Transdisciplinary Research Initiative (TRI)

Spire of Excellence Proposal

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Complex Systems

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1) **Executive Summary:** Over the past few decades, Complex Systems (CSYS) has emerged as a new scientific field of inquiry with its own theories and principles. Facilitated by 21\textsuperscript{st} century computational and data gathering capabilities, CSYS is now maturing into a transdisciplinary research field with new approaches for understanding the integrated behaviors of systems composed of many interacting parts in a wide variety of application domains. We propose to build on a strong grassroots collection of diverse UVM faculty already involved in CSYS research and capitalize on the imminent arrival of world-renowned CSYS pioneer Stuart Kauffman, create the first US PhD in CSYS, continue building strong relationships around CSYS with external enterprises that stimulate Vermont economic development and become the only academic institution that embraces CSYS as a major campus-wide theme. Our relatively modest size, compact campus and multidisciplinary faculty strengths will be advantageous in this endeavor. Strategic investments in CSYS will enable us to attract additional strong and diverse faculty and graduate students to UVM, hence building world-class and well-funded CSYS research programs. UVM is a relatively small research university with outstanding research strengths scattered across campus in units with small graduate programs, in addition to a few fairly strong PhD programs. Creating a spire of excellence in CSYS will provide a unifying theme to connect and synergize currently separated pockets of strength while at the same time helping existing programs to become stronger and enriching undergraduate education. CSYS is an area that is intellectually rich, scientifically important, inherently transdisciplinary and eminently fundable. UVM has a tremendous and unique opportunity to become a world-class leader in CSYS, which many believe will prove to be one of the most important research areas of the 21\textsuperscript{st} century\textsuperscript{84}. To realize this vision, UVM must provide the strategic vision, organizational infrastructure and resources necessary to enable the growth and integration of CSYS across campus.
2) Emerging World-Wide Interest in CSYS: ‘The time is ripe’: As Anderson stated in his ground-breaking paper in 1972, “The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe”. Rather, the self-organizing collective nonlinear dynamics in complex systems of many interacting entities (be they molecules, cells, genes, bacteria, plants, birds, humans, electrical substations, etc.) can give rise to emergent properties at larger scales in space and/or time.

A current NSF solicitation explains “Complex systems are not simply complicated ones. A jet plane, under normal operating conditions, is complicated, consisting of many parts and interacting systems, but it is not a complex system. On the other hand, a single unicellular organism is a complex system. The essential operational difference is that the organism can respond and adapt to changes in its environment, a property which emerges from the myriad chemical interactions and regulatory systems that make up the cell and which is a characteristic of a complex system.” Complex systems are self-organized, which enables them to spontaneously reorganize in response to changing conditions, in contrast to the jet plane that is constructed according to a blueprint. To understand and potentially engineer the behavior of complex systems – harnessing the resilience engineered by evolution acting on self-organizing entities – is the great challenge of CSYS.

Despite the diverse nature of complexity in physical, biological, social and engineered systems, there are universal principles, process abstractions and systems thinking methodologies that unify the study of CSYS. The essential properties of CSYS (e.g., emergence, scaling phenomena and mechanisms, robustness, adaptability, collective dynamics, complex network characteristics, tipping points and phase transitions, selection to the edge-of-chaos) may be studied, modeled and understood using similar approaches, regardless of the application domain. Complex Systems Science is thus an area of fundamental research with a growing collection of theory and methods (as is a field such as Mathematics). As NSF observes, “The promise of Complex Systems research is that universal principles learned from one area could lead to exciting breakthroughs in seemingly
unrelated disciplines"\textsuperscript{48}. Consequently, there has been a recent “call to arms” for using CSYS approaches in diverse application domains such as developmental biology\textsuperscript{26}, cancer biology\textsuperscript{18}, clinical medicine\textsuperscript{12}, chemistry and nanotechnology\textsuperscript{24,25,84}, neuroscience\textsuperscript{22}, ecology and conservation\textsuperscript{14}, management\textsuperscript{3}, economics\textsuperscript{13}, computing\textsuperscript{10}, sociology\textsuperscript{5}, history\textsuperscript{77}, philosophy\textsuperscript{8}, policy analysis\textsuperscript{11}, collective thinking\textsuperscript{9}, governance\textsuperscript{83}, engineering\textsuperscript{12,24} and even in the arts\textsuperscript{7,78,79}. The current confluence of advances in (a) CSYS philosophy, theory and methodologies, (b) computational power, (c) data availability and (d) a growing recognition of the limits of reductionism creates an enormous opportunity for CSYS.

