units. In turn, novel network system architectures, decision support tools, and crisis management systems will be developed, which are relevant to event responses of significance to broader society, including crisis situations, as well as critical infrastructure (i.e. logistics, power) monitoring and protection. Over the long-term, this integrative program of fundamental and applied research will transform all aspects of modern computation and revolutionize computing capability. Specific goals are to:

- Develop new theoretical and experimental foundations of large-scale resilient networks encountered in practical scenarios that demand fast and reliable response to sudden, unexpected, potentially catastrophic events.
- Develop and commercialize next generation decision support and crisis management technologies for large- and multi-scale complex systems involving heterogeneous distributed sensorium in physical, cognitive, cyber, and societal domains, to be of benefit to both public and private sectors.
- Establish optimization science for resilient networks as an interdisciplinary and integrative scientific field through robust educational, outreach, and diversity initiatives.

C. Approach

Assemble a dream team of academic, industry, and government partners: CLION benefits from a world renowned team of researchers from domestic and international universities, government labs, and industry interested in optimization problems involving complex, large-scale networks with rapidly changing operational conditions. Representing the fields of mathematics and graph theory, network science and statistical physics, biologically and brain inspired computation, cognitive dynamical systems, decision support and disaster response, and engineering, this team includes stellar established scientists B. **Bollobas**, R. **Kozma**, and D. **Dasgupta** (University of Memphis); L. **Barabasi** (Northeastern/Harvard), M. **Newman** (Michigan), E. **Szemeredi** (Rutgers); J. **Principe** (Florida); J. **Sztipanovits** (Vanderbilt); O. **Sporns** (Indiana); JA **Kelso**, E. **Tognoli** (Florida Atlantic); D. **Wunsch** and D. **Rogers** (Missouri Science and Technology); J. **Barhen**, N. **Rao**, (Oak Ridge National Labs-ORNL); P. **Erdi** (Kalamazoo College); O. **Riordan** (Oxford); A. **Buczak** (Johns Hopkins); and J. **Caulfield** (Fisk). It also includes several junior level scholars considered leading, new thinkers in their areas such as Haibo **He** (Rhode Island); Jozsef **Balogh** (UIUC); Blair **Sullivan** (ORNL), and Marko **Puljic** (Tulane). With additional collaborators from industry (R. **Venkatesan**-Microsoft; Luda **Werbos** IntControl, John **Gunckel**, FedEx), the US Air Force (Leonid **Perlovsky**), and international academic institutions (Oxford, Cambridge, Hungarian Academy of Sciences, NCTU/Taiwan), CLION is positioned to produce truly transformational scientific advances.

Define an integrative structure to support breakthrough science: The very nature of the proposed challenge requires ongoing and continuous interaction among theorists, experimentalists, and those involved in developing new platforms and architectures. Projects based on isolated, discipline-specific teams will not provide the sustained interaction across disparate fields required to generate fundamental scientific leaps in this domain or to facilitate high-quality educational opportunities.

CLION's integrative approach to project operation and team management is illustrated in **Figure 1**. Our philosophy encourages, in fact requires, continual interaction between team members across disciplinary boundaries and across sub-teams. As depicted, the need for innovative solutions to crisis situations is formulated by team members working in target crisis domains, e.g., logistics, energy systems, layered sensing, natural disasters. Leading experts in the natural sciences (physics, biology, brain sciences, cognition, and social networks) work together to specify major challenges that can be formulated in the language of networks theory. These formulations are used by mathematicians and graph theory experts to develop rigorous theories and provide proofs guaranteeing the existence of specific dynamical behaviors in the networks. These mathematical results provide guidelines to design resilient networks with the desired properties. The developed optimal network designs form the basis of decision support systems for rapid and robust crisis response based on high degree of situational awareness in the large-scale network. The performance of the crisis response, prediction, and decision support system is evaluated at various levels, including mathematical modeling, computer simulations and select set of technical test-beds. During the 5 year project period, it is expected that several cycles of *"Crisis Domain Problems" -> "Manifestations in Natural Systems & Networks" -> "Mathematics & Graph Theory Modeling" -> "Crisis Decision Support and Response System" -> "Crisis Domain Problems" ->...* will be executed with increasing complexity. Due to the pervasive presence of complex networks in all levels of science, technology, and the society, it is expected that our fundamental new graph theoretical approach will produce transformative changes across disciplines.

