BEACON Center for the Study of Evolution in Action

ANNUAL REPORT
November 1, 2011

For any questions regarding this report, please contact:

Danielle J. Whittaker, Ph.D.
Managing Director
BEACON Center for the Study of Evolution in Action
1441 Biomedical and Physical Sciences
Michigan State University
East Lansing, MI 48824
517-884-2561
djwhitta@msu.edu

I. GENERAL INFORMATION

Date submitted	November 1, 2011
Reporting period	February 1, 2011 – January 31, 2012
Name of the Center	**BEACON Center for the Study of Evolution in Action**
Name of the Center Director	Erik D. Goodman
Lead University	Michigan State University
Address	1441 Biomedical and Physical Sciences East Lansing, MI 48824
Phone Number	517-884-2555
Fax Number	517-353-7248
Center Director email	goodman@egr.msu.edu
Center URL	http://www.beacon-center.org

Participating Institutions

Institution 1 Name	**North Carolina A&T State University**
Contact Person	Gerry Vernon Dozier
Address	Department of Computer Science 508 McNair Hall Greensboro, NC 27411
Phone Number	(336) 334-7245, ext 467
Fax Number	(336) 334-7244
Email Address	gvdozier@ncat.edu
Role of Institution at Center	Member Institution
Institution 2 Name	**University of Idaho**
Contact Person	James Foster
Address	Department of Biological Sciences Moscow, ID 83844-3051
Phone Number	(208) 885-7062
Fax Number	(208) 885-7905
Email Address	foster@uidaho.edu
Role of Institution at Center	Member Institution
Institution 3 Name	**The University of Texas at Austin**
Contact Person	Risto Miikkulainen
Address	Department of Computer Sciences 1 University Station D9500 Austin TX 78712-0233
Phone Number	(512) 471-9571
Fax Number	(512) 471-8885
Email Address	risto@cs.utexas.edu
Role of Institution at Center	Member Institution
Institution 4 Name	**University of Washington**
Contact Person	Benjamin Kerr
Address	Department of Biology Box 351800 Seattle, WA 98195
Phone Number	(206)-221-3996
Fax Number	
Email Address	kerrb@u.washington.edu
Role of Institution at Center	Member Institution

CONTEXT STATEMENT

OVERVIEW OF VISION AND GOALS

The BEACON Center for the Study of Evolution in Action is an NSF Science and Technology Center founded in 2010 with the **mission** of illuminating and harnessing the power of evolution in action to advance science and technology and benefit society. BEACON is a consortium of universities led by Michigan State University, with member institutions North Carolina A&T State University, the University of Idaho, the University of Texas at Austin, and the University of Washington. BEACON unites biologists, computer scientists and engineers in joint study of natural and artificial evolutionary processes and in harnessing them to solve real-world problems. Developers of evolutionary algorithms have long borrowed high-level concepts from biology to improve problem-solving methods, but have not captured the nuances of evolutionary theory. Likewise, studying the evolution of artificial systems can provide biologists with insight into the dynamics of the evolutionary process and the critical factors underlying emergent properties and behaviors. BEACON promotes the transfer of discoveries from biology into computer science and engineering design, while using novel computational methods and artificial evolutionary systems to address complex biological questions that are difficult or impossible to study with natural organisms.

As Dobzhansky famously noted, "Nothing in biology makes sense except in the light of evolution." BEACON's **vision** focuses that light, revealing fundamental biological concepts and illuminating the path toward computational applications. The key insight underlying the Center is that transformative discoveries in both computing and biology are possible through studying evolution *as it happens*, in both natural and digital domains. The philosopher Dennett (2002) has pointed out the algorithmic nature of evolution as a process that will occur in any system with "replication, variation (mutation) and differential fitness (competition)." BEACON aims to understand evolution in this universal framework.

Our overarching **goal** for BEACON is to unite biologists with computational researchers and other scientists and engineers in an effort to expand our understanding of fundamental evolutionary dynamics through a combination of theory and experiments on actively evolving systems, whether they are biological or computational systems. The Center helps researchers overcome the typical disciplinary biases and realize the sophistication and universality of evolution. Studies using a wide range of natural organisms (from simple bacteria like *E. coli*, to complex vertebrates, such as spotted hyena) are paired with novel evolutionary computation systems that allow both experimental and applied research. As a bridge between these domains, we also use *digital organisms*, which are self-replicating computer programs that undergo open-ended evolution. Such digital evolution systems are powerful research tools that make transparent the evolutionary process while giving researchers unparalleled control over their experiments.

Our range of study systems and our focus on *evolution in action* allow us to explore fundamental issues in evolutionary theory. While science has come a long way in understanding evolutionary patterns and the history of life on earth, many important questions remain about the causal processes: How do complexity, diversity, and robustness arise in evolving systems? What conditions lead to the evolution of intelligent behaviors? How do ecological communities form?

Why do multicellularity and other forms of cooperation evolve? How much do these processes vary between species or across biological, computational and robotic systems? Answering these and related questions will allow our understanding of evolution to better inform other areas of biological investigation and augment the practical utility of evolutionary design in engineering and industry. A guiding precept of this Center is that we must perform controlled experiments on evolution *as it happens* to fully understand, predict, and control evolutionary dynamics. These concepts demand exploration by interdisciplinary teams, joining biologists with computer scientists and engineers to solve increasingly difficult real-world design and optimization problems.

We share the deep understanding afforded by this transformative research with the broader public, encouraging exposure to and intuition about evolution through first-hand experience. Although evolutionary science is the fundamental explanatory principle in biology, it continues to be widely misunderstood and even rejected by a majority of Americans. Being able to observe and perform experiments on actively evolving systems will help people appreciate not only the creative power of evolutionary mechanisms, but also the nature of scientific reasoning itself. Digital evolution, in particular, provides a revolutionary educational tool that can bring evolution to the classroom, to a museum, and even to a web browser. Our previous successes, such as the Avida-ED digital evolution educational software, have demonstrated the promise of this innovative approach, but the sustained infrastructure of an NSF Center allows us to bring it to fruition. We combine these techniques with new evolution-in-action experiments on natural organisms to advance internal training of students and post-docs as well as external education and outreach efforts (including development of curricula and educational tools). Faculty and students at all partner institutions participate fully in these educational activities, as developers and users. As part of the Center's large-scale effort, North Carolina A&T incorporates these techniques to teach about evolution in their core curriculum, a significant step for any school, and especially for an HBCU where religious pressures often cause such topics to be avoided.

BEACON will have a powerful legacy: we will reframe public perceptions of evolution and increase understanding of scientific methods. At the same time, we will produce a conceptual framework to firmly establish evolutionary biology as an *experimental* science and cement its links to computing in a cross-fertilization that enhances both fields. Once we break these disciplinary barriers, the powerful collaborations that we produce will long outlast the Center, leading to generations of thriving researchers proficient at the intersection of biological and computational evolution. This intellectual legacy will continue to be reinforced and promoted by an open professional research and education conference that we will grow out of the Center's annual all-hands meeting.

PLANS AND PERFORMANCE INDICATORS

Our Strategic Implementation Plan sets goals in six areas: Education, Human Resources & Diversity (EHRD); Leadership and Management; Knowledge Transfer; Integrative Research, Ethical Research; and Research Output. Below is a brief summary of our overall goals, optimal outcomes, performance metrics, and progress in each of these areas.

BEACON's **Education, Human Resources, and Diversity (EHRD) overarching goal** is to integrate cutting-edge, multidisciplinary research, education, and outreach efforts across the Center that will advance innovative training, the diversity of the Center and scientific workforce,

and public education to promote greater understanding of evolution and the nature of science. We have defined four optimal outcomes:

- Multidisciplinary Ph.D. graduates and post-docs placed in faculty positions in line with averages across engineering, computer science, and biology. We will measure our success in this area by the fraction of BEACON graduate students and postdocs receiving offers of positions.
- Exceed national norms for diversity at all levels in the Center. Progress will be measured by the numbers and percentages of faculty, postdocs, graduate students, and undergraduate students that are from underrepresented demographic groups.
- Increased literacy in evolution and the nature of science. We are measuring our progress by our development of educational materials and the frequency of public use of online materials or visits to exhibits.
- An increased interest in STEM careers in both academia and industry. We are measuring our success with pre- and post-program survey instruments administered to K-12 participants, university students, and the public, as well as by feedback from the External Advisory Committee.

BEACON's **Leadership and Management goals** are to envision and enable the Center's mission through inclusive and transparent decision-making as well as effective and responsible implementation; to inspire Center participants; and to facilitate collaborative efforts within and beyond the Center. We have defined six optimal outcomes:

- Increase in cross-disciplinary research and education. We are measuring our progress by: number of cross-disciplinary paper/conference submissions by BEACON authors; number of new interdisciplinary courses offered at BEACON; number of students enrolled in those courses; and the number of cross-disciplinary funding proposals submitted.
- Increase in cross-institutional research and education. Progress is measured by the number of cross-institutional paper/conference submissions, the number of cross-institutional courses offered at BEACON, and the number of students in those courses.
- Increase in new funding sources (cross-disciplinary and cross-institutional). We are measuring our progress with the number of grant submissions and award dollars.
- Increase in new participants. We are tracking the number of faculty, postdocs and students participating in BEACON every year.
- Effective support of Center operations by Management team. We measure this with surveys, interviews and focus groups of participants about the management team and feedback from the External Advisory Committee.
- Center is perceived by NSF as exemplary. Success is determined by renewal of NSF funding and the number of public mentions made by NSF about BEACON.

BEACON's **Knowledge Transfer goal** is to develop effective mechanisms and pathways to facilitate intellectual exchanges among BEACON partners and industrial affiliates that will support the sharing of knowledge and application of new technology. Six optimal outcomes:

- Signed Intellectual Property agreements with Industrial Affiliates, measured by the number of IP agreements signed.
- Industry-provided challenge problems, measured by the number of instances that challenge, problems, data, and feedback are received from industry partners.

- New collaborative research with industry partners, measured by the number of publications and joint grant proposals submitted.
- Dissemination and use of BEACON tools and data, measured by the number of downloads of BEACON tools/data.
- Spinoffs formed, measured by the number of spinoffs formed.
- Adoption of new BEACON-developed technology by industry, measured by the number of instances that BEACON projects, processes, and techniques are adopted by industry.

Our **Integrative Research goal** is to produce transformative, synergistic research through an inclusive collaborative culture that crosses disciplinary and institutional boundaries and is embedded throughout the Center's activities. Our four optimal outcomes are:

- New research collaborations and proposals, measured by the number of research projects and publications, as well as service by members on doctoral research committees across disciplines and institutions.
- New paradigms for research in organic and digital domains. We are tracking our progress in this area with the number of new sessions at scientific meetings or meetings hosted at BEACON; the number of new journals and societies in this area; and new or increased funding for biocomputational research.
- Increase in publications related to evolution in action. We are measuring this by tracking the number of BEACON faculty participants writing these publications and the citations of their work, and tracking high visibility science journalism about BEACON research.
- Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution. We are measuring our progress towards this outcome by tracking the number of requests for information.

BEACON's **Ethics goal** is to practice and promote ethical and responsible research by implementing cross-disciplinary and multi-institutional ethics programs that will inform and guide all participants in the Center. Four optimal outcomes:

- Center participants will understand shared and discipline-specific practices of Responsible Conduct of Research (RCR). We are tracking the percent of student and postdoc participants who complete RCR training courses.
- Center participants will embody general scientific norms/virtues, including objectivity, integrity, community, and transparency. We will track participation in Scientific Virtues workshops.
- Respect for ideas "horizontally" and "vertically." We are measuring the number of Toolbox training sessions, and the number of BEACON participants who get cross-disciplinary training.
- Participants have access to shared resources and mechanisms to negotiate intellectual/philosophical differences. We will use a survey to determine the percent of participants who are aware of such resources.

BEACON's **research output goal** is to disseminate widely an increasing quantity of original and highly regarded scientific research on evolution in action. We have defined two optimal outcomes:

- Original research by BEACON members on evolution in action will be prominent in the evolution literature, as measured by the number of publications in peer-reviewed journals, presentations at scientific conferences, and grant proposals submitted.

- BEACON research output will be perceived as making an important contribution to the literature, as measured by feedback from the External Advisory Committee.

Progress towards Center goals

The following sections summarize progress and significant accomplishments in all of the areas that are described in more detail in the rest of the report: Research, Education, Knowledge Transfer, External Partnerships, Diversity, Management, Center-Wide Outputs, and Indirect/Other Impacts.

RESEARCH

This table summarizes our progress towards the goals and metrics described above.

GOAL	METRICS	PROGRESS
	Integrative Research Goals	
New research collaborations and proposals	Number of interdisciplinary/multi-institutional research projects and publications	At least 49 research projects underway
	Service by members on doctoral research committees across disciplines and institutions	Not yet measured.
New paradigms for research in organic and digital domains	Number of new sessions at scientific meetings or scientific meetings hosted at BEACON	BEACON is hosting the Thirteenth Artificial Life conference in 2012
	Number of new journals and societies	None to report
	New or increased funding for biocomputational research	BEACON researchers submitted 48 proposals for over $36M of external funding, $8M in external funding has been granted
Increase in publications related to evolution in action	Number of BEACON faculty participants writing such publications and the number of citations of their work.	106 publications submitted
	Number of science publications about Evolution in Action authored by researchers outside of BEACON	Not practical to measure, so we are removing this metric from our strategic plan
	High visibility science journalism about BEACON research	33 press releases, articles in NYT, Live Science, Science Daily and other major outlets
Development and	Number of requests for	5244 downloads of Avida-ED,

dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	information	11,470 visits to BEACON website
Ethical Research Goals		
Center participants will understand shared and discipline-specific practices of Responsible Conduct of Research (RCR).	Percent completion of online training courses and face-to-face mentoring by participants.	Exceeded goal of 75% of participants to complete training by August 2011.
	Change in frequency of ethics violations.	No violations to report.
Center participants will embody general scientific norms/virtues, including objectivity, integrity, community, and transparency.	Baseline and follow-up participation in a Scientific Virtues workshop.	Toolbox workshops currently being tailored for use by BEACON teams. Scientific virtues workshop being planned.
Respect for views and ideas "horizontally" and "vertically."	Number of Toolbox seminars and trials	Toolbox workshops piloted at BEACON Congress August 2010; currently planning next steps
	Number of BEACON participants who get cross-disciplinary training	Toolbox workshops piloted at BEACON Congress August 2010; currently planning next steps
Research Output Goals		
Original research by BEACON members on evolution in action will be prominent in the evolution literature.	Number of publications in peer-reviewed journals, presentations at scientific conferences, and grant proposals submitted	106 publications submitted, 91 conference or other presentations, 48 grant proposals submitted
BEACON research output will be perceived as making an important contribution to the literature.	Feedback from the External Advisory Committee	Positive feedback. See Appendix C.

BEACON research falls under three thrust groups, which are based on natural levels of organization: genomes, behavior among individuals, and community-level dynamics. These thrust groups are united by three cross-cutting themes: biological evolution, digital evolution, and evolutionary applications. Below, we describe research projects that are currently under way within each thrust group and their goals and activities.

Many terms commonly used by BEACONites may be less familiar to some readers, so first we offer a brief **BEACON Glossary**.

- **Digital Evolution**: Digital evolution is a field of study where experimental evolution techniques are used on populations of digital organisms.
- **Digital Organisms:** A digital organism is a self-replicating computer program, with a genetic basis (programming language) in which any basic computation could theoretically be implemented (Turing complete). Populations of digital organisms are usually studied in complex and noisy environments where they are subject to mutations and selective pressures that lead to open-ended evolution.
- **Evolutionary Computation:** Evolutionary computation describes a large class of stochastic search/optimization algorithms that are often based on relatively crude models of biological evolution. They typically maintain a population of candidate solutions at any point in time, generate modifications of them, test them in a simulated environment, and select such that higher-fitness candidates tend to survive into the next population.
- **Experimental Evolution:** Research in which populations are studied across multiple generations under defined and reproducible conditions, whether in the laboratory, in nature, or in a digital environment. In such experiments, the selective environment can be manipulated in order to test hypotheses about evolution.

Thrust Group 1: Evolution of Genomes, Networks and Evolvability. The overall goal of this group is to understand the evolution of genome architecture and the processes that govern the production of genetic and phenotypic variation. A total of 20 projects are supported in this thrust group, which fall into a number of broad themes. Many investigators are studying the actual processes of speciation and adaptation—not just evidence that they have occurred in the past, but testing hypotheses about the way the process itself works. Other research themes include: evolution of gene networks underlying complex traits such as regeneration in hemichordates; applying evolutionary perspectives to synthetic biology; and the process and consequences of adaptation to environmental change. BEACONites are using a combination of techniques, including experimental evolution in biological and digital organisms, mathematical modeling and simulation, and integrating data from field and lab biology. Below is a summary of research in each theme.

Understanding the process of speciation: Research in this theme examines the genes involved in isolating populations into separate species, how speciation can occur with gene flow, and connecting so-called "microevolution" on a short time scale to the process of speciation over the long term.

Understanding the process of adaptation: These projects seek to observe and understand adaptation in action at a molecular level, focusing on issues such as the genetics of correlated traits, compensatory evolution, RNA and protein structure, and contingency loci.

Environmental change and adaptation: Another research theme addresses the role of environmental change in adaptation, including investigations into theoretical principles of adaptation using both laboratory and digital systems, and empirical studies of the response of organisms in natural systems to ongoing climate change.

Interactions among genes: Several BEACON projects are focused on the way genes interact, including describing patterns of epistasis in biological systems and uncovering the mechanisms of changes to gene networks underlying complex phenotypic traits.

Synthetic biology: Several BEACON researchers are introducing an evolutionary perspective into the field of synthetic biology, using experimental and directed evolution to evolve synthetic genomes and genetic circuits.

Thrust Group 2: Evolution of Behavior and Intelligence. Research in thrust group two focuses on the evolution of behavior of individuals, both in relation to the environment (e.g., navigation, foraging) and in relation to each other (communication, risk avoidance, cognition and social dynamics). Digital evolution has proven to be a powerful tool in which data gathered from biological organisms can be applied to recreate the evolution of complex behavior in digital organisms. By observing the evolution of self-replicating digital organisms, we can understand the conditions that led to the evolution of complex behaviors in biological organisms. Another major theme in this thrust group is using evolutionary computation to create better, smarter electronic and robotic systems, such as dynamic control systems that respond to the environment, improved detection systems for security, and robots that can navigate on their own through environments that may change unpredictably.

Biocomputational studies of the evolution of behavior: Research projects in this theme combine biological and computational techniques to understand the evolution of such complex behaviors as cooperation, navigation, and sociality.