The increasing excitement in the field of CSYS is evidenced by the large number of academic Complex Systems Centers (a recent Google search turned up at least 30 such centers). In addition, CSYS figures prominently in the strategic plans and current funding opportunities (including solicitations for large Center grants) at NSF\textsuperscript{47-73}, NIH\textsuperscript{29-46}, DOE\textsuperscript{84,85}, DHS\textsuperscript{86} and many other funding agencies. Non-academic organizations around the world, such as IBM\textsuperscript{19}, Mitre\textsuperscript{74,80} and Ontonix\textsuperscript{75}, are also increasingly viewing research, business operations and organizational management from a CSYS perspective. However, opportunities for graduate education in CSYS have lagged behind this growing demand. Non-credit CSYS summer schools are offered by various institutions (e.g., The Santa Fe Institute, the New England Complex Systems Institute, Wolfram Science). There are also some graduate certificate programs or tracks available in CSYS (e.g., UVM, Univ. of Michigan, Duke, Ind. Univ.). Several (primarily large) universities have recently received NSF IGERTs (Integrative Graduate Education Research and Training grants) in CSYS related areas (e.g., Northwestern, Cornell, Carnegie-Mellon, Johns-Hopkins, Univ. of Michigan, Univ. Nebr. Linc., Ind. Univ.) highlighting NSF’s strong interest in this area. Various US universities offer PhDs covering certain aspects or application domains of CSYS (e.g., CalTech, Univ. Minn., Harvard, MIT, Case Western, Fl. Atl. Univ.) and some foreign universities offer PhDs in CSYS (e.g., in Sweden and Japan). To our knowledge there is as
yet no stand-alone PhD in CSYS in the US and we have not identified any academic institutions that are using CSYS as a unifying campus-wide transdisciplinary theme. We believe there is a unique opportunity for UVM to fill these gaps and become a world leader in transdisciplinary CSYS research and graduate education, but we must act on this opportunity quickly.

3) Existing UVM strengths in CSYS:

3.1 A brief history of CSYS Research at UVM: Interest in CSYS has blossomed across campus during the past decade, as demonstrated by research grants and publications, reading clubs, workshops, transdisciplinary courses, co-advising of graduate students and post-doctoral associates, new faculty hires and the development of the Complex Systems Center (CSC) in 2006 (uvm.edu/complexsystems) whose membership currently includes 31 faculty from across campus. Activities managed through the CSC include a CSYS listserve (with 248 current recipients), a CSYS journal club (with 72 individuals currently on this email list), invited speakers, graduate research assistantships, cross-listing courses under a new CSYS prefix and a new Certificate of Graduate Study in CSYS. In addition, we are participating in efforts to build CSYS research connections with external enterprises. As a result, the $1B+ Mitre Corporation just approved the opening of a "satellite" office at UVM. We are discussing similar arrangements with both IBM Research and Sandia National Laboratories.

In May of 2006, funded through a planning grant from the Vermont Advanced Computing Center (VACC), Eppstein and Goodnight organized a Biocomplexity Retreat attended by 33 faculty (from 5 UVM Colleges) with interests in biocomplexity spanning the molecular to ecological scales. Later that summer, several participating biocomplexity faculty and watershed experts in the environmental and life sciences wrote the science portion of the successful NSF-EPSCoR RII submission in “Complex Systems Thinking and Modeling for Environmental Problem Solving” ($6.7M). This funded a large group project, 15 CSYS pilot projects across campus (including Plant Biology, Mathematics, Engineering, Computer
Science, Environment & Natural Resources and Biology) and numerous GRAs in CSYS related work. CSYS research has also been independently evolving elsewhere on campus, including the Gund Institute for Ecological Economics, the interdisciplinary Materials Science group and researchers working in areas ranging from systems biology to complex social and governance structures. In preparation for this proposal, we held 3 open forums (attended by over 100 faculty) and also sought input via email and a detailed electronic survey. A total of 139 faculty from across campus responded to the survey, with 112 completing all questions, 105 of whom are research-active; 85 faculty elected to include their names. We received an additional 29 memos by email or paper and numerous oral comments. Subsequent to initial internal review, we received extensive comments from the various panels of faculty and administrators. All this input greatly shaped our proposal. We have identified at least 52 UVM faculty who describe their research as being all or partly in CSYS, although the degree of CSYS research emphasis and expertise varies widely. At least 50 more research-active faculty would like to, or already do, collaborate with CSYS researchers. We note these numbers are conservative estimates. This is a truly transdisciplinary group of faculty (see Sections 3.2, 3.3 and 3.4).