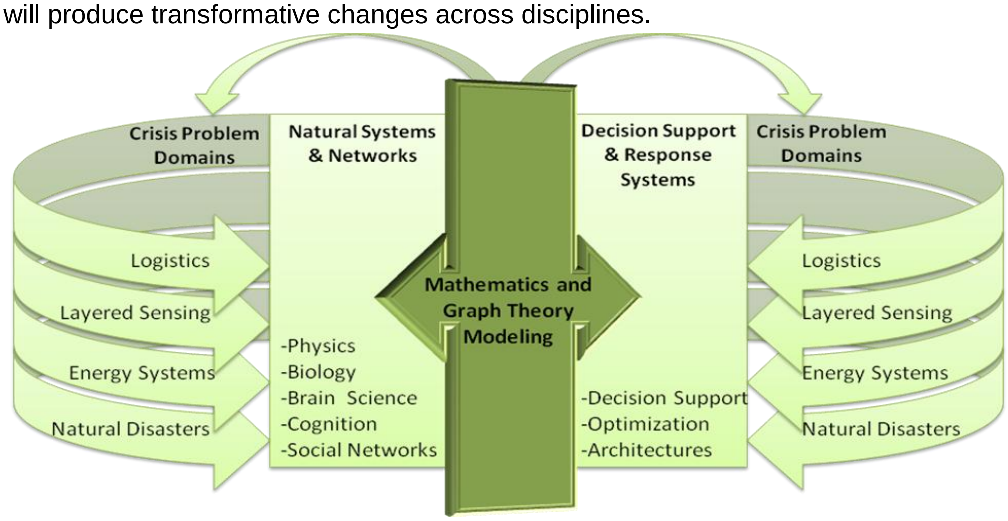

Figure 1: CLION Research Interaction Model

D. Research Themes

The mathematical theory of phase transitions in large-scale random graphs and percolation processes will provide the theoretical foundation undergirding our work. Progress in this fundamental mathematical field creates the tools for a new scientific paradigm of computation by means of phase transitions in biological, cognitive, computational, information-theoretic, and engineering systems. Information processing in brains employs phase transitions in neural correlates of cognition, which will be utilized in developing decision support systems that seamlessly interact with and augment human performance. The developed approaches are embedded in high-performance cyber-physical networked systems providing the required secure, and resilient operational behavior in crisis situations. These themes are highly relevant to national research priorities. In 2009, the National Academies of Engineering has identified the reverse engineering of the brain to be a top ten challenge. Moreover, the proposed research themes directly address NSF research priorities articulated in the Robust Intelligence, Networking Technology and Systems, and Computer Systems Research programs within CISE; support the fundamental research programs in Mathematical Sciences; and support applied research goals in Engineering Sciences and Social, Behavioral, and Economic Sciences Directorates.

Research Thrust A - Graph theoretical models of transitions in dynamic networks

<u>Thrust Lead:</u> *Bela Bollobas-Memphis & Cambridge; Co-leads+Team: E. Szemeredi-Rutgers, L. Barabasi-NEU/Harvard, M. Newman-Michigan, P. Balister-Memphis, R. Kozma-Memphis, V. Nikiforov-Memphis, J. Balogh-UIUC, O. Riordan-Oxford UK, M. Ruszinko-SZTAKI Hungary, R. Venkatesan-Microsoft Research.*

<u>Key Challenges:</u> Developing approaches to describe sudden structural and behavioral changes in large-scale distributed networks poses extremely difficult mathematical challenges in any realistic, spatially extended system due to the combinatorial complexity and scaling issues present.