Evolving smarter electronic and robotic systems: Engineering research in this area is focused on using ever-more-sophisticated evolutionary computational techniques to develop better applications, as diverse as home assistance robots, ambulatory prosthetics, computer security systems, greenhouse controls, and cancer detection systems.

Thrust Group 3: Evolution of Communities and Collective Dynamics. Research in this group focuses on the evolution, stability, and emergent properties of assemblages of organisms, considering both their ecological properties and their ability to perform collective tasks.

Disease networks and transmission: Research in this theme focuses on patterns of disease transmission in populations, evolution of drug resistance through cooperation and coevolution, and the genomics of invasive pathogens. These projects have great potential for medical applications.

Metagenomics: Metagenomics, or the study of the collected genomes of all of the microbes in a shared environment, is the focus of two BEACON projects. Because the vast majority of microbes cannot be cultured and studied in a lab in the traditional manner, the ability to directly sequence genomes from, e.g., a soil sample, holds great promise for understanding microbial communities and their interactions with the environment.

Maintenance of phenotypic variation through collective dynamics: Research in this theme examines how selection at a group level may maintain variation in a population in a way that is beneficial to all members of the population.

Engineering applications of biological collective dynamics: Finally, a group of researchers in this theme are exploring engineering applications inspired by biological studies of collective dynamics.

EDUCATION

The following table summarizes our progress towards the goals and metrics described in the first section of the context statement.

Education Goals		
GOAL	**METRICS**	**PROGRESS**
Multidisciplinary Ph.D. graduates and post-docs placed in faculty positions at rates approaching averages across engineering, computer science, and biology	Fraction of BEACON graduate students and post-docs receiving offers of faculty positions	Too early to measure. Multidisciplinary classes established at all 5 partner institutions. Mentoring programs established.
Increased public literacy in evolution and the nature of science	Development of educational materials	Avida-ED training workshops given at all BEACON U's; initial museum exhibits in place
	Frequency of public use of online materials or visits to exhibits	Collecting baseline data on use of existing online materials.
Increased interest in STEM careers in both academia and industry	Pre- and post-program survey instruments administered to K-12 participants, university students, and the public	High school and undergraduate summer programs offered; teacher training workshops offered; art installation.
	Feedback from the External Advisory Committee	Positive feedback. See Appendix C

Internal Education Activities. BEACON offers cross-disciplinary training for its graduate students. In the fall semester, two courses are offered *Computational Science for Evolutionary Biologists*, taught by C. Titus Brown, and *Evolutionary Biology for Non-Life Scientists*, taught by Alexander Shingleton. Then, in the spring, students who took those courses come together and take *Multidisciplinary Approaches to the Study of Evolution*, taught by Charles Ofria and Ian Dworkin. The goal of these courses is for students to be conversant across disciplines, to be able to design and work on interdisciplinary research projects, and also to learn how to collaborate across institutions. These classes are offered across institutions, so that students at UI, UT, and UW are also participating in the courses at MSU via video-conferencing technology. In the second semester, students work on final projects in multidisciplinary and inter-institutional groups. Final projects in Spring 2011 included a wide array of research on problems in evolutionary biology (for example The Evolution of Sexual Dimorphism; Signaling Loss; The Evolution of Evolvability). At the end of the course, 61% agreed or strongly agreed they will pursue research that integrates evolution, engineering and computer science. These courses were first offered at MSU in 2010-2011, and are currently in their second year. In 2011-2012, NC A&T has begun offering the same courses targeted at upper-level undergraduate and master's students, taught by Gerry Dozier & Gregory Goins (computational science) and Joseph Graves (biology).

BEACON is also invested in training undergraduates in an effort to meet both our mission to (recruit and) train graduate students, as well as our mission to increase understanding of evolution and the nature of science. A number of educational projects are focused on undergraduate education, and a particularly well-developed project is at the University of Texas at Austin. Drs. Claus Wilke and Art Covert received funding to run the computational biology stream (now renamed the computational evolution stream) of the UT Freshman Research Initiative (FRI). An FRI stream is a year-long course designed to give freshman and sophomore students actual research experience. Twenty to thirty students spend one semester learning computational research methods, taught by a Research Educator (Dr. Art Covert) in an inquiry-based lab setting. Successful spring students then spend the summer and fall doing research on evolution in action in the Wilke lab.

External Education Activities. BEACON is currently funding a number of educational activities and programs, all which help to meet our EHRD goals and optimal outcomes. These projects range from evolutionary games for elementary students to software that engages undergraduate students in testing evolutionary hypotheses.

Student-centered activities

- BEACON High School Summer Institute: ~30 high school students spent a week in summer, 2011, on the MSU campus and at Kellogg Biological Station learning about evolution in action, with both computational and field components.
- BEACON REU Field Experience: Undergraduate students participated in BEACON-related field research at Kellogg Biological Station (MSU) and Friday Harbor Laboratories (UW).

Teacher training and educational materials

- Developing a ribozyme evolution assay for undergraduate education and K-12 outreach: This project worked with the UT Freshman Research Initiative to develop, test and distribute a new hands-on inquiry activity for high school students, so they may gain a practical understanding of evolution and selection.
- Online Teacher Education course: Students are introduced to various online resources, including the National Association of Biology Teachers Evolution Symposium webcast, as well as topic-specific content such as Understanding Evolution.
- Engaging educators with evolution in action: Cutting-edge BEACON research will be incorporated into classroom modules for a Science, Technology, & Society class at the undergraduate level.
- Avida-ED infrastructure maintenance and development: The goal of the project is to update the code base of Avida-ED, our digital evolution software designed for educational use in undergraduate and graduate courses, and then to provide training workshops to partner universities so that it can be used across BEACON.
- Teaching evolution through action: The AVIDA challenge: The goal of this project is to develop a set of programming/evolutionary challenges to be addressed in AVIDA. These challenges will be designed to meet several specific objectives: (1) to encourage the learning and exploration of AVIDA; (2) to teach the essential concepts of evolutionary theory and artificial life; (3) to encourage the use of AVIDA at both BEACON partners and other institutions; (4) to encourage the use of AVIDA by undergraduates and high school students.

Activities targeting the general public

- Evolution Podcast: This weekly podcast by Randall Hayes presents evolutionary science topics in an engaging, accessible way.
- Evolutionary Games: Excellent progress is being made on the development of games that help to explain components of evolution and can be delivered on touchscreen kiosks in museums.
- Museum Exhibits:
  - Relevance of Evolution to our Daily Lives at Texas Natural Science Center: Under the supervision of the Director of Education at the Texas Natural Science Center, a graduate student is working with BEACON scientists, starting at UT Austin and then expanding the conversation to include all BEACON partner universities, to develop up to 10 narratives that can be used on interactive exhibit modules.
  - Evolution in Action exhibits at MSU Museum: The MSU Museum is working to deliver educational products that engage the broadest of audiences with the relevance and research of BEACON.
  - "Hyenas Rule!" Virtual Outreach Program at MSU Museum: Products will include a 40-50 minute IVC (interactive video conferencing) program for secondary science students and accompanying teacher materials.
  - Art & Evolution: Evolving social behavior of liminal machines: The Biolume project is a collaborative effort aimed towards creating an evolution-based art exhibit. Using the combined resources of artists, computer scientists, and electrical engineers, the project will bring the concept of evolution in action to the general public.

KNOWLEDGE TRANSFER

The following table summarizes our knowledge transfer progress in the past year in the areas described in the first section of the Context Statement.

Knowledge Transfer Goals		
GOAL	**METRICS**	**PROGRESS**
Signed Intellectual Property agreements with Industrial Affiliates	Number of IP agreements signed	IP agreements signed for collaboration among 5 member institutions; 4 of 5 have signed boilerplate agreement for industrial collaborations
Receiving industry-provided challenge problems ("Real World" problems) and data with feedback	Number of instances that challenge problems, data, and feedback are received from industry partners	2 instances
New collaborative research with Industry partners	Number of publications	1 paper and 1 software program so far
	Number and amount of joint grant proposals submitted	2 proposals submitted

Dissemination and use of BEACON tools and data	Number of downloads of BEACON tools/data relative to baseline	>8,000 downloads of Avida; developing software repository to track other programs
Spinoffs formed	Number of spinoffs formed	1
Adoption of new BEACON-developed technology by industry	Number of instances of BEACON projects, processes, and techniques adopted by industry	None to report.

BEACON's Knowledge Transfer model involves working with industry contacts to obtain challenge problems (i.e. "Real World" problems) and data with feedback, to allow real solutions to real problems. BEACON aims to form collaborative relationships with industry partners.

A number of companies are already working with BEACON, including Ford Motor Company, Google, Inc., Secure Designs, Inc. and SCION, a Crown Research Corporation of New Zealand. Several more are in KT discussions with the Industrial Affiliates Manager and the PIs, including General Motors, Continental Automotive, Northrup Grummon, IBM, National Instruments, Mechatron, 41st Parameter, V-Chain Solutions, and GE Aviation.

EXTERNAL PARTNERSHIPS

Most of BEACON's external partnerships fall under the categories of research or education projects. In this section we primarily focus on sabbatical visits by researchers from other institutions. Our goal is to form partnerships with researchers who are working on the area of evolution in action, and we measure our progress by tracking the number of researchers visiting BEACON for sabbatical, and the number of publications and grant proposals submitted as a result of these visits.

Christoph Adami: During the 2010-2011 academic year, Professor Christoph Adami from the Keck Graduate Institute spent his sabbatical at BEACON headquarters at MSU. So far 9 publications have resulted from this visit. in the summer of 2011 Adami was hired at MSU as a tenured full professor in the department of Microbiology and Molecular Genetics as an “Excellence Hire.” Adami continues to be closely involved in BEACON activities and is a great asset.

Oliver Chikumbo: Goodman and Deb collaborated with Dr. Oliver Chikumbo, of SCION, a Crown Research Corporation of New Zealand, on using multi-objective evolutionary computation methods to provide sets of alternative solutions for problems of agricultural land management in the environmentally sensitive Rotorua region of New Zealand. They applied for and received a grant from Scion’s International Mobility Fund for Dr. Chikumbo to visit BEACON for one month, August, 2011, to collaborate with Goodman and Deb. Dr. Chikumbo has since received indications that financial support to continue the work will be made available through DairyNZ and other agencies.

Other visiting researchers during reporting period: Prof. Robert Heckendorn (from BEACON at UI), Prof. Zhun Fan (Technical University of Denmark), Prof. Kisung Seo

(Seokyeong University), Ling Wang (Shanghai University), Prof. Lihong Xu (Tongji University), Chenwen Zhu (Tongji University), Dr. Chengju Liu (Tongji University), Professor Meng Yao (East China Normal University).

DIVERSITY

BEACON's overall goal is to exceed national norms for diversity at all levels in the Center. We collected demographic data from participants and affiliates through our intranet system, in which each person has an online profile, including confidential demographic information. Among our 222 participants (numbers do not sum to 100% because some individuals reported multiple races/ethnicities):

Category	Number	Percent
Male	149	67%
Female	73	33%
Disability	3	1.4%
White	147	66%
Black	24	11%
Asian	27	12%
American Indian	2	1%
Hispanic	11	5%
Race/Ethnicity not reported	25	11%

Some categories, including disability and Hispanic, are known to be underreported. The proportion of BEACON graduate students that are women or minorities is currently at the national norms for women and Hispanics, and exceeds the national norms for Black Non-Hispanic graduate students, according to 2009 figures from the National Science Foundation.

BEACON is actively working towards increasing the diversity of its participants in a number of ways, including: making diversity an explicit factor in all funding decisions, recruiting diverse faculty and researchers at other institutions through a Faculty Affiliates program, recruiting diverse undergraduates to summer research experiences, actively recruiting undergraduate, graduates, and post-docs at regional and national conferences, and identifying/securing partnerships for future pipelines/pathways of talent. BEACON is also working to ensure that diversity is represented as a connecting thread through all aspects of BEACON; e.g., representation on website, cultural competency training, adaptive environments information and support. Finally, BEACON is creating welcoming, adaptive environments and support for individuals with disabilities.

While BEACON is drawing on its relationship with historically black member institution NC A&T to recruit diverse undergraduates into summer research programs and Ph.D. programs, BEACON is also actively working with several other HBCUs: Tuskegee University (Alabama), Spelman College (Georgia), Morehouse College (Georgia), Jackson State University (Mississippi) and Bennett College (North Carolina).

As part of BEACON's annual budget allocation process, three projects that specifically aim to increase diversity in BEACON and in STEM fields in general were funded.

- Enhancing diversity through evolution in action at the molecular level: a summer research program for underrepresented minority undergraduate students, including a 10-week course designed to teach students the basics of evolution, genetics, molecular biology, and microbiology.
- BEACON Day at A&T: BEACON@NC A&T will host a BEACON-wide day in celebration of BEACON's accomplishments. It will help introduce and/or educate the NCAT administration about BEACON, provide a forum for discussion of BEACON research across the Center, provide an opportunity for faculty across the Center to come to NCAT and discuss possible collaborations, and provide a show case for NCAT students to get excited about research at BEACON institutions or other universities.
- Increase BEACON-UW diversity: The BEACON group at UW has decided to join forces with UW GenOM (genomics for minorities) program to recruit minority students to engage in summer research, and are developing materials including brochures and a website to assist in efforts to recruit more diverse students.

MANAGEMENT

The following table summarizes our metrics and progress towards our goals in the area of management.

Management Goals		
GOAL	**METRICS**	**PROGRESS**
Increase in cross-disciplinary research and education	Number of paper/conference submissions by BEACON authors	Goal: 20 cross-disciplinary submissions in first year: ~45 reported for first 15 months
	Number of new courses	Three BEACON graduate courses at MSU, with participation from UT/UI/UW. Two courses have also been modified as upper-level graduate courses and are being offered in Fall 2011 at NCAT.
	Number of students enrolled in cross-disciplinary courses	Grad courses at MSU/UI/UT/UW: Fall 2010: 43; Spring 2011: 22, Fall 2011: 33. At NCAT: 6 in Bio, 30 in CS
	Number of funding proposals submitted	Goal: 10 per year. 17 submitted Aug 2010-Jan 2011; 31 submitted Feb – Nov 2011.
Increase in cross-institutional research and education	Number of cross-institutional paper/conference submissions	Too soon to measure, as cross-institutional research teams enabled by BEACON still new
	Number of new courses	The three above-mentioned

		MSU courses are successfully cross-institutional.
	Number of students in cross-institutional courses	Fall 2010: 43; Spring 2011: 22, Fall 2011: 23.
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	42 grant proposals submitted by August 2011 (baseline)
	Award dollars	Target of $1 million by Oct 2011: over $8 million awarded by Oct 2011
Increase in new participants	Number of faculty, post-docs, and students	Number involved in August 2010-August 2011 will serve as our baseline: 156 grad students, 124 faculty, 31 postdocs, 25 undergrads
Effective support of Center operations by Management team	Survey for participants about management team	Baseline survey administered October-November 2010; followup interviews/focus groups spring, 2011.We have implemented changes in problem areas identified. Year 2 evaluation plans currently being finalized.
	Feedback from External Advisory Committee	First meeting 8/12/11, feedback was largely positive (Appendix C)
Center is perceived by NSF as exemplary	Renewal of NSF funding	Renewal was approved for our second funding increment
	Number of public mentions made by NSF about BEACON	In 2011, NSF issued 1 press release about BEACON-related research, and 3 stories about BEACON research were featured on the NSF-sponsored webpage Live Science.

The biggest challenge facing the management team is maintaining communication, collaboration, and a sense of community across five institutions. To address this challenge, we have implemented an online management system, an external website featuring a blog and resources, social networking sites, a weekly seminar that participants from all five institutions attend using videoconferencing technology, and a BEACON Student & Postdoc Association. We are evaluating our progress towards reaching our management goals with an external evaluation.

Management systems. Our central management "engine" is our intranet system. This system is used for many applications:

- Individual personnel profiles, where we collect demographic information

- Generation of specific email lists based on status (student, postdoc, faculty, etc) and home institution
- Collecting information on outputs and activities and progress reports on ongoing projects
- Submission and peer reviewing of budget requests
- Collection of suggestions for the annual BEACON Congress in a wiki format
- Sharing of files, such as presentation overheads for BEACON-wide Friday seminars
- Tracking of compliance with Responsible Conduct of Research requirements
- Providing shared data storage areas for collaborating teams

Central website. Our website is located at www.beacon-center.org. The front page of this website is in a blog format. The primary feature is "BEACON Researchers at Work," a blog written by BEACON students, postdocs, and faculty describing their research at a level accessible to the scientific public. The managing director solicits, schedules, and edits these posts. In addition, we also post news stories about BEACON research in that space. Other pages in the website describe BEACON mission, research, and education and diversity efforts, and we maintain an archive of BEACON press releases and media coverage. Access to BEACON's members-only Intranet is through these pages.

Social media. We also connect with our members and the general public via Facebook (120 "likes" as of 10/28/11) and Twitter (95 followers as of 10/28/11). We use these networking tools to announce blog posts and media coverage, to send reminders about Center-wide activities and deadlines, and to help maintain a sense of community. These pages are updated a minimum of 3 times a week.

Videocommunications systems. For our weekly Friday all-location meetings we use Polycom and Tandberg dedicated videoconferencing equipment, augmented by a central "bridge" at MSU (outside BEACON). The audience at all these sites can be seen and heard by the speakers to allow cross-campus interactions. A limited number of individuals can view/hear these meetings from their personal computers and even interact by telephone. For multiple-campus classes (two in the fall and one in the spring) we use the same videoconferencing equipment, but controlled by the local Polycom unit at the BEACON center at MSU. Also, this term we have purchased a set of iPads with video chat and "whiteboard" software to allow students to work in cross-campus small groups -- so far this experiment seems to be working well.

Formation of BEACON Student/Postdoc Association. The first goal of the BEACON undergraduate, graduate, and postdoc association is to promote communication, both within- and among BEACON institutions. Towards this goal, they have chosen liaisons at 4 out of the 5 partner universities, each of whom is planning to build a strong network among students and postdocs at their home institution. These groups will have regular social interactions such as "lunches and lab tours" to learn about different BEACON-related activities at their institutions. The group of liaisons communicate regularly in order to share successes and keep each of the sites connected. They also plan to elect representatives to the various committees within BEACON so that students and postdocs have a voice in the directions of BEACON. These representatives will receive feedback from and communicate to the entire body of BEACON students and postdocs about the activities of these committees. Additionally, the organization aims to use some of its funds to support between-institution travel outside that of funded projects in order to foster new collaborations and maintain a cohesive body of students and postdocs.