3.2 CSYS Theory and Methods Faculty: UVM has a small but strong core group of research-active CSYS theory and methods faculty who, in addition to their own research applications, frequently collaborate with others in a variety of application domains. Josh Bongard (Asst Prof, Computer Science) is an expert in evolutionary computation and neuro-evolution, with a special interest in adaptive robotics. He has NSF funding, was awarded a Microsoft New Faculty Fellowship and was one of MIT Technology Review’s 2007 TR35 (The Top 35 Young Innovators under 35). Chris Danforth (Asst Prof, Math) comes from the #1 NRC ranked U. Maryland Chaos group and develops methods for improving predictions made by mathematical models of chaotic physical phenomena, including global weather forecast systems. Peter Dodds (Asst Prof, Math) studies social contagion including the spread of
ideas, fads and emotions through social networks and recently won a prestigious NSF Career Award to continue this work. Margaret Eppstein (Assoc Prof, Computer Science and founding Director of the CSC) studies agent-based modeling, evolutionary processes and dynamical processes on complex networks in a variety of application domains. She has been funded by various sources, including NSF, NIH and DOT through the UVM Transportation Research Center (TRC). Donna Rizzo (Assoc Prof, Engineering) is an expert in artificial neural networks and multi-scale spatial analysis, which she applies in a variety of diverse problems. She has funding from a variety of agencies, including NSF, NIH, DOD and USGS. Other faculty who have self-identified as having CSYS theory and methods components to their research are Lee and Snapp (Computer Science); Krivov (Gund); and Bentil, Foote, Lakin and Yu (Math). Stuart Kauffman will soon be joining the UVM faculty as a half-time Distinguished Visiting Research Professor in Biochemistry and Mathematics. Kauffman is a founder of the field of CSYS science, a pioneer of Biocomplexity research and a MacArthur "Genius" Fellow. He is the author of about 300 peer-reviewed papers and 5 books on CSYS including the seminal book “The Origins of Order: Self-Organization and Selection in Evolution” that alone has garnered over 4000 citations and influenced research in many fields. Kauffman helped establish the Santa Fe Institute (the world's leading think-tank for CSYS) where he continues as an External Fellow. He is an emeritus professor of Biochemistry at U. Penn., founded the Bios Group (a consulting company that applied CSYS science to business management) and founded the Institute for Biocomplexity and Informatics at U. Calgary. Kauffman will be a terrific asset and catalyst for CSYS at UVM during his 3-yr association.

3.3 CSYS Faculty who work largely in specific application domains: There are too many faculty in this category to describe each in detail. Jason Bates (Prof, Pulmonary Medicine, Physiology & Biophysics) works on complex disease and physiology with a focus on quantitative modeling of lung mechanics. He has brought in over $2.6M in NIH funding over
the past three years. Chris Koliba and Asim Zia (Assoc and Asst Profs, respectively, in Comm. Dev. Appl. Econ) collaborate to use agent-based modeling to study governance structures. David Novak (Asst Prof, Business) conducts modeling and performance assessments of highly dynamic and complex communications and transportation networks with funding from DOT (through the UVM TRC and MIT’s NEUTC). Jane Molofsky (Prof, Plant Biol) has been well-funded by USDA and uses agent based models to study the evolution of invasiveness, population dynamics and coexistence in plant communities. Chris Francklyn (Prof, Biochem) is well funded by NIH and is conducting systems biology research in the context of protein nucleic acid interactions. Jeff Marshall (Prof, Engineering) uses multi-scale agent-based modeling to study self-organizing particle dynamics and fluids, including emergent electric fields. He has ~$2M in funding through NASA, ARO, DOT and elsewhere. NSF Career award winner Randy Headrick ( Assoc Prof, Physics) and other colleagues in the materials science group are well-funded through both NSF and DOE and conduct research in self-organizing nanomaterials including recently discovered self-wiring electronic materials. Paul Hines (Asst Prof, Engineering) studies complex power systems and energy policy including understanding and designing decentralized methods for mitigating cascading power failures. Recent Stanford graduate Randall Harp (Asst Prof, Philosophy) uses game theory to study collective action and collective reasoning as emergent properties of individual reasoning systems. Recently hired MIT graduate Arne Bomblies (Asst Prof, Engineering) uses coupled agent-based and hydrological models to study malaria transmission. Mary Dunlop (Asst Prof, Engineering, starting July 2010) is a synthetic biologist working on engineering genetic regulatory networks (e.g., for efficient biofuel conversion).