<u>Planned Research</u>: Random graphs and network theory provide a new way of looking at those notoriously difficult problems and will be used to develop novel methods to model the evolution of graphs with desired optimal dynamic properties. More specifically, we seek to leverage recent developments in graph theory to formulate new theoretical problems for structural evolution and efficient communication in large-scale networks. We also seek to incorporate important concepts of geometric random graphs and neuropercolation into a broader theoretical framework of resilient architectures. *Szemeredi's Regularity Lemma* will be employed to study the behavior of large networks near critical phase transitions.

<u>Background:</u> Large-scale networks arise in many contexts, including the Internet, biological systems, web graphs, collaboration graphs, cell signaling networks, living neural tissues and brains, and social interactions (Albert, Barabasi, 2002, Gonzalez et al, 2008; Barabasi et al, 2011). These networks often have certain common key features: They are scale-free, i.e., the distribution of the degrees (how many other vertices a given vertex is connected to) follows a power law (Barabasi, Albert, 1999; Newman, 2003), rather than the Poisson distribution of classical random graph theory (Erdos, Renyi, 1959); and they frequently exhibit the small-world phenomenon where the diameter of the network, i.e., the maximum number of steps needed to get from one vertex to another, is often 'surprisingly' small (Newman et al, 2001). In past decades, the study of large-scale networks has grown rapidly and the theory of random graphs has served as a firm mathematical underpinning to these efforts (Bollobas, 1985; Bollobas et al, 2001; Bollobas, Riordan, 2004, Alon et al, 2011). Bollobas et al (2007) introduced a general model of sparse inhomogeneous random graphs, designed for representing graphs with geometric structure. Many other models exist, including the much more general, but harder to analyze model (Cooper and Frieze, 2003). These models have two key features: 1) the graph grows through time, e.g., the evolution of new links with steadily growing and branching connections between sites; and 2) there is some kind of 'preferential attachment' in that new (or existing) vertices are more likely to be joined to existing vertices that are 'popular', i.e., have high degree. Percolation over such graphs are extensively studied (Bollobas, Riordan, 2006; Balogh et al., 2010).

Scale-free networks with their evolving hub structure are widespread and have the important advantage of being resistant to random decay or malicious attacks (Newman, Leicht, 2007; Newman, 2010; Liu et al, 2011). They have, however, their Achilles' heel: well-targeted malicious attacks aimed at their major hub nodes can paralyze the operation of the overall network. Nature invented a unique resilient network in our brain (Freeman, 2003), which is not scale free by its structure (Sporns et al., 2005; Bullmore, Sporns, 2009; Sporns, 2011), but exhibits robust behavior in response to a range of random and targeted attacks. It is a combination of regular short-range cellular structures and a small number of medium- and long-range connections. This network structure has been studied in neuropercolation models (Kozma et al, 2005; Balister et al., 2006; 2010; Puljic, Kozma, 2008) and serves as an example of networks with the desired resilience (Bollobas et al., 2009). During phase transitions in graphs, large clusters of active sties may emerge. To study clustering in graphs, *Szemeredi's Regularity Lemma* (Szemeredi, 1975) is of potential use. *Szemeredi's Regularity Lemma* is a very deep and surprising mathematical finding that, in essence, states that every very large graph can be partitioned into a few "regular components" of about the same size, connected by a "small number" of random links. These mathematical advances will be used to develop resilient networks in our present crisis response objective.

Research Thrust B - Cognitive dynamical systems, brain networks and decision making

<u>Thrust Lead:</u> *Jose Principe-Florida; Co-leads + Team: O. Sporns-Indiana, J.A.S. Kelso-FAU, E. Tognoli-FAU, P. Erdi-Kalamazoo/Hungarian Academy of Sciences, M. Puljic-Tulane, R. Kozma-Memphis.*

<u>Key Challenges:</u> *Decision-making for crisis situations needs to be both instantaneous and robust*. There are no such robust methods for practically relevant problem domains, due to the overwhelming amount of data to be processed quickly. Brains routinely process large amounts of sensory data and make robust decisions fast and reliably. However, in the case of crisis situations, even humans may fail

and can make erroneous decisions. Fundamental questions concerning the relationship between structure and dynamics in brains and cognitive networks must be addressed to resolve this challenge.