BEACON Organizational Baseline Evaluation Report. In fall 2010, Drs. Patricia Farrell and Marilyn Amey conducted a survey to evaluate the performance of BEACON management, and to set a baseline by which to judge our future improvement. In general, respondents expressed high levels of satisfaction with BEACON's mission, and felt connected and committed to the center. However, some respondents expressed concerns about communications and about how the center would actually carry out its mission. Respondents were also satisfied by BEACON's leadership, their ability to provide input into decisions, and transparency of the management, though a number of respondents felt there was room for improvement. BEACON management was generally viewed as promoting collaboration, inclusiveness, and collegiality. Trust and respect among BEACONites were also rated high. The evaluation helped us to identify challenges in the organization that we have addressed by creating the above-described communication systems, including email lists, websites, and social media feeds.

CENTER-WIDE OUTPUTS

Publications submitted: 106 reported

Conference presentations and other dissemination activities (including lectures, seminars): 91

Awards and Honors: 29 participants reported receiving awards and honors

Students that graduated: 4 undergraduates, 3 Master's, 5 PhD's

General outputs of knowledge transfer activities: 1 patent, 1 startup company

Participants: 222 participants, plus another 154 affiliates (under 160 hours/year in Center activities), for a total of 376 BEACONites

Media publicity: In 2011, we put out 10 press releases. At least 23 features on BEACON research appeared in the mainstream and online media in 2011, including *The New York Times*, Science Daily, Live Science, *Scientific American*, and NPR.

INDIRECT/OTHER IMPACTS

International activities: Five faculty members, one postdoc and one graduate student from outside the US (Denmark, Korea, and China) have visited BEACON for an extended period of time in 2011, each funded primarily by the visitor's host institution or a grant from their government. They are engaging in collaborative research with Director Erik Goodman and other BEACON participants.

II. RESEARCH

1a-b. Research goals, metrics, and progress.

Broadly, the Center's overarching research goal is to **produce transformative, synergistic research focusing on evolution in action through an inclusive collaborative culture** that crosses disciplinary and institutional boundaries and is embedded throughout the Center's activities. As described in the Management section of this report, BEACON's internal funding model is to provide competitive seed money for new projects, stressing the creation of interdisciplinary and inter-institutional collaborations that might not exist without the support of the Center. Evolution in action is a new and growing field, especially biocomputational studies in this area, and rather than focusing on a few large, expensive projects, BEACON supports a large number of studies that show potential to attract external funding.

Currently, a total of 49 research projects are supported by BEACON. In the narrative below, we provide a "big picture" overview of all of the research being supported by BEACON, fitting the projects into the broader context of our thrust groups.

Our specific research goals, as outlined in our Strategic Implementation Plan, fall into three broad categories: Integrative Research, Ethical Research, and Research Output. In this table we summarize our optimal outcomes and metrics from our Strategic Implementation Plan, and briefly note our progress towards these goals. For more details on progress, please see section 2b.

GOAL	METRICS	PROGRESS
Integrative Research Goals		
New research collaborations and proposals	Number of interdisciplinary/multi-institutional research projects and publications	At least 49 research projects underway
	Service by members on doctoral research committees across disciplines and institutions	Not yet measured.
New paradigms for research in organic and digital domains	Number of new sessions at scientific meetings or scientific meetings hosted at BEACON	BEACON is hosting the Thirteenth Artificial Life conference in 2012
	Number of new journals and societies	None to report
	New or increased funding for biocomputational research	BEACON researchers submitted 48 proposals for >$36M of external funding, and $8M in external funding has been granted

Increase in publications related to evolution in action	Number of BEACON faculty participants writing such publications and the number of citations of their work.	106 publications submitted
	Number of science publications about Evolution in Action authored by researchers outside of BEACON	Not practical to measure, so we are removing this metric from our strategic plan
	High visibility science journalism about BEACON research	33 press releases, articles in NYT, Live Science, Science Daily, and other major outlets
Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	Number of requests for information	5244 downloads of Avida-ED, 11,470 visits to BEACON website
Ethical Research Goals		
Center participants will understand shared and discipline-specific practices of Responsible Conduct of Research (RCR).	Percent completion of online training courses and face-to-face mentoring by participants.	Exceeded goal of 75% of participants to complete training by August 2011.
	Change in frequency of ethics violations.	No violations to report.
Center participants will embody general scientific norms/virtues, including objectivity, integrity, community, and transparency.	Baseline and follow-up participation in a Scientific Virtues workshop.	Toolbox workshops currently being tailored for use by BEACON teams. Scientific virtues workshop being planned.
Respect for views and ideas "horizontally" and "vertically."	Number of Toolbox seminars and trials	Toolbox workshops piloted at BEACON Congress August 2010; currently planning next steps
	Number of BEACON participants who get cross-disciplinary training	Toolbox workshops piloted at BEACON Congress August 2010; currently planning next steps
Research Output Goals		
Original research by BEACON members on evolution in action will be prominent in the evolution literature.	Number of publications in peer-reviewed journals, presentations at scientific conferences, and grant proposals submitted	106 publications submitted, 91 conference or other presentations, 48 grant proposals submitted

BEACON research output will be perceived as making an important contribution to the literature.	Feedback from the External Advisory Committee	Positive feedback. See Appendix C.

1c. Problems in making progress towards these goals.

The primary ongoing difficulty is enabling communication among researchers in different fields and institutions. We have a number of strategies in place to help overcome this problem:

- **Annual meeting**, with sessions designed to stimulate new collaborations: In August 2011, we held our second annual BEACON Congress, in which BEACON faculty, postdocs, and students were brought together to present ongoing research and discuss opportunities for new collaborations. In the first year (2010), we held "Birds of a Feather" sessions on various topic to bring together people with similar research interests. The feedback from that meeting suggested that a more structured approach would be more useful, so in 2011 we switched to a "Sandbox" format for these sessions. In a "**Sandbox Session**," a research problem is introduced, and a moderator is assigned to lead the discussion of possible ways to address the problem. This approach seemed to work well in several of the sessions at the 2011 meeting, though some people still expressed a desire for even more structure for these sessions, as well as more opportunities for casual, free-form interactions that would lead naturally to new collaborations. We are using the feedback from the 2011 Congress to further improve our 2012 Congress.
- **BEACON Intranet profiles**. We have implemented an intranet system (described more fully in the Management section) to track participants and outputs. As part of this system, every member has a profile. We strongly encourage people to choose research keywords to associate with their profiles, so that someone interested in finding a collaborator to work on, for example, "experimental evolution," can easily find all BEACON members with an interest in that area.
- **Weekly seminars**. We hold weekly meetings, which initially rotated through the three research groups and an all-BEACON session, in which members present the results of ongoing research. These seminars have more than once successfully sparked interest and led to new collaborations. At MSU, we follow the seminar with a "social hour," providing refreshments and an opportunity for casual interaction. We are working to institute the social hour at the other member institutions as well, as it clearly provides an incentive to students and others to attend the seminar and helps create a sense of community. In summer, 2011, in response to BEACONites' requests to know more about what is planned and ongoing in education and outreach activities, the seminar rotation was expanded to five weeks, adding one for reporting from education/outreach projects.
- **Technological solutions**. We have worked to improve the infrastructure at all 5 member institutions to ensure smooth long-distance communication, using **video** whenever possible. At BEACON headquarters, we have a seminar room and a conference room that are both fully equipped to communicate among all partners using Polycom (in the seminar room) or Adobe Connect and/or Skype (in both rooms). The other member institutions also have access to rooms with Polycom capabilities and use them on a regular basis for BEACON weekly seminars, classes, workshops, and other meetings.

Despite the communication difficulties, however, we feel that BEACON is making excellent progress towards its research goals.

We also have found that some of the metrics we initially proposed to monitor are extremely difficult in practice. For example, we have no mechanism to effectively track publications on "Evolution in Action" authored by people outside of BEACON. We will remove that as a trackable outcome from next year's Strategic Implementation Plan, although the overall goal is still very much in effect.

2a. Research thrust areas

BEACON research falls under three thrust groups, which are based on natural levels of organization: genomes, behavior among individuals, and community-level dynamics. These thrust groups are united by three cross-cutting themes: biological evolution, digital evolution, and evolutionary applications. Below, we describe research projects that are currently under way within each thrust group and their goals and activities.

Thrust Group 1: Evolution of Genomes, Networks and Evolvability.

The overall goals of this group are to understand the evolution of genome architecture and the processes that govern the production of genetic and phenotypic variation. A total of 20 projects are supported in this thrust group, which fall into a number of broad themes. Many investigators are studying the actual processes of speciation and adaptation: not just evidence that they have occurred in the past, but testing hypotheses about the way the process itself works. Other research themes include: evolution of gene networks underlying complex traits such as regeneration in hemichordates; applying evolutionary perspectives to synthetic biology; and the process and consequences of adaptation to environmental change. BEACONites are using a combination of techniques, including experimental evolution in biological and digital organisms, mathematical modeling and simulation, and integrating data from field and lab biology. Below is a summary of research in each theme.

Understanding the process of speciation

Research in this theme examines the genes involved in isolating populations into separate species, how speciation can occur with gene flow, and connecting so-called "microevolution" on a short time scale to the process of speciation over the long term.

Richard Lenski (MSU), Jenny Boughman (MSU), Barry Williams (MSU), and Luke Harmon (UI) are coordinating research in a number of systems to understand what Darwin referred to as the **"mystery of mysteries": the process of speciation**. This project focuses on the genetics of speciation, including the genetic basis of prezygotic and postzygotic reproductive isolation, and the genetic basis of ecological adaptations. The work focuses on rapidly speciating organisms in lab (*E. coli*), field (stickleback species pairs), and digital systems (AVIDA).

Richard Lenski and postdoc Zachary Blount have studied a population of *E. coli* that evolved the ability to grow on citrate, a previously unexploited resource, during the course of a long-term evolution experiment. The inability to use citrate is one of the identifying characteristics of *E. coli*, suggesting that a speciation event occurred in this experiment. The key question is whether these two lineages, Cit+ and Cit-, have diverged to the extent that their hybrids are maladapted. Lenski and Blount are testing this possibility by determining whether the Cit+ lineage is

accumulating niche-specific mutations that confer improved fitness on citrate at the expense of fitness loss in the ancestral glucose niche. As a first step, Blount has isolated Cit- mutants of Cit+ clones over a 20,000-generation time series. He will perform competition experiments to determine whether these Cit- mutants have, over time, lost fitness on glucose (the typical resource for *E. coli*), which would indicate that their Cit+ progenitors were accumulating mutations that reduced their performance on glucose. They have also identified a set of candidate Cit+ adaptive mutations, and will move these mutations into an early Cit+ genome and then perform competitions to verify that they confer a benefit in that genetic background. Those that are found to be beneficial in that background will then be moved into Cit- backgrounds. Blount will test the fitness of the hybrids, with the expectation that at least some of the citrate-adaptive mutations confer reduced fitness in the Cit- backgrounds. Identification of such mutations would demonstrate the evolution of genetic incompatibilities between the Cit+ and Cit- types. Such incompatibilities would constitute a barrier to successful genetic exchange and would thus indicate incipient speciation.

Jenny Boughman and postdoc Liliana Lettieri are working to uncover the genetic basis of traits conferring sexual isolation in stickleback fish species pairs, a model for speciation in action. Stickleback fish have speciated repeatedly within the past 15,000 years, an order of magnitude faster than is typically seen in other taxa. This work examines how sexual and natural selection together create premating isolation. They have collected phenotypic data on parental fish from the species pairs as well as F1 and F2 hybrids, on traits known or suspected to be important in sexual selection and reproductive isolation, including morphological traits (body size, shape, male color), behavioral traits (male aggressiveness, sociality, nest building, and courtship; female receptivity and preference). With these data, Boughman and Lettieri will estimate selection through male competition and female choice, and the level of premating isolation for the F2s. They will then test whether these two aspects of sexual selection act to maintain or erode genetic variation in mating traits. Over the coming year they will also generate genotypes for these fish in order to map both the traits and the fitness measures.

Barry Williams (MSU) and Luke Harmon (Idaho) are working to understand basic principles of the genetics of speciation using AVIDA as a novel means of inference. Williams, with graduate student Carlos Anderson, is testing whether adaptation of genomes to overcome the fixation of deleterious mutation can be a strong driving force behind post-zygotic intrinsic reproductive isolation. Not only do such “compensatory mutations” result in faster reproductive isolation than would occur by random genetic drift, but compensatory mutations exhibit stronger hybrid incompatibility than neutral mutations. Also, in response to recent publications in Science that attempted to test the snowball theory of speciation (pairwise hybrid incompatibilities increase with the square of time), Williams and Anderson addressed the same question with AVIDA, and were able to test the hypothesis more directly than any previous experiment. The snowball theory does apply to AVIDA, but incompatibility is just as often due to the lack of a full set of derived mutations in a hybrid as due to the combination of alternative derived mutations (i.e., speciation is due to the lack of a full complement of lineage-specific alleles). AVIDA also exhibits the well-documented biological phenomenon of a linear decrease in hybrid fitness over time (i.e., the “missing snowball”). They reconciled the missing snowball for fitness with the existence of a snowball effect for pairwise incompatibilities by demonstrating higher order genetic interactions that cannot be detected by searching for pairwise interactions. Hence, complex epistasis truly governs the genetics of speciation and pairwise snowball effects exist, but will only rarely provide a complete picture of speciation.

Finally, Harmon and Anderson have examined the compound effects of genetic drift, adaptation and migration on speciation. They find that in allopatry, drift and adaptation do lead to genetic reproductive isolation, but with even small amounts of gene flow, only very strong selection can overcome the homogenizing effects of migration. Future and ongoing work in this vein will examine factors that affect the probability of compensatory evolution and will compare the rates of reproductive isolation under adaptation to the external versus internal environment. Importantly, a new BEACON graduate student in the Williams lab will take this research in all altogether new direction, examining the capability to test hypotheses about gene trees versus speciation trees and the ability of evolutionary biologists to properly infer speciation process and pattern from genetic information.

Jenny Boughman, Tom Getty, Chris Klausmeier (MSU) are working to develop an **adaptive dynamic model exploring signal and preference loss and consequences for speciation**. This work is centered around the question: Can you get a loss of signal without loss of preference?

The goal is to create a model of how signal loss, through signal trait or preference changes, can spread through a population. Graduate student Emily Weigel, with Getty and Klausmeier, is working to code and replicate the results of an adaptive dynamics paper published in Science (2009) by van Doorn *et al.* The van Doorn *et al.* individual-based, 'good genes' model shows that natural and sexual selection can work in concert to drive speciation without requiring a divergence in preferences. Using this as the framework, the group has collaborated to identify and address specifically the implications of important, omitted factors, such as search costs, population size, and female age, on the predicted loss of signal. Several potential, mathematical/ theoretical works address these factors and could be integrated to fit this adaptive dynamics approach. Weigel has begun determining the coding language, model parameters, and theoretical framework(s) needed to proceed.

Postdoc Robin Tinghitella, with Boughman, pursued empirical work with sticklebacks, hypothesizing that variation in female mating decisions facilitates the loss of sexually selected traits, and further that some of that variation may result from environmental influences on traits, including experience like social interactions. They investigated the influence of operational sex ratio (OSR) and seasonality on mating decisions in two recently diverged species of stickleback (*Gasterosteus* spp.). In Enos Lake, British Columbia, a well-established limnetic-benthic species pair collapsed recently and rapidly (< 20 generations) into a hybrid swarm. Previously, divergent mate preferences and selection against hybrids were important for reproductive isolation in Enos. If social experience affects female mating decisions and that extends to heterospecifics, this has implications for the rapid evolutionary loss of nuptial coloration, the loss of species, and more generally, the evolution of reproductive isolation (in the forward direction). In a field study, the group found that the operational sex ratio (OSR) of limnetic and benthic stickleback varies temporally (across the season) and spatially (across lakes). Thus, variation in social experience exists in the field. In a follow-up laboratory study, the team is now manipulating mate availability by housing fish at different OSRs, and assessing preferences and choosiness each time females become gravid throughout the season.

David Hillis (UT) is examining **the role of gene flow in cattle genome evolution and the origin of New World cattle breeds**. Though species are typically defined as being

reproductively isolated, there are many examples of divergent groups that show evidence of historic or current gene flow. Domesticated cattle comprise several breeds that fall into two subspecies groups, *Bos taurus taurus* (first domesticated in Europe or the middle east) and *Bos taurus indicus* (domesticated on the Indian subcontinent). These two subspecies derived from independent domestications of the same progenitor species, the auroch. In this project, Hillis and graduate student Emily Jane McTavish examine the phylogeographic history of cattle breeds and assess the population structure of these breeds worldwide and determine the role of hybridization between the two subspecies in the origin of New World cattle breeds. Using 54,000 genome-wide single nucleotide polymorphism (SNP) data from 1428 individuals in 66 breeds from Europe, North America, South America, Africa and Asia, they determined that most cattle breeds are genetically differentiated, and that breeds derived from the two subspecies *Bos taurus taurus* and *Bos taurus indicus* show the deepest divergence. New world cattle show hybrid ancestry between *B. t. taurus* and *B. t. indicus*, likely due to the African heritage of their southern European cattle ancestors. Global patterns of cattle ancestry track known patterns of human movement.

The process of divergence in the presence of gene flow is also a focus in a project headed by James Foster (UI), David Hillis (UT), and Jack Sullivan (UI), in which they are **testing the divergence-with-gene-flow model of speciation** using both biological and digital systems. Determining the frequency and genetic impact of hybridization during animal speciation remains a central and unresolved issue in evolutionary biology. Recurrent hybridization among animal species has traditionally been viewed as a rare and homogenizing force. Alternatively, genetic factors underlying speciation, either via differential adaptation or sexual selection, may continue to accumulate between divergent populations despite on-going gene flow, eventually leading to lineage differentiation (i.e., speciation). This second model, divergence-with gene-flow (DwGF), predicts that closely-related taxa may retain differentiation despite high levels of hybridization and introgression. If DwGF is common, hybridization may be an important transient phase in speciation and introgression should be heterogeneous across the genome. In this project, graduate student Brice Sarver is testing DwGF *in vivo* with the chipmunk (*Tamias*) radiation, a group with many species pairs at different levels of differentiation, and graduate student Emily Jane McTavish is using computer simulations to explore the effect that interactions of various parameters (e.g., strength of recombination, size of recombining blocks, strength of selection at diverging loci) have on the dynamics of lineage divergence and the spread of reproductive incompatibility across the genome. McTavish will compare hypothesized dispersal trajectories to empirical data from chipmunks generated by Sarver to assess alternative hypotheses in this system. So far, they have completed sequencing of a reference mtDNA genome for *Tamias amoenus* and are developing capture arrays to assess selection on introgressed mtDNA genomes. Preliminary analyses suggest two loci, ND5 and ATP8, have high dN/dS ratios, suggesting a fast rate of evolution.