Other faculty who have self-identified as having a CSYS component to their research programs are Goodnight and Stevens (Biology); Beckage (Plant Biology); Arel and DeWitt (Business); Iatridis, Laible, Lee and Oughstun (Engineering); Todd (Envr & Nat Res); Hulse, Kien, Jetton, Teuscher, Surratt, Poynter, Irvin, Langevin and Young (Medicine); Palmer (Mol
3.4 UVM Faculty who wish to develop collaborations in CSYS. Many other UVM faculty expressed strong interest in forming new and exciting collaborations within the CSYS spire, wherein experiments would be collaboratively designed and analyzed through a CSYS lens. For example, Jeffrey Horbar (Medicine) is the director of a network of over 800 hospitals around the world and is interested in using CSYS to improve efficiency and quality of medical teams in the neonatology units. Mark Bouton (Neuroscience), a world renowned researcher in learning, is interested in using CSYS approaches to investigate how learning unfolds in real time. Michael Zvolensky (Green and Gold Distinguished Professor of Psychology) has been continuously funded since his hire in 2001 and is interested in how CSYS methods could help explain failed attempts to quit smoking. Donna Toufexis (Psychology) is a recent recipient of an NIH Challenge Grant and is interested in using CSYS approaches to understand the role of hormonal feedback loops in determining the development of endocrine-related psychopathologies including post-traumatic stress disorder and post-partum depression.

Some other faculty who either are, or would like to be, collaborating with CSYS researchers include Barlow and Smith (Animal Sci); Vincent, Gotelli and Helms-Cahan (Biology); Bierman (Geology), Hughes (Business); Diamond, Meyers, Mosenthal and Killeen (Education); Frolik, Holmen, Hill and Xia (Engineering); Bowden, Watzin, Ivakhiv and Schaberg (Envr & Nat Res); Lakoba and Archdeacon (Math); Michelson, Jacobs, Holmes, Littenberg, Dienz, Plante, Tracy, Carr and Budd (Medicine); Wargo (Microbiol & Mol Gen); Nagle (Neurology); Ring (Nursing); Costa and Neher (Plant & Soil Sci); Newhouse (Psychiatry); Rellini, Pinel and Murray-Close (Psychology); and Rodriguez (Romance Lang).
3.5 Current CSYS Educational Activities at UVM. As CSYS activities at UVM have increased, so have the opportunities for both graduate and undergraduate education in CSYS. Graduate courses in CSYS (e.g., Principles of Complex Systems; Modeling Complex Systems; Evolutionary Computation; Applied Geostatistics; Applied Artificial Neural Networks; Complex Networks; Decision-Making Models) offered in recent years have had healthy enrollments of graduate (and some motivated undergraduate) students from a variety of disciplines from across campus, despite their significant analytical and computational components. Several other courses are offered at the combined undergraduate/graduate level (e.g., Chaos, Fractals & Dynamical Systems; Neural Computation; Mathematical Biology & Ecology; Evolution; Thermal Physics). There are also new undergraduate offerings (e.g., 3 Civil & Environmental Engineering Systems courses recently developed with support from an NSF curriculum reform grant (~$800K); a new transdisciplinary Honor’s College course in Embodied Cognition) and many faculty also incorporate complex systems concepts into their existing undergraduate courses. The Certificate of Graduate Studies in CSYS (just launched fall semester, 2009) already has 10 students enrolled and more have expressed interest in applying this spring. Many complex systems faculty currently employ undergraduate and graduate research assistants on funded projects.