Planned Research: The goal is to achieve significant improvement in understanding and mathematical modeling of large-scale communication networks. This requires improvements in robust decision making based on cognitive models. Within CLION's crisis response and prediction framework, we will study functional macro-networks of the brain, both in the case of normal and impaired conditions. The co-evolution of structure and function leads to meaningful behaviors and gives hypotheses for future studies with lessons learned from cognitive processing applied in the design of intelligent data processing and decision support systems. A dynamic system with meta-stable states embodying various real life scenarios provides seamless decisions in the framework of an integrated distributed decision support.

Background: Progress in research on cognitive processing and decision making in humans and higher mammalians provides tools for advance knowledge-based adaptive data processing and decision support (Dayan, Daw, 2008; Haykin et al., 2006); Perlovsky, Kozma, 2007; Hagmann et al., 2010). Research has shown that higher cognition exhibits an intermittent character (Freeman, 2003; Kozma, Freeman, 2003). Namely, the cognitive state is relatively stable for some time, then suddenly switches to a new state. The new state is maintained for some time until conditions for a new quick switch are ready, at which point the whole cycle starts again. This process is characterized as meta-stability (Kelso, Engstrom, 2007; Kelso, Tognoli, 2007) or edge-of-stability in intentional dynamic systems (Caulfield, Kozma, 2009). Higher cognition has a mechanism to maintain such meta-stable states (Tognoli et al., 2007; Kelso, 2010), which allow for efficient and robust decision in rapidly changing scenarios. Information-theoretical approaches to brain functions helped to develop improved brain computer interfaces (Berger et al., 2006; Hild et al., 2006; Principe, 2010). Combined brain imaging and computational studies contributed to the understanding of the multiple relationships between lesioned neural architectures and reduced cognitive abilities. The impairment of cognitive control of the prefrontal cortex on hippocampal processes implies uncertainties in the task to be solved and results in poorer performance in learning and recall processes (Gore et al., 2010). Bayesian model selection has been used to investigate hypotheses on differences in model architecture across groups (Banyai et. al, 2011).

Research Thrust C - Optimization & evolution in biological & technological networks & clustering
Thrust lead: Don Wunsch–Missouri Science and Technology (MST); Co-leads + Team: D. Rogers-MST, A. Buczak-JHU/APL, L. Werbos IntControl, D. Dasgupta-Memphis

Key Challenges: The key technology challenge is to use *learning to achieve optimum performance of network and decision support system*. Although learning and adaptation has produced spectacular advances in the past decades, those approaches still suffer from the scaling problem. Systems that successfully deal with disparate, confusing, sometimes conflicting, nonlinear and nonstationary data tend to be sensor-rich and rely on local processing using greedy heuristics, like clustering. The second challenge is to *achieve emergent collective computational capability from local elements with limited processing and connectivity*. There are no robust and widely applicable tools available to design the network with optimum performance in rapidly varying conditions.

Planned Research: Regularity and order has to be found in seemingly disorganized, heterogeneous datasets, and this search must happen reasonably quickly within limited computational resources. From a graph-theoretic point of view, clustering can be considered as the creation of a partition where the resulting subgraphs share interesting properties. For our purposes, this means patterns of connections that can be used to make inferences, or at least associations, on data. Nature comes up with robust solutions for optimal performance by using evolution, thus existing optimization methods can be augmented by evolutionary computation. Novel methods for incorporating evolutionary computation into extraction of fuzzy association rules from data and evolution of more general rules, will allow automatic generation and testing of association rules. The concept is similar to the automatic hypothesis generation and testing (Kozma and Buczak, 2006).

Background: Large-scale optimization problems were addressed using various linear programming approaches during the 70's and 80's. The time is ripe now to take the next step and make practical use of nonlinear optimization techniques, including Approximate Dynamic Programming (Prokhorov et al.,1997; Si et al., 2004; Seiffert, Wunsch, 2010). Recent progress includes very fast learning procedures (Ilin et al., 2007), which give 10-100 times improvement over the state-of-the-art learning speed.

Data mining techniques are used for hypotheses generated for observed rules or concept maps pertaining to the behavior of criminals and terrorists, requiring very fast execution in a huge search space.