Joe Felsenstein (UW) and Luke Harmon (UI) are taking a broad view of the **long-term consequences of evolution in action** and working to connect the observable processes of evolution to a phylogenetic scale. Rates of long-term evolution ("macroevolution") are much slower than what one might expect given how quickly traits change over short time scales ("microevolution"). Despite the critical importance of linking micro- and macroevolution, the

two areas of study remain mostly separate. In this project, Felsenstein and Harmon are developing new statistical comparative methods to connect long-term patterns of evolutionary change with short-term studies of evolutionary processes. The first aim of the project is to develop methods that fit quantitative genetic models to comparative data. Current methods for analyzing comparative data are limited to heuristic models that are disconnected from biological processes. This project will develop methods to fit models that include measurable biological parameters, such as population size, mutation rates, and the mode and strength of selection. Second, they will use these new methods to test evolutionary hypotheses in five large datasets across the tree of life, from plants to lizards and mammals. This project will make much-needed connections between "evolution in real time" and "evolution in deep time."

Understanding the process of adaptation

These projects seek to observe and understand adaptation in action at a molecular level, focusing on issues such as the genetics of correlated traits, compensatory evolution, RNA and protein structure, and contingency loci.

Jenny Boughman (MSU), Luke Harmon (UI), and Bree Rosenblum (UI) are examining the **genetic architecture of multidimensional adaptation and speciation**. Divergent natural selection has long been recognized as one of the central processes leading to adaptation and speciation in the wild. Generally, evolutionary biologists study divergent selection on individual traits with adaptive value in novel environments. However, recent research suggests that selection in novel environments is often multidimensional - acting on many traits simultaneously, and that this multidimensional selection is necessary for adaptation to novel environments and for speciation to occur. The dimensionality of selection has far-reaching implications, particularly for studies that attempt to link genotype to phenotype and phenotype to fitness. In the last decade many studies have identified the genetic basis of individual adaptive traits in natural populations and we are beginning to understand the genetic architecture of such traits. However, little is known about the genetic architecture of multidimensional adaptation and how the genetic architecture may influence evolutionary change. This project integrates field, lab and computational approaches and focuses on two rapidly evolving groups, stickleback fish and White Sands lizards. In both taxa the team is studying a suite of traits, which are under correlated selection (*i.e.,* body color, body shape, habitat use, mate preference, and locomotor performance). This work focuses on the genomics of these adaptive traits in an effort to understand how and why they evolve together. In the first months of our project the group has initiated several genome scale projects for the White Sands lizards - most notably, a project looking at genomic islands of selection between ecologically diverging pairs of lizards. This will complement (and ultimately be integrated with) data from sticklebacks.

Christopher H. Chandler and Ian Dworkin (MSU) are using experimental evolution in digital and biological systems to examine **the role of sexual selection and standing genetic variation on compensatory evolution**. Organismal populations face a constant and continuous input of new, often deleterious mutations. Some of these mutations are filtered out by selection, but others persist or even become fixed, setting up the potential for organisms to evolve compensatory adaptations to these harmful mutations. The aim of this project is to test the

hypothesis that sexual selection increases the rate of compensatory adaptation, and to evaluate the relative contributions of standing genetic variation and new mutations in the process of compensatory adaptation. These questions are being addressed with two complementary experimental systems: *Drosophila melanogaster* and Avida.

In the *Drosophila* experiment so far, the team has selected and characterized a mutation affecting the development of the male sex comb, a male-specific structure crucial for courtship and mating success. This mutation has been introgressed into a wild, outbred population, and the effects of the mutation are variable and dependent upon the genetic background in which it occurs. Populations of flies are being evolved under different levels of sexual selection (mate competition in large cages vs. monogamous matings) and genetic variation (populations founded by either 2 or 200 individuals). After ~40 generations the team will use high-throughput sequencing to examine the genetic basis of any evolutionary response.

The team has added some features to Avida to test these hypotheses, including the ability for Avidians to have distinct sexes (males and females) that invest different amounts of resources into reproduction, and a framework in which individuals can assess multiple potential mates, providing an opportunity for mate choice and sexual selection to evolve. This system will allow not only testing of the original hypothesis, but also research on fundamental questions about sexual selection that are of broad interest to biologists.

Claus Wilke (UT) is **developing mathematical and simulation models that predict aspects of microbial adaptation**. Different regions of genes evolve at different rates in microbes like yeast and *E. coli*. For example, sites in a gene that correspond to buried regions in the expressed protein tend to be more conserved than sites that correspond to exposed regions. Likewise, sites that interact with other proteins tend to be more conserved than sites that don't interact but have otherwise similar properties. Thus, it is important to calculate local, context-specific evolutionary rates and to find biologically meaningful interpretations for them. The Wilke lab has studied how RNA and protein structure influence microbial evolution, and has developed a mathematical model of microbial evolution that can explain the puzzling linear relationship between evolutionary rate at individual sites in proteins and the relative solvent accessibility of these sites in the 3D protein structure. The linear relationship is puzzling because on average very exposed and very buried sites tend to be occupied by a smaller subset of amino acids than sites of intermediate solvent accessibility. The analysis has shown that even though sites of intermediate solvent accessibility are compatible with the widest range of amino acids, each individual site is more conserved than a typical exposed site. The mathematical model integrates the two seemingly contradictory observations into a single coherent theory.

Codons – the three-base-pair sections of genes that code for individual amino acids in a protein – evolve at different rates, given varying mutation probabilities at each of the three sites within a codon. These differences can have profound implications for constraints on the process of adaptation. As other BEACON studies have shown, digital evolution platforms are very powerful tools for studying the process of evolution. Thus, Julius Jackson and Erik Goodman (MSU) are working to **improve the encoding of instructions in digital organisms to increase evolvability**. Graduate student Gowon Patterson is creating a new virtual machine for the Avida platform that will be capable of representing organisms that carry out catalyzed chemical

reactions, rather than performing arithmetic computations, in order to receive rewards. This will enable research on questions about encoding (representation) in both biological and digital organisms, and understanding the non-uniform probabilities of mutation from any given genetic instruction to another.

Titus Brown (MSU), Linda Mansfield (MSU), and Jeffrey Barrick (UT) are looking at how a specific adaptation is possible, by examining **genomic mechanisms underlying increased virulence in *Campylobacter jejuni***. The enteric pathogen *Campylobacter jejuni* adapts quickly to its host environment, rapidly gaining virulence in serial transfers through a mouse model of campylobacteriosis. This gain of virulence appears to be caused entirely by mutations in contingency loci, homopolymeric tracts that experience frequent base insertion and deletions that alter gene sequence and expression. These loci have evolved to randomly toggle ON/OFF the expression of many virulence factors as a form of bet hedging against detection and clearance by the immune system. Previously, population-level resequencing showed that these were the only differences between a pre- and post-passage population, supporting the hypothesis that contingency loci generate genomic diversity that enables *C. jejuni* to rapidly evolve to exploit new host environments. This team is now sequencing other replicate *C. jejuni* lineages, already passaged through mice, as part of the same experiment, to determine whether or not the same contingency loci changes are responsible for adaptation in these populations. This project is the first to study bacterial evolution in action through rapid alteration of contingency loci.

Environmental change and adaptation

Another research theme addresses the role of environmental change in adaptation, including investigations into theoretical principles of adaptation using both laboratory and digital systems, and empirical studies of the response of organisms in natural systems to ongoing climate change.

Ben Kerr (UW) and Charles Ofria (MSU) are using digital evolution to understand **how changing environments affect the process of adaptation**. Adaptation is the process of populations becoming better suited to their environment. The process requires generations to pass to allow the fitter members of a population to displace inferior competitors. However, the environment for almost every population is unlikely to remain constant for any length of time, and may change during the course of a population's evolution. In this project, Kerr and Ofria are studying the implications of varying environments for the adaptation of populations therein, as well as how the nature of the environmental change (whether it is caused by the population itself or external factors) affects the ability of populations to adapt towards complex environments, using the Avida digital evolution platform as the study system.

The results of the first experiment by graduate student Joshua Nahum suggested that populations evolved under a “dynamic” treatment (that is, they were moved to a different environment, requiring new adaptations, in the middle of the experiment, and then back to the “reference” environment) were better adapted (had higher evolved fitness) in the reference environment than those that stayed in the reference environment for the full length of the

experiment. This affect may be due to the ability of populations to more efficiently move across adaptive valleys when the environment changes.

The next step is investigating the effect of evolving populations to affect their own environments, a process called niche construction. In a Negative Frequency Dependent treatment, the population members consume resources when they perform tasks, reducing the reward for other members of the population performing that task. Results suggest that allowing populations to consume resources also benefited adaptation with respect to the reference environment more than the static treatment, in which the population does not affect resource availability.

Kerr and Ofria are currently developing tools to analyze the adaptive landscape of the organisms in the different environments as well as expanding the scope of the original Frequency Dependent treatments. On the tools side, they are working toward a way to visualize/interpret the adaptive landscape near the transition points (moving between different environments) to better understand the reason for the improved adaptations in certain treatments. In a related study with graduate student Luis Zaman, they are using parasites within Avida to develop an alternative Frequency Dependent treatment that is entirely separate in mechanism from current methods, to corroborate explanations.

Kerr, with Eric Klavins and Georg Seelig (all UW) are also examining **the role of the *rate* of environmental change in evolutionary adaptation.** Much is known about the how populations evolve when shifted suddenly into a new environment. However, less is understood about how populations adapt to a slowly changing environment, versus one that changes rapidly. Do different mutational paths become accessible only in certain environmental states? In slowly changing environment, are population drawn to fitness peaks that, while attractive in the transitional environment, become less so in the final environment? In this project, experimental evolution is used in conjunction with genetic engineering to explore these and other questions.

Previously, the group evolved 1,103 *E. coli* populations over 170 generations by serial transfer into fresh media with the antibiotic rifampicin, the concentration of which differed according to treatment group. The three treatments were: 'Rapid' in which the populations were immediately transferred into the highest level of rifampicin; 'Gradual' in which the populations were slowly exposed to the antibiotic, reaching a level fatal to the ancestor halfway through the treatment and the highest level at the end; and 'Moderate' in which the populations reached the level fatal to the ancestor 1/4 of the way through the treatment and the highest level at the halfway point. The Gradual and Moderate exposures resulted in much higher survivorship (90% and 44% of populations at final transfer, respectively) than Rapid exposure (2%). Gradual and Moderate populations also had a greater variety of mutations and a greater frequency of multiple mutations in the gene of interest rpoB (a subunit of RNA polymerase to which rifampicin binds) than the Rapid populations, which had only a single mutation per population. From these preliminary findings, it is easy to imagine a scenario in which a mutation arises early on in a Gradual population, conferring resistance to a low level of rifampicin. This population would have been immediately selected against in the Rapid treatment, but in the Gradual it is able to persist and acquire other rpoB mutations that together allow the population to survive in the final, highest rifampicin environment. The mutational pathway taken by this population could have been completely inaccessible in the Rapid treatment.

After identifying a few candidate Gradual and Moderate populations with multiple rpoB mutations, the group used a genetic engineering protocol to construct multiple mutants and all their possible intermediates by transforming the mutagenic plasmid into the ancestral background, selecting for homologous recombination into the chromosome, and then counter-selecting for excision from the chromosome. Using this process they have now constructed a Moderate double mutant and all its possible intermediates and are working on a spectrophotometric assay to test the fitness of the constructed mutants relative to their ancestors across a spectrum of rifampicin concentrations. The next step is to construct mutants of the candidate Graduals and Moderates, as well as a few of the Rapid single mutants for contrast. Once the fitness protocol is finalized, the growth rate of the constructed mutants over the range of rifampicin levels they experienced during the evolution series will be measured. They will also sequence isolates from our chosen populations at various time points along the evolution series. Together, these data will lay out all the evolutionary pathways that were theoretically possible to get to a certain final genotype, as well as the pathway that was actually taken.

BEACON researchers are also working to understand the rapid responses of organisms to current climate change. Virginia Armbrust (UW), Chris Klausmeier (MSU), and Elena Litchman (MSU) are studying the **rapid evolutionary responses of marine phytoplankton to rising temperatures**. Marine phytoplankton are globally important primary producers contributing ca. half of Earth's carbon fixation. Diatoms are the dominant players in marine phytoplankton, generating approximately 20% of global primary production and forming the base of marine food webs. Due to their large size and weight, they contribute a disproportionately high amount to carbon sequestration in the oceans. Global climate models predict a rise in mean ocean temperatures of up to 3°C this century under a business-as-usual scenario. Diatoms experience drastic fitness changes over small temperature ranges, and this rise in temperature could have negative effects on their populations and global carbon sequestration. It is likely, however, that diatoms will be able to adapt to rising temperatures. Such adaptation is likely to involve complex trade-offs in cellular investment and eco-physiological strategies, requiring interdisciplinary research approaches. This project takes a three-pronged approach to unraveling the mechanisms of evolutionary responses of marine phytoplankton to rising temperatures.

First, the team has characterized thermal niches of several strains of diatoms and run laboratory evolution experiments with individual clones of ecologically important diatom species and clone mixtures to determine the nature of adaptation (either through increased temperature optima, growth rate at higher temperatures, change in niche width, etc.). The team, with graduate students Colin Kremer and Mridul Thomas, gathered data on thermal responses from 170 strains of marine phytoplankton isolated from a wide range of locations in the world ocean, from polar to equatorial regions, and determined the temperature optima and thermal niche widths for these strains. The data reveal a significant latitudinal gradient in optimum temperatures, suggesting local adaptation of strains on a global scale and physiological trade-offs in temperature optima, niche widths and maximum growth rates. Thermal niche widths were also significantly positively correlated with the range of temperatures experienced at the isolation location. The evolution experiment will begin this fall with several strains of *Thalassiosira pseudonana*, a marine diatom with a sequenced genome. Next, the group will investigate the genetic basis of such adaptation by comparing the genomes of ancestral and evolved populations and identify candidate genes responsible for thermal adaptation in phytoplankton. Finally, the team will use

adaptive dynamics models to predict the most plausible routes of evolution under different environmental scenarios.

Idelle Cooper (MSU), Molly Cummings (UT), Thomas Getty (MSU), Chris Klausmeier (MSU), and Muraleedharan Nair (MSU) are using computational and empirical approaches to understand **rapid evolution of damselflies in response to anthropogenic change**. Understanding how contemporary evolution in action will mitigate or exacerbate the impacts of anthropogenic change on biodiversity is a critical research need that requires investigation at many levels within nature, from the cellular and biochemical level within individuals to dynamics within populations and to interactions between species. This project combines empirical research at all these levels with computational modeling to understand and anticipate the potential impacts of global change on the evolution and biodiversity of Hawaiian damselflies. The "Beautiful Hawaiian damselfly," *M. calliphya*, presents an ideal opportunity to address direct effects of anthropogenic change because color variation in this species is correlated with solar radiation levels. Males are red and defend mating territories around open water, and females are either red or green, depending on elevation and forest canopy cover. Red pigmentation in both sexes is prevalent under high solar radiation and may function as an antioxidant. Free radicals produced under high UV can cause tissue damage and mutation, making antioxidant production an important adaptation in plants and animals under stressful abiotic conditions. By determining how the red pigmentation in the Hawaiian damselflies influences survival, mating success, and species distributions, computational modeling can be used to predict how changes in UV exposure will affect biodiversity in this system. Three specific goals will integrate our understanding of evolutionary change at multiple levels (biochemical, population, and species).

The first goal is determining the biochemical basis of *Megalagrion* damselfly pigmentation. Preliminary work indicates that the pigment is a secondary metabolite like other antioxidant pigments, and its expression is likely influenced by a genotype (red, green) and environment (UV exposure) interaction. The pigment origin, structure, and expression may enable rapid evolution of the *Megalagrion* genus to a changing climate, but may also be applicable to phytoceutical research. Continuing work will examine the protein composition of the red and green pigments using high-performance liquid chromatography (HPLC) and include assays to determine antioxidant function of the pigments. The second goal is to quantify *Megalagrion* distribution and selection relative to UV, and build computational models to predict range shifts during anthropogenic change. Extensive surveys of *Megalagrion* species distributions and body color relative to UV levels were conducted, and natural selection on pigmentation was measured in one species in a caged experiment. With the additional data for rare and disappearing species, Klausmeier, Getty, and Cooper will build a computational model of range shifts. The third goal of this project is to measure variation and selection on coloration in two local damselflies species that underwent a recent range overlap, *Calopteryx maculata* and *C. aequabilis*. While we are interested in how species may persist through trait changes or species distribution changes, these responses will also affect species interactions, particularly because color is often used as a sexual signal for mating or species recognition. Cooper and Getty measured geographic variation in wing and body pigmentation in the overlapping ranges of sister species *Calopteryx aequabilis* and *C. maculata*. This survey extended over 4800 kilometers through the Midwest and Canada. These data indicate that the species range of at least one of the species, *C. aequabilis*, has shifted

north by several hundred kilometers in the last 35 years. Additionally, preliminary data on sexual selection indicate that wing pigment is a signal of species identification and that shifts in ranges could lead to hybridization between allopatric populations of the two species.

Interactions among genes

Several BEACON projects are focused on the way genes interact, including describing patterns of epistasis in biological systems and uncovering the mechanisms of changes to gene networks underlying complex phenotypic traits.

Robert Heckendorn (UI) is examining **the influence of epistasis on artificial and natural evolution**. Epistasis is the influence of one gene on the fitness of another and is a critical factor in determining the structure of the fitness landscape upon which evolution operates. Although many examples of epistasis in biological systems exist, the roles played by epistasis in the grand scheme of evolution are poorly understood. Epistasis is also a critical confounding condition of combinatorial and numerical optimization problems. This project will combine expertise in epistasis in optimization problems with an understanding of biological epistasis and will further the understanding of epistasis in problem optimization, evolution of antibiotic resistance, ontogenesis, etc. Heckendorn's sabbatical leave at MSU in 2011-12 will provide ample opportunities for collaboration with BEACON biologists. The primary goals are to use mathematics and tools developed in the Computer Science field of Evolutionary Computation to search for higher order epistasis in natural (biological) systems, and to test the hypothesis that most natural evolutionary systems are faced only with problems of low epistasis.