3.6 Core Facilities at UVM. Several existing UVM Core Facilities will support a CSYS spire. Most notably, the Vermont Advanced Computing Center (VACC) and the College of Engineering & Mathematical Sciences Computing Facility already support UVM faculty who are implementing computationally intensive CSYS research projects. There are also a host of core facilities that support data collection and analysis in a wide variety of application domains relevant to CSYS including: the Vermont Genetics Network’s Bioinformatics, Microarray, & Proteomics Cores; NIH COBRE-supported Lung Center core for Bioengineering; the NIH COBRE-supported Neuroscience Core facilities in Imaging/Physiology, Cellular/Molecular & Translational Neuroscience; the Rubenstein
Ecosystem Science Laboratory; the Transportation Research Center; a new NSF-DMR funded magneto-microscopy facility under construction by Furis (Materials Science); and a host of other core facilities largely in biological and environmental areas.

4) Opportunities for growth of CSYS at UVM over next five years

4.1. New Faculty Hires in CSYS. To increase the core strength in CSYS to a critical mass, we believe it will be crucial to hire more core CSYS faculty. These faculty might have backgrounds and academic appointments in a variety of disciplines, including computer science, mathematics, statistics, engineering, physics, economics, social sciences, biology, philosophy, medicine, etc., as long as their research is primarily in CSYS, they are collaborative across disciplines and they can contribute to developing core transdisciplinary graduate curricula. This will be essential for developing a world-class reputation in CSYS research, building a robust curriculum of CSYS graduate education and stimulating collaborations across campus that increase extramural CSYS funding. The current core CSYS faculty (see Section 3.2) are already inundated with collaboration requests and cannot meet the existing demand for CSYS collaborators on campus (see Section 3.4). Similarly, graduate course offerings in core CSYS theory and methods are currently limited in both number and frequency of offering.

We believe it is equally important to hire faculty in the category of disciplinary scholars using CSYS approaches. While there are currently at least 35 faculty on campus who self-identify as falling into this category, the degree to which these faculty emphasize CSYS in their current research and teaching varies greatly. There are natural overlaps between CSYS and potential UVM spires in both (i) Multi-Scale Integrative Biosciences and (ii) Neuroscience, Behavior & Health, and further developing these overlaps would support CSYS tracks and the development of related Center grants

The potential spire in Food Systems could similarly synergize with CSYS through joint hires, and we note that a pending NSF IGERT proposal already emphasizes the links between Food & Energy Systems and
CSYS. UVM would also benefit from hiring disciplinary CSYS scholars in other disciplines not currently being considered as spires, ranging from environmental disciplines, including geology and transportation, to policy, materials science, philosophy, etc. Such hires would promote the creation of graduate level CSYS tracks in these areas (see Section 4.3) and help enfranchise units across campus in the CSYS spire.

Dr. Kauffman’s 3-year association with UVM offers tremendous opportunity to attract and recruit top researchers. Already, the announcement of his appointment has brought UVM international attention and stimulated a number of unsolicited inquiries from strong CSYS researchers in varied disciplines interested in joining UVM. One strategy for consideration of new faculty lines is to specifically target top CSYS researchers. This would jump-start the UVM CSYS initiative with additional well-funded research programs, help provide mentorship in CSYS, recruit faculty who will make the CSYS initiative succeed and create a snowball effect attracting other CSYS-interested faculty and graduate students.

4.2 Faculty Development in CSYS: A complementary approach to achieving a critical mass of CSYS faculty is to “grow our own”. As many UVM faculty have expressed interest in incorporating CSYS approaches into their research, opportunities should be provided to facilitate professional development in CSYS and to help establish successful CSYS collaborations. The percent of 105 research-active faculty respondents to our survey (an admittedly biased sample of UVM faculty) who expressed interest in attending the following types of CSYS activities were: (i) CSYS Seminars geared to specific application domains (79%), (ii) Seminars in CSYS geared to a wide transdisciplinary audience (77%), (iii) 1-day intensive Workshops in CSYS concepts and methodologies (73%), (iv) loosely organized faculty get-togethers for establishing CSYS connections (62%) and (iv) a multi-day UVM-based CSYS conference (56%). We also asked faculty which incentives they felt would be important for stimulating CSYS research across campus, with the following results: (i) Pilot funding for transdisciplinary CSYS collaborations (90%), (ii) faculty fellowships that provide
release time for developing new CSYS research projects (87%), (iii) faculty fellowships that provide some release time for professional development in CSYS (80%), (iv) having visiting CSYS scholars in residence for 1-3 months (79%), (v) transdisciplinary CSYS graduate assistantships (67%), (vi) designated space for co-housing transdisciplinary graduate students (63%) and faculty (51%) involved in CSYS research. Other incentives could include competitive funding for CSYS sabbatical leaves or for faculty to attend CSYS conferences or summer schools, such as at the Santa Fe Institute.