It will become possible only with enhancements to evolutionary computation, fuzzy association rule mining, concept map generation, immune computing (Buczak et al., 2006, 2010; Dasgupta, 2006).

Clustering is one of the most important modes of learning in general and is also the first line of defense against an onslaught of data that defy analysis in many applications. For this reason, the number of publications in the field has increased rapidly, including implementations of a brad range of customized applications (Xu, Wunsch, 2005, 2009). Clustering invokes many design choices regarding inter-data and inter-cluster distances, algorithm design, data analysis and interpretation.

Research Thrust D - Resilient and Secure High-performance Cyber-Physical Networked Systems
Thrust lead: Jacob Barhen–Oak Ridge National Labs (ORNL); Co-leads + Team: N, Rao-ORNL, J, Sztipanovits-Vanderbilt, J, Caulfield-Fisk, H. He-Rhode Island, B, Sullivan-ORNL, L, Perlovsky AFRL

Key Challenges: *Designing and implementing a fully embedded and integrated data processing system operating adaptively in real-time, starting with data acquisition and feature extraction, and then moving to pattern identification, high-level classification, and decision support*. System integration is critical bottle-neck in large-scale system design. Often we cannot reliably integrate complex components into complex systems. Our current technology cannot provide predictability for partially compositional properties, which is a common situation in all large scale system development. The emerging technology of embedded systems and model-based engineering has the potential to make real change here.

Planned Research: We will build general tools, benchmarks, and applications and extend this work to an extensive investigation of embedded systems, including an assessment of algorithms that leverage the current and anticipated future cost-effective, high-performance computational intelligence solutions (Caulfield, Dolev, 2010). Many future computing platforms will be organized in a non-homogenous hierarchical configuration in order to achieve better performance. Extending this work to embedded systems (Sastry et al., 2003), including assessing algorithms that leverage the current and anticipated future of cost-effective, high-performance computational intelligence solutions, will immediately impact image processing, massive data analysis, and optimization applications. An early step to this is establishing the mathematical theory of heterogeneous populations of nonlinear components, including hierarchical structures. This includes proofs of emergent natural partitions (clusters), and phase transitions that will lead to definition and validation of critical parameters that determine dynamic behavior. We seek to integrate the results of clustering methods for enhanced management of risk-performance tradeoffs and real-time triage for crisis management.

Background: Enhancing situation awareness in crisis situations due to terrorist attacks, crime in large cities, and/or weather-related emergencies necessitates rapid processing of petabytes of data coming from diverse data sources (Barhen et al.,1997; Dasgupta, 2007; Luna et al., 2007; Rogers 2008, 2009; Barhen, Imam, 2009; Chung, Rogers, 2010). Those petabytes of data need to be processed almost instantly in order to come up with decisions that will help thwart terrorist attacks and address emergencies (Rao et al.,2005, 2011). Increasingly powerful computers are unable to perform data mining and make sense of such massive amounts of data in a reasonable time. Buczak et al. (2010) have developed novel algorithms for fast extraction of association rules from data; however, when those algorithms are applied to crime data from a megacity and run on powerful computers, it still takes days or even weeks to produce results. Situation awareness requires results that are instantaneous indicating the critical importance of robust and resilient network formulation based on the proposed novel graph-theoretical concepts.

E. Education, Outreach, and Diversity

Goals and Objectives: CLION STC seeks to prepare a diverse cadre of researchers able to address optimization challenges of significance to society in academic, industry, and government sectors while advancing understanding of which activities and structures best support interdisciplinary graduate education and student research (Hilton, 2010). More specifically, our objectives are to: 1) Increase the number and diversity of US students who complete advanced degrees and pursue research careers related to optimization science; 2) Develop new integrative academic and research programs in optimization science; and 3) Advance understanding of best practice related to preparing next generation researchers and innovators for careers in collaborative research in academic, industry, and government.