Several BEACON studies are looking at a specific, complex trait to understand interactions among genes and gene networks. Billie Swalla is studying the process of **gene network activation during hemichordate development and regeneration**. Unlike many chordates, some hemichordates have a remarkable ability to regenerate. The Hawaiian acorn worm *Ptychodera flava* is one such example, capable of regenerating entire anterior and posterior structures when amputated in half. Such structures include the anterior heart-kidney complex and central nervous system. Further, in addition to elucidating the origins and evolution of chordates, the study of hemichordate regeneration **may benefit human health**. Hemichordates are deuterostomes and share many developmental genes with vertebrates, including humans. In this project, Swalla and postdoc Charlotte Konikoff are determining which developmental signaling networks are necessary for *P. flava* regeneration and identifying additional candidate genes that may also play a role. So far, they have cloned a subset of developmentally relevant genes (including BMP2/4, multiple Wnt genes and Shh) from *P. flava*. To investigate if these genes are indeed crucial for regeneration, they will use drug treatments to activate or inhibit these pathways and examine how gene expression is altered via *in situ* hybridization in *P. flava* and in *Saccoglossus bromophenolosus*, a hemichordate incapable of regeneration. To discover additional candidate genes that may participate in hemichordate regeneration, they will perform a comprehensive transcriptome analysis to examine global transcription levels in control and regenerating *P. flava*.

In another study of a complex trait, Billie Swalla (UW) and C. Titus Brown (MSU) are studying **genomic mechanisms underlying the loss of tails in the Molgulids**. The Molgulid clade of ascidians (commonly known as sea squirts) contains multiple species that have at least three times independently lost tails during their larval stage. While the vast majority of the 3,000+ described species of ascidians develop swimming tails, replete with muscles and notochord, 15 of the 150 Molgulid species have lost a larval tail, suggesting that there is some genomic preadaptation for tail loss. Extensive prior investigation of two Molgula, *M. occulta* (tailless) and *M. oculata* (tailed), and their hybrids, has demonstrated that the loss of the tail in *M. occulta* is most likely due to loss of function mutations. Moreover, this loss of function may have been potentiated at the base of the Molgulid clade by genome rearrangements. Studying the Molgula can lead to insight into the mechanisms by which significant changes to gene networks occur; how downstream components of gene networks change with upstream changes; and how genomic changes lead to changes in evolvability. Swalla and Brown are using high-throughput expression analysis of mRNA sequence from early developmental stages of hybrid embryos to detect allele-specific expression differences between *M. occulta* and *M. oculata*. Specifically, they will produce hybrid embryos; do quantitative sequencing of mRNA with 454 and/or Illumina sequencing at cleavage, mid-gastrula, and early neural stages; and analyze the expression levels of mRNAs to determine which coding variations display allele-specific expression variation. These markers would then provide an opportunity to do either localized genomic sequencing or hypothesis-driven whole genome sequencing in order to determine the precise genomic changes that led to the transition from a urodele to anural mode of development. The ultimate goal is to produce a detailed hypothesis for the urodele-to-anural transition and root it in molecular mechanisms of evolved gene networks through transcript and genome analyses. The genomes of these closely related molgulids are small and compact, with the largest intron and/or intragenic space being <1kb. Therefore, genome analyses combined with expression data are likely to yield interesting insights into the evolution of morphology.

Phenotypic plasticity refers to the ability of a single genotype to express multiple phenotypes dependent upon environmental differences. Alexander Shingleton (MSU) and Herbert Sauro (UW) are examining **the regulation and evolution of plasticity pathways**. Plasticity pathways transduce environmental information to developmental processes resulting in phenotypic variation. Nevertheless, we have very little understanding of how the structure of such pathways amplifies or attenuates environmental signals to regulate developmental processes. The goal is to model the function and evolution of plasticity pathways *in silico* and subsequently test these models *in vivo.* The team is using the well-elucidated insulin/IGF-signaling (IIS) pathway to achieve this goal. The IIS pathway regulates body and organ size with respect to nutrition in all animals and the pathway has evolved so that, within a species, some morphological traits are more nutritionally plastic than others. The proximate changes underlying this evolution are, however, unknown. The specific aim is to generate a mathematical model of the IIS pathway, evolve this model *in silico* using different levels of plasticity as an objective function, and predict which components of the pathway are likely targets for selection on plasticity. These predictions will be tested using experimental data from existing wild-type and artificially-selected *Drosophila* lines that show evolved variation in nutritional plasticity.

So far, the team has constructed and evaluated a model of the IIS pathway. Model simulations are consistent with published data and indicate that the changes in the expression

levels of components of the IIS pathway can amplify or attenuate variation in an environmental signal. More intriguingly, the model has generated new insight into the influence that feedback loops have on the robustness of transducing a variable environmental signal. In short, negative feedback loops ensure that the pathways maintain the amplitude of a variable environmental signal over a wider range of pathway states, a form of robust plasticity.

The next step is to explore what insights the model generates about how the pathway evolves. Selection for an increase or decrease in plasticity can occur by targeting the expression of specific genes within the IIS pathway. Nevertheless, the model suggests that changing the expression of many genes will have a similar effect. Why then has selection targeted these specific genes? The team hypothesizes that this may be because of how changes in gene expression influence the robustness of the pathway to accurately and precisely signal variation in an environmental signal, and is in the process of exploring this hypothesis.

Synthetic biology

Several BEACON researchers are introducing an evolutionary perspective into the field of synthetic biology, using experimental and directed evolution to evolve synthetic genomes and genetic circuits.

Holly Wichman (UI) and Andrew Ellington (UT) are exploring **evolution of synthetic genomes**. Synthesized genomes have been mostly a recapitulation of those that appear in nature. This is understandable, since to achieve even this goal of mirroring nature has been a daunting feat. For example, a single base error in the synthesis of the *Mycoplasma mycoides* genome delayed successful transfer into *M. capricolum* by 3 months. Yet moving to the next step of engineering genomes for designer functions, and using parts cobbled together from a wide variety of sources, will require consideration of many evolutionary and ecological issues. In some cases – for production purposes, for example – one might desire a high fitness organism; an evolutionary perspective is necessary both to engineer and to improve fitness of a synthetic genome. In other cases – to produce a vaccine, for example – a low fitness genome may be desirable; an evolutionary perspective is necessary both to engineer and to prevent adaptation of a low fitness synthetic genome. In order to examine some of these issues, and also to begin to uniquely apply evolutionary perspectives in synthetic biology, the group will produce synthetic bacteriophage genomes, express phage from these genomes, assess their fitness, and examine their evolution over time. The model system is Microvirdae bacteriophage grown on *E. coli* C. Their ssDNA genomes are 5.4 to 7 kbases, making them ideal for these studies. The gene functions and structures of the capsid and procapsid are known, and this is a widely used model system for experimental evolution.

Herbert Sauro is (UW) is using **directed evolution to optimize mutational robustness of genetic circuits**. Synthetic biology involves the engineering of cells with genetic circuits to perform a function that does not exist in nature. One problem with genetic circuits is their stability over evolutionary time in the absence of a selective pressure. Sauro and postdoc Sean Sleight are using part shuffling and mutation randomization to engineer genetic circuits and then use a directed evolution approach to identify circuit designs that are the most robust. Part

shuffling involves developing a novel PCR-based assembly method to shuffle the biological parts (e.g. promoters) in genetic circuits. Mutation randomization involves randomizing parts via mutagenic PCR in order to change parts at the sequence level. New engineered circuits will be transformed into *E. coli* and evolved via serial transfer. Using directed evolution, circuits that are the most robust over evolutionary time will be selected and the part shuffling and randomization methods will be re-applied to these circuits for at least 5 cycles. This evolutionary approach is expected to lead to re-engineering circuits that are more robust than can be designed rationally, give insight into the evolutionary dynamics of genetic circuit stability, and lead to the development of improved design principles for engineering mutationally robust genetic circuits.

Since the introduction of foreign metabolic pathways into *E. coli* usually results in an increased metabolic load and decreased fitness, these pathways are often mutationally unstable. The lycopene biosynthesis pathway consists of three foreign genes from Pantoea ananatis (crtE, crtB, and crtI), and when it when inserted into *E. coli*, it is sufficient for the cells to produce lycopene (as seen by a visible red color). Sauro and Sleight randomized the RBS of the first gene in the pathway, crtE, for the first round of directed evolution. Eight clones with varying degrees of red pigmentation were picked, grown overnight, and saved in the freezer for future study. A pilot evolution experiment was performed using these eight clones to determine the most mutationally robust clone or clones for the first round. The pigmentation was relatively constant after 50 generations in all eight populations. This increased stability is likely because the RBS randomization method creates a weaker RBS, decreasing translation of the first enzyme in the pathway, and thereby decreasing metabolic load. In subsequent rounds of directed evolution, the "winner" of each previous round will have the RBS of the second, third, and fourth genes in the pathway randomized. The evolutionary stability dynamics and loss-of-function mutations in the winners and losers of each round will then be compared. By the end of the fourth round, the experiment should result in a clone that is substantially more mutationally robust than the original. The results may lead to a better understanding of the evolutionary dynamics of foreign metabolic pathways in *E. coli*, development of design principles for engineering robust circuits, and be useful for industrial purposes (e.g., the production of biofuels).

Thrust Group 2: Evolution of Behavior and Intelligence.

Research in thrust group two focuses on the evolution of behavior of individuals, both in relation to the environment (e.g., navigation, foraging) and in relation to each other (communication, risk avoidance, cognition and social dynamics). Digital evolution has proven to be a powerful tool in which data gathered from biological organisms can be applied to recreate the evolution of complex behavior in digital organisms. By observing the evolution of self-replicating digital organisms, we can understand the conditions that led to the evolution of complex behaviors in biological organisms. Another major theme in this thrust group is using evolutionary computation to create better, smarter electronic and robotic systems, such as dynamic control systems that respond to the environment, improved detection systems for security, and robots that can navigate on their own through environments that may change unpredictably.

Currently 12 projects are funded in this thrust group, and can be grouped into two broad areas: 1) 1) Biocomputational studies of the evolution of behavior; 2) Engineering applications that are evolving smarter electronic and robotic systems.

Biocomputational studies of the evolution of behavior

Research projects in this theme combine biological and computational techniques to understand the evolution of such complex behaviors as cooperation, navigation, and sociality.

Kay Holekamp (MSU), Benjamin Kerr (UW), and Risto Miikkulainen (UT) are working on a project to understand **the evolution of cooperation among competing predators**. This project is a collaboration of biologists and computer scientists, focusing on understanding, on one hand, how certain complex behavior in hyenas can be understood as arising from evolutionary processes, and on the other, how such behaviors could be established in artificial intelligent agents, such as those in videogames.

Spotted hyenas of Eastern Africa often hunt alone, but occasionally cooperate to catch zebras. Using hyenas as inspiration, Holekamp, Miikkulainen, and Kerr evaluated three potential factors that affect the evolution of cooperation in a team of game agents: reward structure (whether fitness reward is given to an individual agent or shared by the team), coordination mechanism (stigmergic [indirect] vs. direct communication), and net return (the size of reward relative to the difficulty of obtaining it). Through neuroevolution using "Multi-Component ESP," three predators were evolved in a field containing multiple fixed-behavior prey. Six such experiments showed that (1) although shared reward strongly promotes cooperation, it is not strictly necessary for evolving cooperation; (2) although stigmergic coordination works well in simple, unambiguous tasks (*i.e.,* with a single prey), direct communication is more effective in more complex tasks (multiple prey); and (3) the predators evolve to hunt alone or cooperatively based on which approach results in higher net return. Insights from these computational simulations can be used to develop more intelligent behaviors for video game agents in the future; they also constitute a computational explanation for the observed cooperative hunting behaviors in hyenas.

A parallel stream of research focuses on the role of communication in establishing cooperation among the hyenas and intelligent agents. Students extracted data on over 600 lion-hyena interactions from archived field notes and video footage from the Mara Hyena Project. Three data sets describe 1) the context, duration and outcome of each interaction, 2) the participation by, and risks and pay-offs for, each individual hyena present at each interaction, and 3) the communication signals emitted by each individual to facilitate coordination of group attacks on lions. Data for each interaction also include the number of lions and hyenas present, the age and sex of each lion present, the individual IDs of each hyena, the source of the conflict (food, dens, etc.), whether the hyenas mobbed the lions, and how frequently and which individual hyena participated and led each mobbing event. The dataset also includes information on whether the hyenas successfully drove away the lions and, when applicable, if they acquired the food and which of the hyenas fed and how long. These three data sets will be integrated into the larger ACCESS database maintained by the Mara Hyena Project, and will be analyzed by graduate student Marc Wiseman this fall as part of his participation in Ian Dworkin's class on

quantitative methods. In the coming year, such a characterization of hyena behaviors will be used to guide and constrain computational modeling, aiming at a theory of the role of communication in these particular cooperative behaviors.

Philip McKinley and Chris Waters (both MSU) are also using **biocomputational techniques to study the evolution of cooperation** – in this case, **in bacteria**. This project couples *in silico* evolution experiments using artificial life systems with *in vitro* studies of specific bacteria (*Vibrio cholerae* and *Vibrio harveyi*) to characterize complex collective behaviors, such as biofilm formation and quorum sensing (QS), which are integral to many bacterial functions. Biofilms are the dominant form of bacterial growth in natural environments, but their shielding properties make them a serious problem in human health, agriculture, and the operation of mechanical systems. An NIH report estimates that 80% of all infections involve biofilms, as the biofilm matrix helps to protect the bacteria against antibiotics and the host's immune system. QS is a collective signaling behavior whereby actions of individuals depend on the density of the surrounding population – for example, bioluminescent microorganisms only expressing light when the population is sufficiently large.

The team first evolved a cooperative process in Avida analogous to biofilm formation, with different levels of resource available. The Avida platform revealed a sigmoidal response and the rapid transition between non-cooperative and cooperative states, when the resource level reached a critical threshold, decreasing the relative cost of cooperation. According to Hamilton's rule, cooperative behavior is then favored. The Waters Lab tested this novel finding using *V. cholerae*, where biofilm formation in the presence of increasing environmental resources showed a sigmoidal response strikingly similar to what we observed with Avida. These results are significant because they show that bacteria induce biofilm formation more akin to an all-or-none strategy as opposed to intermediate states.

The team has also initiated an experimental evolution approach in the model QS system, *Vibrio harveyi*, to study the evolution of cheater cells over time. *V. harveyi* expresses bioluminescence at high cell density in a QS-dependent manner. Serial passage of *V. harveyi* through a host was hypothesized to lead to the evolution of dark cells, which might represent cheaters or freeloaders that do not participate in high-cell-density cooperative behaviors. Unexpectedly, serially passaged wild-type *V. harveyi* did not give rise to light-deficient cheating cells, judged by the maintenance of QS-regulated production of bioluminescence, after several hundred generations. To further explore this result, the locked low-cell-density (LCD) QS mutant strain luxO D47E, which is dark, was serially passaged. After 140 generations, light-producing revertants emerged, and these revertants eventually swept through the population. However, based on luminescence production, these revertants appear to exhibit a locked high-cell-density (HCD) phenotype. These results suggest that QS in *V. harveyi* is more robust and resistant to invasion by cheating than previously predicted, and that *V. harveyi* harboring the QS system may enjoy resulting fitness gains. These findings suggest that in addition to promoting cooperative behaviors, QS systems also provide individual fitness benefits.

Continuing and future investigations include the development of a new artificial life platform, SEEDS, that enables users to capture the spatiality of positive interactions among organisms, such as intraspecific cooperation and interspecific facilitation. Previous work has highlighted the importance of spatial structure in explaining these behaviors as well as its role in

maintaining biodiversity. This method allows for a more fine-grained examination of the effects that increasing interactions have on maintaining diversity. In addition, the SEEDS platform enables the development of a spatial model to examine how conjugation, one mechanism of horizontal gene transfer, can be maintained in populations. Future studies will use SEEDS results to help explain observed behavior in bacteria and to inspire new wet bench experiments with both model organisms.

Chris Adami (MSU), Fred Dyer (MSU), Robert Heckendorn (UI), Benjamin Kerr (UW), Charles Ofria (MSU), and Robert T. Pennock (MSU) are working together to examine the **Foundations of Intelligence,** specifically looking at **behavioral flexibility in a spatial context.** This group has studied several aspects of behavioral flexibility in Avida and other evolution-focused software systems. The long-term goal is to evolve dynamic organisms that are able to navigate through a complex environment, form stable groups, and cooperate in those groups.

Evolution of Navigation. The group set up environments where organisms must collect resources in one geographic location and use those resources to reproduce in a different location. Results show that (I) organisms tend to perform the task in a modular fashion: Module A - Find a region with food. Module B - collect sufficient food. Module C: return home to reproduce. (II) Timing for moving from one module to the next was governed by either the life-cycle of the organism or inputs from the environment. (III) High-fitness organisms in one organism also tended to have high fitness in slightly different environments.

Evolution of Tolerance. Organisms evolve to be tolerant or intolerant of others based on their need to defend resources. If resources are too scarce, organisms remain tolerant because they cannot afford the cost of decreasing tolerance; if resources are plentiful, organisms remain tolerant because there is no reduction in fitness when resources are shared; if resources are at a mid-level, however, organisms become less tolerant of others and protect their limited resource supplies.

Evolution of Behavioral Plasticity. The team developed a heterogeneous resource environment in which organisms must forage to find a (roving) resource patch and navigate back to a nest to reproduce. Movement of resources and collisions between organisms require dynamic responses. Organisms proved capable of this flexibility when accurate sensors could inform them of the nest position, but failed to find efficient solutions when they needed to remember the nest location. The team is now evaluating the efficacy of more complex and flexible hardware for evolving more intelligent navigators capable of solving this hidden nest challenge.

Evolution of Range Formation & Grouping. The group is now working toward evolving spatial groups among range-forming predators in a spatial, predator-prey environment. In patchy-resource environments, we have seen clear signs of range formation and range clumping among predators, phenotypic divergence between predators and prey, and a coevolutionary race between them. They now have the bases for a single line of inquiry, which will ultimately allow direct tests of evolutionary and ecological models of spatial group formation, group stability, intra-group cooperation, and sociality.