4.3 Opportunities for Graduate Education: We envision a range of graduate educational opportunities in areas ranging from core CSYS theory and methods to those in specific CSYS application domains, including the possibilities of a new CSYS PhD, new CSYS tracks in existing PhD programs, continuing the Certificate of Graduate Study in CSYS, and new graduate CSYS courses.

A new umbrella PhD in CSYS with named tracks would have core requirements under the jurisdiction of core CSYS theory and methods faculty while track requirements would be under the jurisdiction of faculty in the track’s discipline. Supported tracks could be both in pre-defined and self-designed areas. An NSF IGERT should be immediately sought to help develop this novel graduate education approach. A strong CSYS PhD program at a UVM-sized institution would help create and retain a solid student cohort, facilitate multidisciplinary enrollments in graduate courses (and therefore attain both minimum course enrollments and provide transdisciplinary graduate student education and interactions), encourage team-teaching, facilitate more efficient coverage of graduate curriculum and offer students a larger array of graduate course options.

Being the first US institution to create a broad-based PhD in CSYS would distinguish UVM and attract top faculty and a strong graduate student pool. Disciplinary tracks would help develop students with breadth in transdisciplinary CSYS thinking and methodological approaches as well as depth in specific disciplines. We believe it will be critical to have track
names appear in degree titles to facilitate subsequent hiring of graduates into more traditional disciplinary departments. In our recent survey, 46 respondents said they were somewhat (26) or very (20) interested in advising in such a PhD program. Currently, of the 21 PhD programs at UVM, 13 programs have each graduated 0-3 students per any given year over the past 5 years.

A PhD program in CSYS would provide an opportunity for smaller PhD programs to voluntarily merge and/or for individual faculty in these areas to elect to advise students through the umbrella program. Additionally, there are many strong graduate faculty scattered across campus in areas that do not currently offer any PhD (e.g., statistics, geology, geography, public administration, policy, economics, etc.). A PhD in CSYS would provide faculty in these fields with an opportunity to advise PhD students through a track related to their area, thereby increasing the UVM graduate population and strengthening research across campus. A nationally recognized umbrella program in CSYS would attract stronger students and would benefit from a larger cohort size and array of class offerings relative to currently existing small individual graduate programs.

Additionally, creating CSYS Tracks within existing PhD programs could further strengthen the larger PhD programs on campus (such as Psychology, Natural Resources, Cell & Molecular Biology, Chemistry, Microbiology & Molecular Genetics, Biology and Neuroscience) by offering their students new opportunities and attracting additional more quantitatively-minded students interested in CSYS. These candidates might not otherwise apply to UVM. In our survey, 54 faculty indicated they were somewhat (32) or very (22) interested in advising students through a new CSYS track in an existing PhD program. This would simultaneously help to boost enrollments in the core CSYS courses shared by these tracks, the new CSYS PhD and the CSYS Certificate. Additionally, this would encourage the development of application domain-specific CSYS courses within these programs that would, in turn, be available to students in the umbrella CSYS PhD program. This CSYS track option would have potential benefits complementary to the umbrella CSYS PhD program, in
that some students would feel more comfortable getting their degree in more traditional disciplinary areas and faculty in these existing PhD programs would see CSYS as synergizing with and strengthening their programs rather than competing with them. By developing disciplinary scholars with knowledge of CSYS approaches and by building stronger analytical and computational skills into other disciplines, our graduates will have a competitive edge and be better prepared to tackle many important current problems.