Major Proposed Initiatives:

1) Research, mentoring, and internship experiences targeting early career faculty, and doctoral, graduate, and undergraduate students: Optimization science is truly a team science requiring significant grasp of advanced theoretical concepts and techniques associated with complex systems in the natural and manmade world, mathematics and modeling, and engineering as well as a firm grounding in applications research related to optimization issues of significance to society, industry, and government. Reflecting prior successful STC endeavors, findings from NSF reviews of both REU and IGERT programs, and the 2010 Report from the National Academy of Science, all of which identify the need for interdisciplinary and integrative approaches to preparation of next generation researchers, CLION will implement the following 3 experiential learning initiatives:

- Research rotation fellowship program in optimization science: A 12-18 month program targeting doctoral, post-doc, and early career faculty for short term (4-6 weeks) and longer term (3-6 months) rotations at partner academic institutions or collaborating industry and government laboratories domestically or abroad to acquire specific skills by working on STC research projects outside their primary area of expertise.
- Optimization team challenge prize: Annual competition targeting multidisciplinary teams of advanced undergraduate and graduate students to find the optimal solution to a real world optimization challenge problem. CLION researchers and doctoral students will mentor their respective university teams through the competition which will be patterned after the DARPA Challenge program.
- Optimization Science Summer Institute: 3-week intensive summer seminar series designed to expose advanced undergraduate and graduate students to key concepts and contemporary problems. Following the 3-week program, students will be dispersed to work with CLION STC research teams or to participate in industry or government internships for 8 weeks, returning to the Institute host site for the final week of their program to discuss their work experiences and/or research findings.

In addition to these three signature initiatives, CLION will recruit students at partner institutions to participate at The Budapest Semester in Cognitive Science (BSCS) with the collaboration of Hungarian Academy of Sciences (team member Erdi). BSCS is an undergraduate study abroad program aimed at broadening student understanding of cognitive science from an interdisciplinary perspective. Similar experiences will be offered through the decade-old, Budapest Semesters in Mathematics events, organized by Co-PI Bollobas and team member Balister.

2) New, interdisciplinary graduate concentration in optimization science: A core set of 6-8 new integrative courses will be developed by CLION researchers to include fundamental concepts and methods of complex systems research as well as advanced topics related to challenges associated with modeling and developing network architectures that support adaptive behavior. Courses will be delivered across partner institutions via a team taught live and virtual special topic seminars and will combine mathematics and theoretical computer science approaches with those of biological and brain computing, intelligent techniques, nonlinear optimization, and approximate dynamic programming.

3) Informal learning programs for advanced high school/beginning university students: CLION will leverage existing NSF-funded STEP programs, established 'find your major', open house, and career exploration programs at the University of Memphis and partner universities along with STEM-related summer camps and weekend scholar programs to reach out to high school and beginning university students. We will develop a focused session on optimization for inclusion in the University of Memphis' longstanding Girls Experiencing Engineering Program for high school girls (featuring 95% minority female participation) and/or offer a weekend scholars program or summer program in optimization in partnership with Vanderbilt University's Program for Talented Youth. We also plan to establish new partnerships with local/regional science centers and professional organizations, to develop a multi-tiered approach to informal learning based.

Robust program evaluation: CLION will engage the services of one or more experienced educational evaluators to assess the effectiveness of these programs in meeting stated goals as well as to contribute to our understanding of what works best. We have relied on the literature of the Center for Innovation and Research in Graduate Education at the University of Washington when planning our programs and expect to engage their services to refine this design and develop robust evaluation and assessment activities. Moreover, we plan to work with the Center for Advancement of Informal Science Education to identify an appropriate evaluator for programs targeting learning outside the classroom.

F. Knowledge Transfer:

Goals and Objectives: Through a multi-tiered set of knowledge transfer activities, CLION will 1) Facilitate dissemination of research findings and new approaches to the broader R&D community; 2) Promote on-going dialog and information exchange among faculty from diverse disciplines and public and private sector interests; 3) Aggressively transfer new technologies and applications to the public and private sectors; and 4) Leverage planned education, outreach, and diversity programs to increase awareness of CLION activities and strengthen the future U.S. research workforce by exposing students to integrative research and education.