Albert Esterline (NCAT) is working to **model the genesis and stability of social norms** using agent-based modeling and genetic algorithm (GA) techniques. Esterline and MS student Austin Blackmon are converging from the two extremes in software agents: agents with very simple behaviors as used in agent-based simulation, and agents as supported by APIs for complex behaviors, agent communication languages, system support, and many other features. Norms are viewed in terms of ideal behavior. For example, actual behavior may violate an obligation or prohibition. Formalism is provided by deontic logics, one version of which typically has a formula such as $Oa\phi$ to express that it is obligatory of agent *a* ϕ. Permitted behavior is expressed for *a* ϕ as $\neg Oa\neg\phi$, and that it is forbidden of *a* ϕ as $Oa\neg\phi$. Agent behaviors will be represented with simple state machines, where some states are ideal ("green"), and some non-ideal (violation or "red"). A collection of agents has a joint task, and reward depends not only on achieving goals but also on avoiding red states. (Non-ideal behavior is possible but is penalized.) If an agent enters a red state, it must recover from the violation (generally at some cost). A speech act may occur at a transition and is required to trigger a transition in another agent's behavior. Certain performatives establish obligations, which must be discharged by a later transition. Co-evolution will drive random sampling of the joint behavior space. Note that obligations, permissions, and prohibitions may exist at least at three levels: those applying to all agents, those applying only to agents fulfilling certain roles, and those applying to specific agents in given social situations usually as the result of speech acts (and which are generally too specific to count as norms). The current effort is directed to coding agents as simple state machines whose behavior is subject to GA operations and that involve states that, while accessible, carry a penalty, representing situations that are possible but not ideal. Such situations relate to violations of prohibition norms (equivalently, violations of obligations not to do something). What are sought are populations that converge to desirable behavior that is self-enforced, possibly with different sub-populations assuming different roles (that is, behaving differently in similar social situations).

Evolving smarter electronic and robotic systems

Engineering research in this area is focused on using evolutionary computational techniques to develop better applications, as diverse as home assistance robots, ambulatory prosthetics, computer security systems, greenhouse controls, and cancer detection systems.

Two of these projects focus on systems to help the elderly or disabled. Abdollah Homaifar (NCAT) is working on the design and implementation of an **assistive robotic residence home**. Homaifar is designing a fully RFID (radio frequency identification) augmented home setting with an assistive robot that interacts meaningfully with that environment and residents through its sensors and RFID antennae. The robot is required to improve the quality of life of the cognitively impaired living in the house by running errands. It does this by learning to decide on and execute some daily activities such as searching for items e.g. gadgets, drugs, food items, literature, etc.; giving indoor directions, etc. The knowledge acquired from the RFID fully augmented environment will then be deployed in a RFID partially augmented home. The robot has full or partial knowledge of targets and partial knowledge of target location. Thus, learning and decision-making are integral parts of this project.

Currently, Homaifar and his students are investigating evolutionary learning algorithms and developing a hybrid evolutionary learning algorithm capable of robust learning of common household items features and decision-making routines. Consequently, the assistive robot should be equipped with a vision system to aid maneuverability and recognition. Thus, they are developing a hybrid hierarchical blend of low-level and high-level object segmentation and recognition techniques capable of robust and near real-time recognition of some selected household items and actions. Work so far has focused on self-localization, path-planning in an environment with obstacles, and learning. The learning aspect of the research so far has mainly focused on designing a hierarchical learning algorithm using learning classifier systems (LCSs), a form of evolutionary computation. To this end, a fast, compact and robust decentralized loaning-based bidding strategy is implemented to expedite the rate of learning (convergence to optimal solution set). Research on achieving a viable default hierarchy formation and evolving mechanisms for even more compact rule representation in LCS and investigation of Niching Genetic Algorithms is currently ongoing.

Gary Lebby (NCAT) is working on **evolving artificial neural networks for control of ambulatory prosthetics**. The world's population is aging at a phenomenal rate. Risk factors that lead to a diminished quality of life involve: chronic health conditions, physical and functional impairments, medication and alcohol use, and environmental hazards. In accommodating an aging population, end-users could benefit greatly from devices that can sense the user's informational needs and adjust the parameters of their sensors to optimally meet these needs in an autonomous fashion. The interaction between the system and human must be carefully addressed to make the autonomy and reliability truly possible. This task involves the development of a cooperative set of biological interfaces between the human operator and the robotic assistants that enable a smooth and transparent symbiotic relation to exist, where the human operator's informational needs are sensed and internal system parameters and sensor inputs are adjusted to meet these needs optimally in an autonomous fashion.

Electroencephalographic signals were captured from human subjects (19 nodes collecting data at a rate 250 samples/sec for approximately 30-45 seconds.) This equates to 142500-213750 observations for one pass. When considering parallelizing we have to ensure that problem is indeed parallelizable, meaning there are no dependent calculations rather than independent ones. The program's hotspots and bottlenecks should be identified so the parallelization may be used more efficiently. Hotspots are where most of the real work is being done. Lebby and his students are pursuing the first steps in designing parallel algorithms to handle tasks responsible for the assistive robotic actions. Over the first year, the focus was on identifying evolutionary algorithms and concepts that could be used in the structuring and training of different neural networks. The research resulted in a method for modeling short-term power flow using a support vector machine whose structure is determined using simulated annealing.

Another project has important medical applications. John Deller (MSU), Erik Goodman (MSU), and Yao Meng (East China Normal University, visiting in BEACON) are developing **evolutionary algorithms for enhanced ultra-wideband microwave imaging of breast cancer tumors**. Near-field tomography medical diagnosis of breast tumors has been the hotspot of breast cancer non-invasive diagnosis for decades. Compared to the traditional diagnostic method

of soft X-ray mammography imaging, microwave near-field tomography is a safer method of imaging diagnosis of breast tumors, producing no detectable damage to the human body. Breast tumor medical imaging diagnosis requires determining the target location on a contour line or in a defined context. In the case of microwave imaging, the imaging is based on differences between the dielectric properties of normal breast tissue and malignant tissue. When an electromagnetic wave enters malignant tumor tissues, it interacts differently with the medium (for example, absorption, dispersion, emission, etc.), and the electromagnetic wave transmission path is changed. The electric-field intensity and the magnetic field strength are enhanced in certain regions and weakened in other regions. Based on this characteristic, breast tumors can be detected by surveying the electrical field produced by reflection and scattering of near-field microwave pulses. However, because the differences in microwave returns from normal and cancerous tissues are much less studied, construction of images with maximal discriminatory power requires identification of complex, likely nonlinear, features, and assembly of optimal combinations of such features. In this research, genetic programming will be used to evolve optimal methods to identify and depict tumors based on their microwave "signatures." This method can facilitate the early discovery and localization of breast cancer, with minimal risk from diagnostic radiation exposure. Professor Yao has continued to work on development of improved transmitter/receiver apparatus for ultra-wideband microwave imaging of breast cancer tumors. MSU graduate student Blair Fleet will analyze test data collected from the experimental UWB microwave apparatus from Shangai First People's Hospital, China. Fleet will begin seeking ways in which evolutionary methods may be used to recognize and highlight synthetic features of the data, which represents differences in dielectric constants of various breast tissue types.

In addition to medical applications, BEACON research can improve safety, emergency response, and security. Erik Goodman (MSU), Norman Groner (John Jay College, CUNY) and Robert Till (John Jay College, CUNY) are using **evolutionary techniques to optimize strategies to improve emergency response planning**. Critical Incident Analysis is an emerging field of study that encompasses modeling of natural disasters and man-caused incidents, responses to minimize their adverse impacts, and understanding of the short- and long-term effects these incidents and the responses to them have on society, particularly on people's trust in government and willingness to follow emergency directives. In this project, undergraduate Matthew Durak, under guidance of Goodman, Till and Groner, is developing an agent-based model for urban evacuation in response to a hazardous chemical leak from a train wreck, modeling behavior of individual drivers and effects of toxic chemical exposure on their fates and behaviors. Evolved control of the traffic lights for purposes of rapid evacuation after a toxic gas spill could cut fatalities by nearly 90% in the scenario simulated. This performance was dramatically superior to the types of evacuation strategies currently employed in some major cities.

Evolutionary techniques are particularly well suited to solving computer security issues – for example, there are many parallels between computer viruses and biological viruses. Gerry Dozier (NCAT) is partnering with Secure Designs, Inc. on a system for **vulnerability analysis of intrusion detection systems and firewalls**. This proactive and self-healing system is named GENERTIA-II (GENEtic inteRactive Teams for Information Assurance) and is an extension of

GENERTIA-I. The system will perform multi-packet vulnerability analysis, design, and redesign. Anomaly detection is concerned with identifying patterns that deviate from the normal behavior of a system; with applications including intrusion detection in computer systems, fraud detection in banking, and cancer cell detection in medicine. Anomaly detection solutions apply concepts from statistics, information theory, spectral theory and typically employ two phases. In the learning/training phase, a dataset is used for producing a classification model. The testing phase then uses the classifier to identify whether an observation is normal or anomalous, evaluating the probability that it was generated from the training model.

Dozier, with Joseph Graves (NCAT), is also developing a number of Genetic & Evolutionary Feature Extractors (GEFEs) and Genetic & Evolutionary Feature Selection (GEFeS) methods in a field called **Genetic & Evolutionary Biometrics**. The GEFEs have been used to evolve novel feature extractors for Face & Periocular Recognition. GEFEs have been used to reduce the size of feature sets while increasing accuracy for Face, Periocular, and Iris Recognition. At present, the methods used include modifying steady-state genetic algorithms, estimation of distribution algorithms, and particle swarm optimizers. Both projects led by Dozier (GENERTIA-II and Genetic & Evolutionary Biometrics) are leading to a better understanding of the types of biometric and security problems that conventional genetic & evolutionary computing (GEC), as well as our newer forms of artificial evolution, can be successfully applied to.

Evolutionary engineering can lead to better control of electronic systems with industrial applications: Erik Goodman (MSU), Lihong Xu (Tongji University, Shanghai, visiting BEACON), several of his graduate students at Tongji University and one visiting BEACON, MSU postdoc Prakarn Unachak, and MSU graduate student Jose Llera are developing **multi-objective compatible control of greenhouses**. In looking at how to improve the accuracy of the model of greenhouse dynamics -- an essential feature in controlling it in an energy-efficient manner -- the team recognized that it would be important to add to the greenhouse model a model of the growing crop, including its contributions to CO_2, moisture, light capture, thermal stratification and air circulation. Also, having an explicit model of plant growth will allow for more direct multi-objective optimization of crop production versus energy/materials costs, instead of merely setting a target interval for environmental conditions. The team is now working on getting code for an initial greenhouse model running under an MOCC control algorithm -- Multi-Objective Compatible Control, developed by Xu and refined in work with Goodman in recent years. That code will be augmented with new components representing the dynamics of the plant population, as guided by new collaborators David Kramer (MSU), Jeffrey Cruz (MSU) and their students.

Finally, Zhun Fan (Tongji University, Shanghai), Xiaobo Tan (MSU), Kisung Seo (Seokyeong University, Korea), Erik Goodman (MSU), and Philip McKinley (MSU) are working on an **evolutionary design of a bio-inspired fish-type flying robot actuated by artificial muscles**. Biomimetic features are important in design and control of robotic systems. Researchers have also used experimental results from robotic systems, especially in the case of biomimetic designs, to increase our understanding of the behaviors of biological creatures. However, most actuators used in these biologically inspired robotic systems are still traditional

electric motors, which use a strikingly different drive mechanism from the muscles used in biological creatures, strongly limiting the transfer of information between the two domains. This project attempts to bridge this gap by using artificial muscles to actuate the biologically inspired robotic systems. Prototype work by Fan and others has shown the feasibility of creating a robot that is neutrally buoyant in air, then powering it with EAP- (electroactive polymer)-based artificial muscles. However, such a vehicle will require an adaptive control system controlling actuators that are very different from traditional motors, and the team proposes to evolve such a controller on the basis of the CPG (center pattern generator) methodology. Thus, the initial work has focused on developing a non-flying robot prototype, an associated CPG controller and actuator configuration to be co-evolved to achieve the desired classes of behaviors. The team has decided that it is more productive, in terms of evolutionary lessons learned, to spend its initial effort on a non-flying system based on evolutionary adaptation of existing robotic modules, rather than spending its effort on a lighter-than-air system. The team has begun obtaining the raw materials, a modular robotic development platform, which will be used in building its prototypes. It was clarified that the essence of the research is to use evolutionary principles to design a robot body, that can move in some medium (air, land or water), and in which body shape and the controller for the locomotion are co-evolved. The obtaining of a 3D printer on another grant to McKinley and Tan will ease the process of building robot appendages for the base platform based on an evolved design. Software tools are being assembled to use in the design process. The initial emphasis of the team will be on deciding the architecture for the robot's controller, as that can have a major impact on the technology to be used. Thus, while the team has broadened the scope of the work to allow considering types of locomotion other than flight, to better reflect the capabilities of the assembled team and the difficulty of obtaining some of the materials originally planned for use, the thrust -- simultaneous evolution of morphology and behavior -- will remain unchanged.

Thrust Group 3: Evolution of Communities and Collective Dynamics.

Research in this group focuses on the evolution, stability, and emergent properties of assemblages of organisms, considering both their ecological properties and their ability to perform collective tasks.

Disease networks and transmission

Research in this theme focuses on patterns of disease transmission in populations, evolution of drug resistance through cooperation and coevolution, and the genomics of invasive pathogens. These projects have great potential for medical applications.

Two projects are investigating the evolution of drug resistance. Using *Escherichia coli* biofilms, Luke Harmon (UI) and postdoc Jon Eastman show that **heritable variation for broad-spectrum antibiotic resistance can arise and accumulate rapidly during biofilm development**, even in the absence of antibiotic selection, and have modeled the evolutionary dynamics of bacteria growing in the highly structured environment of a bacterial biofilm. They have also compared the accumulation of phenotypic diversity from the bottom to the top of a growing biofilm, in order to better understand the structure of the biofilm itself.

Eva Top (UI) is examining the development of **enhanced stability of a drug resistance plasmid through coevolution with its host**. Comparative analysis of bacterial genomes clearly shows genetic mosaics that have evolved through horizontal as well as vertical inheritance of genetic material. Among the mechanisms responsible for horizontal gene transfer, plasmid-mediated conjugation is of particular interest because many plasmids can transfer and replicate in a wide range of bacteria. One example of their critical role is the rapid horizontal spread of multi-drug resistance. One group of plasmids known to have a broad host range is the incompatibility group IncP-1. While these plasmids are not always stably maintained in their novel host in the absence of selection, they can adapt and become more stable over evolutionary time. In order to control the rapid spread of antibiotic resistance in environmental and clinical habitats, we first need to have a better understanding of the evolutionary mechanisms of plasmid stability improvement. The goal of this BEACON project is to determine the tempo and mechanisms of plasmid-host coevolution that cause improved plasmid stability. This research builds on the Top lab's earlier study, in which a model mini-replicon pMS0506, derived from the natural IncP-1 plasmid pBP136, was evolved in five independent lineages of *Pseudomonas koreensis* R28 for 1,000 generations under selection for the plasmid. Through testing the stability of ancestral and evolved plasmids in ancestral and evolved hosts, Top showed that only the evolved plasmids in their co-evolved host showed improved stability, strongly suggesting that mutations in both host and plasmid were required. In the current project, the team is determining the specific evolutionary mechanisms involved in this plasmid-host coevolution.

First, the dynamics of coevolution were examined by testing plasmid stability for archived populations. Significantly improved plasmid stability was first observed by generation 600, with at least two more evolutionary steps until generation 1,000. Second, the genome sequences of ancestral and 10 evolved strains from 5 lineages were determined by Roche 454 sequencing. When plasmid pMS0506 genomes were compared, the only difference between the ancestral and evolved variants in 9 out of 10 clones was the insertion of a type II transposon, with the insertion site varying among clones. This transposon apparently transposed from an indigenous plasmid present in *P. koreensis* R28. Based on its sequence, the only relevant phenotype was the resolution system. Since a corresponding resolution system of pBP136 had been deleted during construction of pMS0506, they hypothesized that the acquisition of such a system from the transposon contributed to the increased plasmid stability. Preliminary results from testing the stability of various transposon deletion mutants support this hypothesis. Moreover, the only sequenced clone in which the plasmid had not undergone transposition showed stability patterns consistent with host evolution only.

The results of this research strongly suggest that coevolution through interacting mutations in both plasmid and host genome was responsible for the improved stability of the model plasmid in a naive host. Moreover, while plasmids are known to receive foreign genes through transposition, the involvement of this process in the evolution of plasmid stability is novel. Since this is the first time that plasmid-host coevolution has been analyzed in such detail at the molecular level, this study will contribute to our understanding of the coevolutionary mechanisms by which drug resistance and other plasmids can be become more stably maintained upon transfer into novel bacterial hosts.

Research on the spread of infectious disease is another aspect of this theme. Bree Rosenblum (UI) is conducting **comparative and functional genomic analyses of invasive pathogens**.

Emerging infectious diseases present a great challenge for both biological diversity and human health. This BEACON project focuses on developing a mechanistic understanding of emerging diseases by studying a recently discovered fungal pathogen and its vertebrate hosts. The initial goals focused on whole-genome studies of the chytrid *Batrachochytrium dendrobatidis* (Bd), a fungal pathogen responsible for frog population declines and species extinctions around the world. In addition, the Rosenblum lab conducted studies on an essential and complementary objective: understanding host response to Bd. Even closely related hosts exhibit varying levels of susceptibility to Bd; therefore the project investigated the genetic determinants of disease susceptibility in frog species pairs. A pilot experiment comparing disease outcome in two species pairs has been completed: *Bufo boreas* (susceptible) vs *Bufo marinus* (resistant) and *Rana muscosa* (susceptible) vs *Rana catesbeiana* (resistant). The team is now optimizing genomic and immunological assays to determine the functional differences between these species pairs.

Lauren Ancel Meyers (UT) is modeling **trans-seasonal herd immunity of flu** in human populations. The Meyers lab has developed a multi-season contact network model to describe the long-term dynamics of a flu-like disease that confers immunity but evolves to escape the host immune response. The model provides a rich dynamical system that can produce periodic and chaotic dynamics depending on parameterization, and is likely to be useful in modeling a range of immunizing diseases. Currently, they are comparing the predictions of the model to influenza hospitalization data from the state of Texas during the last decade.

Meyers is also examining network models of the **spread of ectoparasites in Verreaux's sifaka (*Propithecus verreauxi verreauxi*) grooming networks**. Allogrooming is cleaning the hair, fur, feathers or scales of conspecifics, and is particularly common in primates. While most primates use their hands to groom each other, Strepsirhines (lemurs, galagos, lorises, pottos) use their tongues and teeth to groom each other, and have even evolved a specialized anatomical disposition of the lower incisors and canines called a toothcomb, which efficiently cleans their skin and fur for ectoparasites (e.g., lice, ticks). At first sight, allogrooming seems evolutionarily advantageous. Groomees are cleaned of ectoparasites while groomers may, in exchange, receive food, coalitional support or reciprocal grooming. However, physical contacts between groomers and groomees may also promote the transmission of the ectoparasites. Thus allogrooming may simultaneously decrease short-term parasite loads and enhance long-term parasite transmission. In order to investigate this trade-off, the Meyers lab is collecting data on the dynamics of both ectoparasite burden (lice, *Trichophyloterus babakotus*) and between-host contact patterns in a lemur species, Verreaux's sifaka from Kirindy Mitea National Park, Madagascar. With this data, they will (1) test for correlations between lice burden and contact patterns in Sifaka, and then (2) fit a theoretical model of ectoparasite dynamics that includes both parasite life history and host grooming patterns to the collected data. Through an ongoing collaborator with Rebecca Lewis (UT Austin), the team has access to five years of extensive grooming and physical contacts data for five different groups ranging in a one square kilometer area. Once per year, lice are counted on 2/3 of the individuals in the population. Using data from 2006-2010, they have estimated lice burden for each individual and the structure of the contact network, and found, preliminarily, that (1) ectoparasite load is positively correlated with social group size, (2) males tend to have more lice than females, (3) in females, the total number of physical contacts an individual has correlates positively with ectoparasite load, and (4) grooming frequency does not seem to be

negatively correlated with parasite load. This study has important implications for understanding the spread of pathogens through social networks.