**Continuing to offer the Certificate of Graduate Study in CSYS** will (i) serve as a bridge program until the CSYS PhD and tracks are approved, (ii) help maintain strong enrollments in CSYS courses and (iii) reach a different audience than the PhD options including Master’s level students, post-baccalaureate continuing education students and students in areas without a CSYS Track.

As the number of CSYS faculty increases, we foresee continued development of new graduate level CSYS theory and methods courses as well as new application-specific CSYS courses (e.g., in systems biology, neural modeling, self-organizing nanostructures, etc.). All of these courses can be cross listed with the CSYS prefix increasing CSYS course visibility and facilitating meeting minimum enrollments by attracting students from multiple disciplines.

**4.4 Opportunities for undergraduate education in CSYS.** Increasing the number of CSYS faculty in disciplines across campus would increase exciting opportunities for undergraduates by (a) offering more opportunities for undergraduates to work on research projects related to CSYS, (b) having CSYS concepts introduced into the undergraduate courses these faculty would be teaching in their disciplines, and (c) creation of new undergraduate CSYS courses. All of these activities are currently happening (see Section 3.5), but as we increase our CSYS faculty base, more such opportunities for undergraduates will naturally arise. Once we have established strong CSYS graduate research and education, we can logically expand our undergraduate offerings, offer an undergraduate minor in Complex Systems, and seek an
NSF REU (Research Experience for Undergraduates), which could also serve as a feeder for our CSYS graduate programs.

4.5 Establish Stronger Relationships with other Institutions around CSYS: UVM should continue to build relationships with other institutions around CSYS. Seeking to establish Vermont-based research centers in partnership with these institutions (such as recently agreed on with the Mitre Corporation, and currently under discussion with IBM Research and Sandia National Laboratories) will directly stimulate Vermont’s economic development. These collaborative relationships will foster high-skills jobs and companies in VT, industry-sponsored funding for graduate students, cutting-edge applied research at UVM, technology transfer from UVM to business and industry, and CSYS related spin-off companies. In addition, we should seek to strengthen existing ties to other CSYS Institutions, such as the Santa Fe Institute, where we already have several connections. For example, we might offer graduate transfer credits for attendance at CSYS Summer Schools, become external faculty at these institutions, hold joint workshops and seek collaborative proposals with them. Such arrangements would boost our reputation as an important player in the CSYS arena and effectively serve as recruiting tools for students, post-docs, and faculty.

4.6 Creation of an Institutional Structure to Support CSYS: University infrastructure is traditionally hierarchically organized by disciplinary areas and UVM is no exception. Consequently, processes regarding hiring, mentoring, review for promotion and tenure, creation of new courses, workload and course assignments, all favor disciplinary areas. To make a CSYS initiative succeed, institutional organization, policy, and procedures must be aligned with the transdisciplinary nature of this area. One possible approach is through the creation of a new transdisciplinary Matrix Center or School in CSYS. All CSYS faculty should have joint appointments between CSYS (some primary, some secondary) and another
discipline, to preclude CSYS from becoming its own silo. There must be specific benefits and responsibilities associated with such joint appointments. We outline some general ideas.

Because faculty and students with shared physical space are more likely to share ideas and collaborate, we envision co-housing of faculty (and their graduate students) with primary appointments in CSYS, as well as rotating spaces for both visiting CSYS faculty and UVM CSYS collaborators. Faculty with joint appointments in CSYS would contribute to undergraduate teaching in their disciplinary units but would also develop and teach graduate courses that are cross-listed as CSYS, particularly those that support the graduate initiatives described in Section 4.3. We believe the single largest barrier to success will be lack of time for participating faculty to engage in development of collaborative CSYS research projects. Therefore, teaching loads for research-active core CSYS faculty must take this into account and CSYS faculty must be allowed and encouraged to buy-out from courses with research dollars within reason. Tenure and promotion review would have to be structured so as not to make it more onerous for faculty with joint appointments, and to recognize and value the unique difficulties and contributions of transdisciplinary research. Faculty with joint appointments would be expected to contribute to the CSYS spire through one or more avenues – developing and teaching courses cross-listed with CSYS, supervising PhD students in CSYS, actively participating in Service related to CSYS (such as serving on search and curriculum committees), and helping to organize and/or regularly attending CSYS seminars, workshops, conferences. The creation of new joint faculty lines would help other disciplines to see CSYS as a partner, not a competitor, thereby enabling these units to increase their faculty numbers without having to foot the entire bill and developing new cutting-edge research portfolios to further raise the disciplinary units’ reputations.