Major Proposed Initiatives:

- CLION will annually host a research forum to disseminate findings of CLION supported faculty and student research and offer government lab and industry perspectives on current challenges and needs related to CLION research thrusts. To facilitate broad access to this event among dispersed researchers, we will simulcast presentations and provide web-based question and answer interface.
- The CLION-STC website will include links to working papers, publications, conference presentations, and annual CLION forum proceedings to facilitate ready access to common work products.
- CLION will organize quarterly web-based symposia featuring special topics presentations and dialog tied to CLION research thrusts. Academic, industry, and government members of the CLION advisory board will be invited to participate, along with individuals who choose to become CLION affiliates by joining one or more of our research affinity groups. Membership in these groups will be structured similar to the TRUST-STC working group model to maximize involvement across domains.
- The University of Memphis' *Office of Technology Transfer and Office of Entrepreneurship and Innovation,* will leverage existing programs and services to support aggressive transfer of new tools and technologies developed by CLION-STC teams for relevant public and private sector use. Information on new technologies will be widely distributed to regional and national angel and venture investor networks. CLION-developed ideas and technologies will be featured at the annual FedEx Institute Research Showcase and Exposition before audiences of industrial R&D executives and interested investors. Special technology briefings and meetings with angel investors and venture capitalists as well as mentored support for business plan development and launch will be provided through the Center for Entrepreneurship & Innovation and Ventures Labs.

G. Description of Team Members

PI and Co-PIs:

Dr Robert Kozma is Dunavant University Professor of Mathematics and Director of the Center for Large-scale Integrated Optimization and Networks CLION at the University of Memphis. His primary interests include spatio-temporal effects in dynamical memory networks, intermediate-range effects in spatially distributed systems, and random graph models. He has extensive domestic and international collaborations, has conducted research on behalf of industry, NASA, and the Air Force. He is credited with developing, with Bela Bollobas and Walter J. Freeman, the theory of neuropercolation, which is a unique fusion of neuroscience, dynamical systems, and graph theory. It represents a drastic departure from traditional analytical approaches and creates a new scientific and computational paradigm. Dr. Kozma will serve as PI and Director of the STC, and he will contribute his expertise to the mathematics and graph theory and cognitive science thrusts.

Dr. Bela Bollobas holds the Hardin Chair of Excellence in Combinatorics at the University of Memphis, is a 30 year+ Fellow of Trinity College, Cambridge, UK, and is a corresponding member of the Hungarian Academy of Sciences. He is an expert on probabilistic and extremal combinatorics, and has done fundamental work on extremal graph theory, random graph theory (especially phase transitions in random combinatorial systems), and on random graphs modeling real-life networks. He will be Co-PI and lead of the mathematics and graph theory thrust and will contribute to analysis and theorems pertaining to random graphs and their applications in all 4 research thrusts.

Dr. Donald Wunsch is the M.K. Finley Missouri Distinguished Professor at Missouri University of Science & Technology (Missouri S&T). Clustering is one of the most important modes of learning in general and is also the first line of defense against an onslaught of data that defy analysis in many applications. Wunsch is among the foremost and most highly-cited researchers in clustering and can customize its implementation as appropriate for a broad array of applications (Xu and Wunsch, 2005, 2009). He will serve as Co-PI and lead of the optimization and evolution in biological and technological networks thrust and will contribute his combinatorics and clustering expertise to the graph theory thrust.

Dr. Jose Principe is Distinguished Professor of Electrical and Biomedical Engineering at the University of Florida, Gainesville, where he teaches advanced signal processing and machine learning. He is BellSouth Professor and Founding Director of the University of Florida Computational Neuro-Engineering Laboratory. His research interests are centered in advanced signal processing and machine learning, Brain Machine Interfaces and the modeling and applications of cognitive systems. Dr. Principe will be Co-PI and lead the cognitive dynamics thrust area.

Dr. Jacob Barhen is Director of the Center for Engineering Science Advanced Research (CESAR) at the Oak Ridge National Laboratory (ORNL) and concurrently serves as Manager for CESAR programs in ORNL's Computing and Computational Science Directorate, and Manager of the Engineering Science Program within the Physical and Chemical Sciences Directorate. Dr. Barhen's research interests include global optimization, and intelligent signal processing and large-scale emergent computational systems. He will be Co-PI and the lead of thrust on resilient and secure high-performance cyber-physical systems.