Efficient and easy-to-use software plays a critical role in computational biology research. Contact network approaches in epidemiology provide sophisticated analytical and efficient computational methods, but currently no opensource toolkit is available for facilitating contact network epidemiology research. The Meyers lab developed the software **EpiFire**, an applications programming (BSD license) and graphical interface (GPL), available for Windows, OS X, and Linux online at sourceforge.net/projects/epifire. EpiFire has been used extensively for research and teaching at the University of Texas at Austin and the Summer Institute for Statistics and Modeling in Infectious Diseases at the University of Washington. EpiFire is freely available for download.

Marwan Bikdash (NCAT) is investigating **epidemiological simulation using diffusion-type equations.** In this project, Bikdash and his students are seeking to develop and compare computational paradigms as applied to epidemiology, population dynamics, and evolution. Two cases are considered: interspecies infection, where infection can cross species boundaries; and intraspecies infection, where a given infection is constrained to one species. A number of approaches are currently being considered, including the possibility of modeling genetic spread through the population using concepts from epidemic theory. In such models, a gene or meme can be thought of as propagating through the population like a virus. Several approaches, including the Susceptible-Infected (SI) and the Susceptible-Infected-Susceptible (SIS) models, were considered. Also a model of circular predation in the paper-scissors-rock cycle was considered within the epidemic diffusion paradigm. Finally, social-network theory is a possible analysis tool for the widespread transmission of new genetic material in a population. In such a theory, the emergence of the so-called giant cascade may be able to accurately and quantitatively predict the probability of extremely rapid propagation of new genetic material in a population.

Metagenomics

Metagenomics, or the study of the collected genomes of all of the microbes in a shared environment, is the focus of two BEACON projects. Because the vast majority of microbes cannot be cultured and studied in a lab in the traditional manner, the ability to directly sequence genomes from, e.g., a soil sample, holds great promise for understanding microbial communities and their interactions with the environment.

C. Titus Brown (MSU), Larry Forney (UI), Thomas Schmidt (MSU), and Barry L Williams (MSU) are conducting a study of **evolutionary metagenomics**. The overall goal of this project is to determine if evolutionary principles can be used to enhance the analysis of metagenomes - DNA sequences derived directly from complex microbial communities. The first objective has been to assess the potential of using the ratio of synonymous to nonsynonymous mutations (dN/dS) as a means to understand selective pressures on microbes in nature. The dN/dS ratio has been used traditionally to identify positive and purifying Darwinian selection in model organisms, and this team is extending this formalism to compare selective pressures in complex

microbial communities. The first experimental steps towards meeting this goal have been to investigate the effects of agriculture on the composition of microbial communities in soil. This portion of the project is focused on the microbes responsible for the production of nitrous oxide (N_2O), a potent greenhouse gas. Microbes in soil produce approximately half of the N_2O in today's atmosphere, and so it is important to understand environmental conditions that select for denitrifiers.

The research team, with postdoc Bjørn Østman, posited that standard agricultural treatments (AG) that include nitrogen fertilization would increase the selection pressure on the microbes to optimize the function of the denitrification pathway, compared to that in soil never used for agriculture (DF). To test this idea they collected sequences of a particular gene in the denitrification pathway, nitrite reductase (nirK), and computed the ratio of dN/dS, which informs us about the strength of selective pressure on protein coding sequences. Results show that, as expected, the microbial communities in agricultural treatments are under increased purifying selection on nirK, consistent with agriculture practices shaping the community of denitrifying bacteria. However, it must be emphasized that as far as we can tell, the effect of selection is to sort among existing sequences, rather than selecting for novel proteins. In other words, those sequences/organisms already better adapted to the increased need to obtain energy using nitrate rather than oxygen thereby increase in abundance in AG vs. DF. The team has collected soil samples from a series of fertilization gradients, and should be able to distinguish between the effects of fertilization and other aspects of agriculture. The goal is to implement this approach for shotgun metagenomic data in order to take advantage of the growing number of such sequences available from various natural habitats.

James Foster (UI) is conducting **experimental metagenomics**. The goal of this research is to develop the foundation for a new kind of biological model system, the model ecosystem. Biological model systems are reproducible, experimentally tractable and subject to genetic manipulation and artificial selection. Can we satisfy these requirements using an ecosystem? When we consider that the fundamentals of our biosphere depend almost entirely on microbial life-forms, the answer is clearly yes. This project will show that microcosms containing diverse microbial communities satisfy the requirements of a model system.

During the last year, Foster and postdoc Mitch Day have completed the artificial ecosystem selection (AES) experiment using the ginger-beer "plant" - a symbiotic consortium of bacteria and yeasts. The initial culture-independent diversity survey has revealed the existence of about 70 distinct operational taxonomic units (OTU; a weak proxy for microbial species). AES data sets have been generated from selection on three different systems: the ginger-beer "plant", a forest soil and a microbial fuel cell powered by a rice paddy soil community. Even though these are vastly different microbial communities, a common pattern has been identified. The community-level phenotypes measured and selected upon fail all tests of normal distribution, a finding at odds with typical organismal phenotypes.

The team is now exploring the statistical issues with detecting a response to selection upon non-normally distributed traits. This is an area that has been explored from a statistical and mathematical perspective in older literature, and they are using the data from the pilot experiments to determine the proper "population" sizes and other critical experimental design parameters. The consistent pattern across multiple community types is intriguing, but the

analysis also shows that the statistical conclusions could be made much stronger with a significantly larger numbers of replicate communities (the "population" size parameter).

This work will serve as the basis for a new project to fund the technical development of a biofilm community system bound to identical inert beads in an airlift bio-reactor. An automatic fluorescence-based sorting system will allow selection of a vast number of different island communities and thus direct experimental confirmation of the statistical framework being developed in the current work.

Maintenance of phenotypic variation through collective dynamics

Research in this theme examines how selection at a group level may maintain variation in a population in a way that is beneficial to all members of the population.

Ben Kerr (UW) and Wenying Shou (FHCRC) are testing hypotheses about **individual versus group selection in cooperative communities**. Cooperation is widespread yet paradoxical: why cooperate if cheating is an option? Underpinning the conundrum of cooperation is the conflict between individual and group interest: a cooperator pays a cost to generate, for its partner, a benefit greater than the cost. A “cheater” consumes the benefit without paying the cost of cooperation. Thus, in a mixed community of cooperators and cheaters, cheaters have a fitness advantage and should therefore out-compete cooperators, resulting in a group of pure cheaters. However, a group of cheaters is less fit than a group of cooperators, since only in the latter do individuals derive a net benefit from reciprocal cooperation. The conflict between individual and group interest predicts that selection at the individual and the group level will yield dramatically different outcomes, selecting for cheating and cooperation, respectively. To test this prediction, Kerr and Shou will use CoSMO, an engineered yeast cooperative system that consists of two metabolically complementary strains, each overproducing and subsequently releasing a metabolite essential for its partner strain. Since metabolite overproduction incurs a fitness cost, cheaters would be cells that consume but not supply metabolites. The team will perform a comparative evolution experiment on CoSMO to test the difference between individual and group selections. In individual selection, all CoSMO cocultures will be propagated, effectively selecting for fastest-growing individuals. In group selection, only the top tier of fastest growing cocultures will be selected, each expanded to multiple progeny cocultures. This project will test whether group, but not individual, selection results in stable cooperation.

Patricia Hartzell and Alan Caplan (UI) are examining the **maintenance of phenotypic variation in the highly social bacterium *Myxococcus xanthus***. *M. xanthus* is a soil-dwelling, antibiotic-producing, bacterium whose dramatic social activities, including swarm expansion and development, have yielded a wealth of information about cell-cell interactions, signaling and cooperativity. These social processes are linked intimately with the ability of *M. xanthus* cells to undergo phase variation, which produces two inter-convertible cell types, called yellow and tan, that differ greatly in their abilities to swarm, survive, and develop. Wild-type colonies are composed of ~90% yellow and ~10% tan phase variants. Remarkably, both phase types are critical for long-term survival, which demonstrates that evolution of phenotypic heterogeneity in *M. xanthus* includes a fail-safe mechanism to ensure the maintenance of both cell types. As

evidence of this, during starvation-induced development, *M. xanthus* builds fruiting bodies within which some cells differentiate into heat-resistant spores. Tan variants predominate as spore formers, but only in the presence of yellow variants. Hence, both tan and yellow variants must participate in sporogenesis. To understand how phenotypic heterogeneity is generated and why maintenance of heterogeneity is critical for survival, Hartzell and Caplan compared the transcriptomes of yellow and tan variants. A total of 37 genes with increased expression in yellow variants (relative to tan variants) and four genes with increased expression specifically in tan variants were identified. A dkx (DK xanthene synthesis) mutant produced nonpigmented (tan) colonies but still phase varied with respect to swarming, suggesting that pigmentation is a consequence, but not the cause, of phase variation. Disruption of a gene encoding a HTH-Xre-like (helix-turn-helix, xenobiotic response element) regulator, highly expressed in yellow variants, abolished pigment production and blocked the ability of cells to switch from a swarm proficient to a swarm deficient phenotype, showing that HTH-Xre is a key regulator of phase variation. Results show that Xre is a key component of the master regulatory switch; putative Xre-DNA binding sites were identified for five genes whose expression is regulated by Xre. Analysis of functional Xre-mcherry fusions is in progress. Deletion of a second gene, up-regulated in yellow variants (ypg for yellow phase gene), encoding a hypothetical protein, yielded a mutant with defects in sporulation and plating efficiency. Preliminary investigation of a ypg-mcherry fusion shows that Ypg is an integral membrane protein with a large periplasmic domain that forms a disulfide-mediated loop. Ypg plays a role in regulating the phase variation switch because ypg mutants are unable to produce tan variants. The ypg mutant exhibits accelerated formation of fruiting bodies and diminished production of heat resistant spores. The team hypothesizes that the ability of Ypg to regulate the balance of yellow and tan variants in the population determines whether fruiting body development and spore formation will be robust (Y/T ratio of 18) or weak (Y/T ratio 0.1). Several genes showed increased expression in tan variants. Among these was pkn14, which encodes a serine-threonine kinase that regulates programmed cell death in *Myxococcus* via the MrpC-MazF toxin-antitoxin complex. Low levels of Pkn14 may explain why yellow cells tend to lyse while tan cells persist during stationary phase. Furthermore, differential expression of pkn14 may govern cell-type specific autolysis during development and provide a mechanism for release of DKX from yellow phase variants.

The BEACON goal for the next period is to use marked yellow and tan phase variants in competition experiments and modeling studies to test the hypothesis that the balance of swarm-proficient yellow variants and swarm-deficient tan variants synchronizes the temporal and spatial events during fruiting to optimize spore production. In addition, they will use a subset of phase mutants to look for mutations that give rise to cheaters that might reveal information about the mechanism governing the balance of each phase variant.

Christoph Adami (MSU) and Ben Kerr (UW) are examining **the evolution of the rules microbes use to "play games."** This group has been exploring the evolution of a type of competitive restraint in a rock-paper-scissors community of bacteria. There is a form of negative feedback in this community, such that the player improving its growth rate leads to a lowering of its density. In a well-mixed community, the evolutionary increase in growth rate of one player can lead to its demise. However, things can change in a structured community. Using a combination of computer simulations and experiments with *Escherichia coli* in metapopulations, the researchers discovered that restraint can evolve in a structured community. Here, patches of

restrained competitors simply outlive patches of unrestrained competitors in a fluid mosaic of the three players.

They have studied the fixed points and the stability conditions for deterministic as well as stochastic strategies for agents playing bacterial games, as a function of the parameters that determine the payoffs. Varying the payoffs of the three-player game including the sensitive type (S), the producer type (C), as well as the resistant type (R) produces game dynamics in different game-theory classes, including the rock-paper-scissors communities, but also communities of stably coexisting types. For two player games (S and C), the fixed points and stability conditions for deterministic and stochastic strategies coincide. However, parameters that encode unstable fixed points when dealing with deterministic strategies become stable if the strategies are stochastic. Thus, Strategies that can stochastically switch from one type to the other do not get eliminated when conditions favor a loss of diversity for deterministic strategies. The next step is to directly encode the evolution of the parameters of the landscape, in order to make a connection to the research going on in the lab at UW.

Kerr and Georg Seelig (UW) are studying **the role of protein interactions in the evolution of novel toxins**. Many essential cell functions are carried out by highly specific interactions between two proteins (i.e., protein pairs). For some functions, these protein pairs are extremely diverse. Understanding how these protein pairs can diversify when highly specific interactions within protein pairs are necessary for survival is the focus of our research. Kerr and Seelig are exploring this question using colicinogenic *Escherichia coli*. Colicinogenic *E. coli* simultaneously produces antimicrobial colicin proteins and a neutralizing immunity protein that prevents self-poisoning. Once the colicin is released from the cell, it can kill competitor cells. One major theory for the diversification of new colicin-immunity pairs is that their evolution proceeds through an immunity protein intermediate; this intermediate can bind its own colicin as well as the colicin of a different colicinogenic strain. This may then allow for the evolution of a novel colicin protein. In addition, duplication of the immunity gene may play a role in allowing an extra copy of the immunity gene to "explore" protein space without interrupting the function of the ancestral immunity protein.

The team is currently in the final stages of designing a directed evolution protocol to select for the real-time evolution of novel colicin-immunity pairs, using the highly-related E-series (E2-E9) colicin operons. To optimize a directed evolution approach, high efficiency is crucial so that a large library of mutants can be screened, and they have spent the last year preparing an efficient protocol. They have constructed a plasmid containing the colicin operon and an antibiotic cassette for screening, and are currently optimizing a random mutagenesis kit so that ~1-2 mutations per immunity gene are introduced. Mutated immunity genes are then ligated into the plasmid and transformed into competent *E. coli*. Once intermediate broadened immunity proteins have been discovered, the intermediates will be used to select for the evolution of novel colicin proteins. This experiment aims to address fundamental questions about protein evolution and elucidate the role of gene duplication and protein intermediates.

Another aspect of this theme is the study of **coevolution of multiple species**, including **predator-prey dynamics**. Species do not evolve in a vacuum, and there are many examples of ecologically linked species that drive evolution in each other.

Jay Lennon (MSU), Jeffrey E Barrick (UT), and Chris Klausmeier (MSU) are examining the **contemporary evolution of cyanobacteria and viruses, and its implications for marine nutrient cycling**. The goals of this project are to explore the effects of rapid evolution on the ecological dynamics of bacteria and their phage. In a five-month long chemostat experiment, the research team challenged a marine cyanobacterium (*Synechococcus*) against a lytic virus (phage). The interactions between *Synechococcus* and its phage were explored under contrasting nutrient regimes: nitrogen (N) vs. phosphorus (P) limitation. Stoichiometry theory predicts that differences in N and P limitation should affect the ecological dynamics of the bacteria and host, but differences in nutrient limitation may also affect rates of microbial evolution. These questions are being addressed using two complimentary approaches: 1) Adaptive Dynamics modeling, which allows for the incorporation of evolution into a dual currency food web model, and 2) Genomic sequencing and bioinformatics to compare the evolution of bacteria and viruses in response to nutrient stress and antagonistic predator-prey interactions.

Adaptive Dynamics modeling is being used to understand the interplay between ecology and evolution that gives rise to complex predator-prey dynamics in different nutrient regimes, and to understand the effects of fixed and variable stoichiometry on the eco-evolutionary dynamics of a host-phage system. The three steps of this project include the development of a: 1) single species ecological model, 2) single species model that includes evolution of bacterial traits, and 3) multi-species model that includes evolution of bacteria and phage.

The team will also use whole-genome sequencing of bacteria isolated from different time points in our chemostat experiment to identify traits that are under selection by phage and nutrient limitation. Bacterial isolates to be used for the whole genome sequencing effort are currently being screened against phage isolates from the chemostat experiment for the expression of resistant phenotypes. This information, in the form of breadth of resistance profiles, will provide the 46 isolates to be used for this part of the project. Prior to DNA isolation, each culture will go through a series of isolation techniques to ensure removal of heterotrophic contaminants and high sequencing coverage of the *Synechococcus* isolates.

In an extremely multidisciplinary collaboration, Ian Dworkin (MSU), Gerry Dozier (NCAT), Richard Lenski (MSU), Charles Ofria (MSU), and Ben Kerr (UW) are examining the **evolutionary dynamics of traits that mediate predator-prey/host-parasite interactions**. The language of evolution often uses terms such as "target" of selection, that imply a unidirectionality to natural selection. Yet in most systems, complexity arises through interactions, whether intra-specific (competition and mate choice) or inter-specific such as between host-parasite or predator-prey. Hence, there is increasing interest in novel theoretical and empirical work that examines co-evolutionary dynamics and outcomes. However, the details of such interactions can vary substantially based on the nature of the interactions, as well as the relative evolutionary rates of the "partners." For instance, in microbial systems, a viral parasite and its bacterial host may both evolve rapidly; while a viral pathogen and a human host will evolve on dramatically different time scales. These observations lead to diverse questions about the dynamics of such interactions at varying time scales, and in particular the evolution of traits that mediate such interactions. The research team will investigate the dynamics of such traits in diverse biological and computational systems, with the long-term goal of determining what

features are universal across these interactions, and which features reflect scales of time and complexity that are particular to certain systems. They are investigating interspecific interactions using experimental evolutionary approaches in digital (anomaly detection software & digital evolution) and biological (phage-bacterial and praying mantids-Drosophila) systems that vary with respect to absolute and relative rates of evolution:

Postdoc Justin Meyer and Rich Lenski (MSU) will study coevolution in action using bacteria as prey and Lambda phage as predators. Lambda infects *E. coli* through a particular surface protein, LamB, that *E. coli* use to transport maltose. Meyer and Lenski use genetic and phenotypic data to identify different classes of resistance mutations, and then test which classes can be countered by "host-range" mutations that allow Lambda to attack cells resistant to the original phage. Using a coevolutionary experimental design, they observed a set of Lambda mutants that infect *E. coli* through another surface protein. Lambda have never been seen using this alternative receptor, despite decades of study. Sequencing these Lambda mutants suggests why they were not discovered before – they have multiple mutations, whose accumulation required multi-step coevolution of predator and prey. Replay experiments – in which coevolution is restarted from various intermediate states – show that the emergence of these novel viruses depends on mutations in the bacterial population. In collaboration with Jeff Barrick (faculty at UT-Austin), genomes of both the evolving bacteria and viruses will be sequenced to understand how this new function arose. This project integrates phenotypic and genomic evolution in action in a multi-species system, in order to understand the emergence of a new function that impacts the dynamics of that system.