5) Anticipated Resource Needs: The new faculty hires described in Section 4.1 would come from a combination of currently open positions and replacement positions over the coming years. To launch and support a strong PhD in CSYS we believe it will be essential to
hire (a) more faculty who could contribute to core CSYS curriculum and (b) discipline-specific CSYS scholars in units seeking to establish CSYS tracks. Faculty in both of these categories would be jointly appointed between CSYS and a variety of disciplines across campus (see Section 4.1). Some of them should be synergistic hires with other spires that are endorsed by the Board of Trustees, and some should be in other disciplines including areas not currently served by PhD programs. We believe interested disciplinary units should voluntarily propose CSYS tracks, and we recommend that the Provost consider giving priority to fulfilling requests from units requesting new or replacement faculty lines when those descriptions include a CSYS component in support of CSYS tracks.

The initial success of the CSYS spire will dictate whether future hires should continue to be made in this area. In addition to faculty lines, we envision other potential resource requirements. The Center or School will need a Director and two full-time supporting administrative staff who will steer and manage the strategic and operational activities of the CSYS spire, including grant writing and grant administrative support. UVM Faculty must be provided with sufficient opportunity, time and resources with which to explore and develop new cross-campus collaborations in CSYS. In support of this, we propose the creation of 5-10 one-semester competitive CSYS faculty fellowships awarded annually to provide release time for specific CSYS related activities, such as developing collaborative CSYS grant proposals or enhancing CSYS methodological skills. In addition, pilot funding for new transdisciplinary CSYS research projects should be available on a competitive basis. For UVM to be competitive for an NSF IGERT, the administration must commit strong support to the IGERT including matching of graduate assistantships, rebalancing workloads of the IGERT PIs and committing to the new faculty lines and administrative support mentioned above. Support should also be provided for both formal and informal get-togethers for faculty and graduate students interested in CSYS including external and internal seminar series, workshops and conferences in CSYS as described in Section 4.2. Additionally, funding should be provided for graduate student recruitment. The resources needed for these
activities must initially come from Central Administration to jump-start the CSYS initiative, but would ultimately be sustained through partial return of grant overheads to the CSYS Center or School.

6) **Metrics for success:** UVM must methodically track CSYS activity with various metrics including those used for NRC rankings. For example, we should track the number of proposals and external dollar amount both requested and awarded in CSYS-related areas (facilitated by a CSYS checkbox on the institutional proposal cover page and the signature of the CSYS Director on the routing form); the scholarly productivity (books, papers, citations, invited talks, etc.) of faculty with joint CSYS appointment (these faculty could identify which publications were CSYS related); the success of UVM in attracting IGERT, REU and Center grants in CSYS areas; the creation of a CSYS PhD; the creation of CSYS tracks in other PhD programs; the enrollments in CSYS courses and the number and quality (e.g., GRE scores) of graduate students (applicants, matriculated students, and graduates) in CSYS-related graduate programs (existing Certificate, new PhD Tracks, and new PhD). A specific timetable of targets should be developed, commensurate with the level of resource investment UVM puts into the spire, and progress methodically tracked by the support staff.

7) **Conclusions:** We propose a UVM campus-wide transdisciplinary spire of excellence in CSYS that will stimulate cutting-edge research at UVM as well as VT economic development. We propose that the CSYS spire will comprise a new Matrix Center or School, a new CSYS PhD with named tracks, new CSYS tracks within existing strong PhD programs, strong relationships with other institutional enterprises, opportunities for faculty development, and an enhanced undergraduate experience. UVM already has an excellent core of established researchers in CSYS theory and methods, a larger body of faculty who employ CSYS approaches in a variety of application domains and an even larger group of faculty who are excited by the possibilities of incorporating CSYS approaches into existing research
programs especially in light of the strong CSYS calls that pervade current Federal solicitations for funding. The relative lack of CSYS graduate educational opportunities at US academic institutions provides a unique opportunity for UVM to fill this niche and create a world-class reputation in this rapidly growing transdisciplinary research area, while simultaneously strengthening disciplines across the campus.
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