Other Key Management Personnel: **Dr. Kevin Boggs** is Assistant Vice President for Technology Transfer and Commercialization at the University of Memphis. He is responsible for operations of the University's FedEx Institute of Technology, all technology transfer and commercialization activities, the center for entrepreneurship and innovation, and the University's New Ventures Lab. He brings 12 years of private sector and academic experience managing intellectual property, technology commercialization, and new business development and will be responsible for managing the Knowledge Transfer components of the project.

Education, Outreach, and Diversity Coordinators have not yet been named.

Other Key Research Team Personnel:

'*Graph theoretical models of transitions in dynamic networks'* led by B. Bollobas requires the significant brain trust represented by senior academic scientists **Laszlo Barabasi** (NEU), **Endre Szemeredi** (Rutgers)**, Oliver Riordan** (Oxford)**, Mark Newman** (Michigan)**, Miklos Ruszinko** (Hungarian Academy of Sciences), **Jozsef Balogh** (UIUC)**, and Robert Morris** (Brazil). All are experts in graph theory and are expected to contribute to analysis and theorems pertaining to random graphs and their applications in all four thrusts and across all crisis problem domains. They are joined by **Ramarathnam Venkatesan,** who conducts graph theoretical research for Microsoft and will lend important insights concerning cross-over between this thrust and practical considerations for commercialization; and academicians **Paul Balister and Vlado Nikiforov** (Memphis) who will contribute theoretical mathematical aspects and the computational studies of cellular automata models and their phase transitions.

'Cognitive dynamical systems, brain networks and decision making' is led by Jose Principe of Florida. **J.A. Scott Kelso and Emmanuelle Tognoli** (Florida Atlantic) lend considerable prowess related to neurocognitive networks and coordination dynamics, particularly with respect to human social behaviors. **Olaf Sporns** (Indiana) contributes complex network measures (based on graph theoretical analysis) of brain activity in normal and impaired states. **Peter Erdi** (Kalamazoo) brings a physical chemist's perspective to social dynamic modeling and decision making. **Mark Puljic** (Tulane) computationally models large systems to study the cortex during sensory information processing. **Leonid Perlovsky** (AFRL) contributes to neurodynamics of high level cognition and dynamic logic.

'Optimization and evolution in biological & technological networks & clustering' is led by Don Wunsch of Missouri S&T. **David Rogers** (MST) will contribute his considerable expertise on natural hazards and disaster response to this team. **Dipankar Dasgupta** (Memphis) is a leading authority in the emerging research area of Immunological Computation of significance to evolutionary computation research and its implications in cyber security. **Anna Buczak** (Johns Hopkins) will bring her expertise in algorithm development for problems ranging from disease outbreak prediction of diseases of military importance to discovery of crime and terrorist behaviors in order to enhance the situation awareness. **Ludmilla Werbos** (IntControl) and **John Gunkel** (FedEx) are experts in energy and logistics systems optimization research.

'Resilient and Secure High-performance Cyber-Physical Networked Systems' is led by Jacob Barhen of Oak Ridge National Lab (ORNL). He is joined by, **Nageswara Rao** and **Blair Sullivan** (ORNL) who contribute methods based on combining results from statistical estimation, game theory, functional analysis and algorithms; **John Caulfield** (Fisk) who brings expertise in optical computing and imaging systems; **Amir Shirkhodai** (TSU) with research in machine vision; **Haibo He** (Rhode Island) who contributes studies on adaptive dynamic programming; and **Janos Sztipanovits** (Vanderbilt) a leading expert on embedded software and multi-agent networks.

H. Institutional Commitment: The University of Memphis has allocated 1) 5,000 s.f. to CLION in the FedEx Institute of Technology and will renovate 2,500 s.f. of additional space as needed; business management, office management, marketing/communications, and tech transfer support staff; 3) funds for a visiting scholar and travel; and 3 graduate assistants. Key partner universities (Missouri S&T and Florida) will also provide necessary resources to ensure project goals are met.