Grad student Christal Eshelman and Ben Kerr (UW) will complement the Lambda study by looking at coevolutionary trajectories of phage T7 and E. coli in metapopulation contexts. Previous experiments have shown greater variance in evolved characteristics (i.e., phage productivity) in treatments with restricted migration, suggesting higher diversity in more structured populations (potentially involving adaptation of phage to locally differentiated hosts). Evolved T7 genomes will be sequenced to gauge genetic diversity and evaluate the evolutionary consequences of population structure in a host-pathogen community.

Grad student Luis Zaman and Charles Ofria (MSU) will investigate the evolution of host diversity and complexity in response to coevolving parasites. Predators and parasites are known to increase host diversity in natural and experimental populations, but traits of parasites and the resulting properties of coevolving populations that affect diversity and complexity are not well understood. We will test the effects of many traits such as virulence, host-range, and both relative and absolute mutation rates on coevolved responses.

Gerry Dozier (NCAT) is exploring this dynamic in the context of anomaly detection software, using the program GENERTIA (described earlier, in Thrust Group II). In this project, GENERTIA is applied to anomaly detection such as intrusion detection system (IDS), and spam-phishing detection (SPD). GENERTIA, in the form of genetic and particle swarm search, can discover vulnerabilities of existing IDS and SDP. GENERTIA contains two subsystems based on evolutionary computation: a GENERTIA blue team (GBT) and a GENERTIA red team (GRT). The objective of GBT is to design artificial immune system (AIS) based anomaly detection with high attack detection rates, low error rates, and a minimal number of detectors. The GRT analyzes anomaly detection systems, provides feedback concerning the strength of detectors to the GBT, which the GBT uses to redesign the anomaly detection system. Through GENERTIA,

the team will enhance the effectiveness of existing anomaly detection systems, and aid IDS and SPD designers' patch development.

Grad student Michael Denieu and Ian Dworkin (MSU) are investigating the evolution of behavioral and morphological traits in populations of *Drosophila* subjected to episodic predation by *Tenodera* mantids. Populations have been subjected to 48 generations of selection already, and exhibit increased survivorship relative to controls. Initial results suggest wing shape and size appear to be targets of selection, and we propose to investigate a set of behavioral traits (i.e., exploration, social aggregation and wariness) to determine how they are evolving under the risk of predation. Furthermore, we aim to initiate a set of new selection regimes, where risk of predation varies across life history stages (adult vs. complete life history) as a comparison.

In another interdisciplinary collaboration, Xiaobo Tan (MSU), Philip McKinley (MSU), and Jenny Boughman (MSU) are **exploiting robot-fish interactions and evolutionary computing to understand and synthesize complex collective behavior**. By merging biology, robotics, and computational evolution, the goal of this project is to enable the development of robotic fish that are highly maneuverable and possess adaptive, autonomous group behaviors, and conversely, to use such robots to advance fundamental understanding of live fish behaviors. The team has developed a dynamic model for robotic fish propelled and maneuvered by a rigid caudal fin, which has been validated experimentally. The model has been utilized to evolve a neural network-based controller for a robotic fish, and we have demonstrated in simulation the effectiveness of such controllers in various missions such as waypoint navigation. Recently, the dynamic model has been extended to accommodate a flexible tail, and they are using it to investigate evolutionary computing-based design of tail stiffness to optimize the robot performance.

The group has also made significant progress in the evolution of controllers for collective behavior, which will eventually be tested in collections of simulated robots, and finally in actual robots. Specific accomplishments include evolution of artificial neural networks that enable a group of swimming agents to remain interconnected by wireless links, and evolution of collective foraging behavior using a new evolutionary computation method called digital enzymes. In addition, they have conducted a study of biased group selection and demonstrated its advantage in evolving collective behaviors, relative to the clonal group method most commonly applied in evolutionary robotics.

The team has successfully landed an NSF Computing Research Infrastructure (CRI) grant this year. Called "Evolution Park," this grant is being used to expand an existing testbed for evolutionary robotics and opens the door to many exciting research thrusts relevant to BEACON. Using this grant, they have acquired a 3D printer with a unique capability to print simultaneously materials with different properties, enabling us to quickly prototype and experimentally evaluate robots with evolved morphologies. They have already been able to use the printer to produce the majority of the parts for swimming and crawling robots.

On the live-robotic fish interaction side, the team has decided that a robotic fish modeled after a 10-inch cutthroat trout would be suitable for serving as the programmable predator. The creation of such robots is in progress. In the meantime, the experimental setup for conducting initial tests on fish-robot interactions is being prepared with existing robotic fish from Tan's lab as predators. Progress is also being made in developing miniaturized robotic fish (robotic

sticklebacks); in particular, the development of a high-voltage circuit for driving novel actuation mechanisms is near completion.

This BEACON project has been leveraged in various outreach programs, including the presentation at the inaugural US Science and Engineering EXPO in 2010. To further engage the audience, they have also created a haptic system that allows one to "feel" the swimming of robotic fish in addition to watching it.

Engineering applications of biological collective dynamics

Finally, a group of researchers in this theme are exploring engineering applications inspired by biological studies of collective dynamics.

Paul Stanfield (NCAT) and grad student Patrick Wanko are **using the dynamics of schooling fish to improve automatic identification technology**. This research is inspired by applications in durable product life cycle management intended to improve future design, current operating processes, and sustainability. The applications are enabled by sensor-integrated automatic identification technology that renders product function similar to that of interacting similar organisms in ecosystems. The plan is to evolve product design and operating parameters considering the operational environment based on bio-inspired processes. First, they conducted the conceptual development of a product performance simulator as a function of design parameters, operating parameters, and environment. Now, they have begun practical development of two types of specific products - cell phones and helicopter auxiliary power units. Wanko is currently developing a "schooling" evolutionary algorithm that incorporates fish group dynamics within an evolutionary algorithm to search for better parameter selection in product design/operation. The algorithm includes school merging, food foraging, and predator avoidance behaviors. They are also developing a "social network" evolutionary algorithm that incorporates social network/Facebook dynamics within an evolutionary algorithm to search for better parameter selection in product design/operation. This algorithm includes fuzzy set modeling of group membership and changing social preferences.

2b. Progress towards metrics listed above.

Integrative Research Goals

1. New research collaborations and proposals

- Several projects include funding for students/postdocs/faculty to travel between partner institutions. Videoconferencing equipment at each institution has been improved.
- We have completed two rounds of the budget allocation process, and the data suggest that the criteria used to evaluate projects has resulted in a significant increase in collaboration: number of investigators per project changed from an average of 1.97 in 2010 to 3.11 in 2011 (one-way ANOVA, $p<0.001$), and number of institutions per project changed from 1.26 in 2010 to 1.81 in 2011 ($p<0.001$). BEACON funded 34 research projects (out of 41 proposed projects) in the period August 1, 2010-July 31, 2011 (from BEACON budget periods 1 and 2), and has funded 26 projects (out of 52 proposed) for the period August 1, 2011-July 31, 2012 (from BEACON budget periods 2 and 3).

- We held "Birds of a Feather" sessions at the 2010 Congress, and somewhat more collaborative "Sandbox" sessions at the 2011 Congress, and shared the discussions at a general session at the end of each Congress. Several new collaborations have begun.
- The Toolbox team piloted a workshop at the first BEACON Congress in 2010, and is revising the workshop format in response to feedback. The team was unable to attend the 2011 Congress because of a conflicting training commitment.
- Service by members on doctoral research committees across disciplines and institutions: We have not yet begun to track this.

2. New paradigms for research in organic and digital domains

- Number of new sessions at scientific meetings or scientific meetings hosted at BEACON: The PIs have discussed which scientific meetings would be strategic for hosting sessions on evolution in action, and have agreed that the general field of evolutionary computing needs to be made more visible to the broader computer science community. In service of that goal, BEACON has prepared display materials and handouts for distribution at several computer science and evolution-related conferences, where BEACON will rent a "booth." One such booth has already been hosted at the 2011 Genetic and Evolutionary Computation Conference, Dublin, Ireland, where several BEACON attendees also presented papers or tutorials. In 2012, at least the Evolution conference and the IEEE World Congress on Computational Intelligence, which includes three conferences on other areas in computer science, will have BEACON booths. In service of the need to put more focus on evolution in action, in both biological and digital realms, BEACON has agreed to host the 13th Conference on Artificial Life (ALife13), at BEACON headquarters (MSU). The Call for Papers has already been distributed, a set of notable keynote speakers arranged, and posters for distribution to advertise the conference are nearly completed. BEACON faculty are assuming many of the leadership roles for the conference.
- Number of new journals and societies: None to report yet.
- New or increased funding for biocomputational research: BEACON researchers have submitted at least 48 proposals for over $36M of external funding, and at least $8M in external funding has been granted.

3. Increase in publications related to evolution in action

- Number of publications: 106 publications submitted by BEACONites in 2011
- Number of non-self citations of work: It is too early to track citations of articles that have just appeared in the first year, but we will begin tracking this statistic in the next reporting period. It is not realistic to track non-self citations, so we have edited our goals in the Strategic Implementation Plan and will only provide total citations in the future.
- Number of non-BEACON evolution in action publications: We have realized that this is not a realistically trackable statistic, and have removed it from our Strategic Implementation Plan.
- High visibility science journalism about BEACON research: In 2011, we put out 10 press releases. At least 23 features on BEACON research appeared in the mainstream and online media in 2011, including *The New York Times*, Science Daily, Live Science, *Scientific American*, and NPR.

4. Development and dissemination of new curricula and resources to train multidisciplinary scientists

- At least 5244 downloads of Avida-ED
- Avida and Avida-ED trainers held Introduction to Avida-ED workshops at all BEACON sites in 2011.
- Multidisciplinary graduate and upper-level undergraduate courses in place at all five BEACON member institutions.
- Visits to BEACON website, where all resources are linked, since March 2011:
    - 11,470 visits
    - 25,255 page views
    - Average time on site: 2:07
    - 56.6% new visits

Ethical Research Goals

1. Responsible Conduct of Research (RCR) training

- BEACON RCR Policy clearly articulated and posted on website, distributed via email and described at in-person discussions at BEACON seminars and Congress
- Brian Baer developed a tracking system for self-reporting RCR training on BEACON's Intranet
- Baer, Whittaker, and Goodman analyzed the Year 1 data, after granting an extra week grace period after the original deadline of August 31. We exceeded our Year 1 goal of 75% of participants in compliance: 81% of undergraduates, graduate students, and postdocs who self-identified as "participants" were in compliance. Whittaker then contacted the students and postdocs who were not in compliance and requested that they report training within one month.
- In the Year 3 Budget Request forms (to be distributed in December 2011), the RCR training requirement will be explicitly stated and applicants will have to check a box certifying that all project members are in compliance.
- No ethics violations to report.

2. Scientific norms/virtues, respect across disciplines

- Robert Pennock is still working on a Scientific Values workshop, and will begin by discussing the topic at an All-BEACON Friday meeting in Fall 2011.
- The weekly Friday meetings have been going on continuously since October 29, 2010, and we consider them a success.
- One barrier is a lack of "social" hour at the partner institutions, making attending the Friday seminars less attractive to students. We will encourage the partner leads to include refreshments and make time to interact with the students at the end of the meetings.

3. Respect for views horizontally and vertically

- The Toolbox team gathered feedback from participants in the pilot sessions, and is working to adapt the Toolbox sessions for BEACON participants.

4. Access to shared resources and mechanisms to negotiate intellectual/philosophical differences

- Rob Pennock is meeting with the Toolbox team in early November 2011 to discuss a new plan and timeline for this goal.

Research Output Goals

1. Original research by BEACON members on evolution in action will be prominent in the evolution literature

- Internal reporting system fully implemented by January 2011
- Number of publications: 106 submitted (goal was 150 – there was likely underreporting)
- Conference presentations: 91 reported (goal was 150 – again, likely underreported)
- Grant proposals submitted: 48 submitted (goal was 40)

2. BEACON research output will be perceived as making an important contribution to the literature

- First External Advisory Committee meeting held August 2011
- Feedback from External Advisory Committee was very positive (Appendix C)

2c. Research plans for the next reporting period.

Most of the projects described above will continue into the next reporting period and end in August 2012. We will hold our project selection process for Year 3 (see explanation in VII. Management) in January 2012 in order to choose projects that will be conducted August 2012-August 2013. We do not anticipate any changes in thrust groups or research themes.

III. EDUCATION

1a. Overall Education Goals

BEACON's **Education, Human Resources, and Diversity (EHRD) overarching goal** is to integrate cutting-edge, multidisciplinary research, education, and outreach across the Center that will advance innovative training, increase the diversity of the Center and scientific workforce, and promote greater understanding of evolution and the nature of science throughout public education. We are approaching this goal in two ways: by educating a diverse new generation of interdisciplinary scientists and engineers, and by advancing K-16 programs that address the pressing national need to bolster U.S. pre-eminence in science and technology by educating people about the importance of understanding, managing and harnessing biological and computational evolutionary processes.

1b. Performance and management indicators/metrics

In this table we summarize our optimal outcomes and metrics from our Strategic Implementation Plan, and briefly note our progress towards these goals. For more details on progress, please see section 2e.

Education Goals		
GOAL	**METRICS**	**PROGRESS**
Multidisciplinary Ph.D. graduates and post-docs placed in faculty positions at rates approaching averages across engineering, computer science, and biology	Fraction of BEACON graduate students and post-docs receiving offers of faculty positions	Too early to measure. Multidisciplinary classes established at all 5 partner institutions. Mentoring programs established.
Increased public literacy in evolution and the nature of science	Development of educational materials	Avida-ED training workshops given at all BEACON U's; initial museum exhibits in place
	Frequency of public use of online materials or visits to exhibits	Collecting baseline data on use of existing online materials.
Increased interest in STEM careers in both academia and industry	Pre- and post-program survey instruments administered to K-12 participants, university students, and the public	High school and undergraduate summer programs offered; teacher training workshops offered; art installation.
	Feedback from the External Advisory Committee	Positive feedback. See Appendix C

1c. Problems encountered in making progress towards goals

Internal education activities: The graduate training courses offered across institutions experienced some challenges during their first administration. There were some issues due to different academic calendars (for example UW is on a quarter system whereas MSU is on a semester system). Courses offered in Fall 2011 also experienced some technological problems associated with the distance learning environment. However, in year 2, technological problems have been minimized and we have strong partner participation across campuses.

External education evaluation activities: To develop a general evaluation plan for all our educational projects, we began working with the Institute for Research in Math and Science Education (IRMSE) at MSU. These collaborations led to a few general survey instruments. Following administration changes at IRMSE, and given the breadth of our educational projects, we are working with each project leader to identify appropriate external evaluators and/or an assessment team who have more specific content and assessment experience. For example, Dr. Claudia Vergara at the Center for Engineering Education Research (CEER) at Michigan State University is evaluating our graduate courses. Dr. Celeste Sturdevant Reed is evaluating our BEACON MSU Evolution in Action exhibits, and we are working with Dr. Mark Urban-Lurain from CEER and Dr. Julie Libarkin at the Center for Integrated Studies in General Science and the Geo-Cognition Lab to continue our evaluation and assessment of undergraduate projects.

2a. Internal Education Activities

Activity Name	**Interdisciplinary Graduate Education**
Led by	Titus Brown, Alexander Shingleton, Charles Ofria, and Ian Dworkin
Intended Audience	Beginning graduate students
Approximate # of attendees	~50 per year

BEACON has instituted a series of courses specifically designed to train graduate students across disciplines. Courses include Computational Science for Evolutionary Biologist (CSE 891, Fall) taught by Dr. Titus Brown; Evolutionary Biology for non-Life Scientists (ZOL 890) taught by Dr. Alex Shingleton; and Multidisciplinary Approaches to the Study of Evolution (CSE 891, Spring) taught by Drs. Charles Ofria and Ian Dworkin.

Computational Science for Evolutionary Biologists: Twenty-five students (18 MSU, 3 UT, 4 UW) enrolled in the course for Fall semester 2010. This course introduces biologists to computational thinking, practical computational techniques, and research topics in computational evolution. The course consists of three intensive hands-on modules: computational competence in UNIX; data mining and hypothesis generation using the Avida digital life platform, and computational analysis of large scale resequencing data from the Lenski Lab E. coli long term evolution experiment. In year 1, Dr. Brown received additional funding to enhance the bredeq software and build the educational materials around the Lenski LTEE data. For Fall 2010, the course did not use the breseq software and Dr. Brown was able to identify a number of

challenges that prevent breseq's use and adoption in future courses, and is addressing those with the help of a postdoc, Dr. Robinson, and a follow-on technician hire, Brian Klahn.

Twenty three (14 MSU, 4 UI, 3 UT, 2 UW) students are enrolled in the course for the Fall 2011 semester. Dr. Brown has made modifications to the course based on feedback from the previous year. These changes include refocusing the computational course on group interaction within the course (a persistent issue in year 1). Funds were used to purchase 16 iPads. These iPads are being used to collaborate within small groups split between the 4 institutions participating in the computational science course (UT, UI, UW, and MSU). Preliminary results are encouraging, with groups regularly doing teleconferencing and collaborative "whitepad" projects. Our expectation is that these iPads will serve as the foundation for collaborations in the spring graduate course taught by Drs. Ofria and Dworkin, so we are also developing effective practices for their use in class in general. Dr. Art Covert (UT) was hired as a TA to help track students in the course, and will be running some of the classes later in the term, facilitating cross-institutional teaching collaborations. Dr. Brown has also traveled to the remote institutions to meet with enrolled students there and to conduct distance learning from there.

Evolutionary Biology for Non-Life Scientists: ZOL 890-002 was taught for the first time in the fall semester 2010, with a total of 18 students enrolled (14 MSU, 4 UT). The learning goals of the class are for students to: (1) understand key concepts of evolutionary biology; (2) relate evolutionary concepts to patterns of biological diversity; (2) be able construct and test evolutionary hypotheses; (3) be excited about evolutionary biology; (4) be able to explain evolutionary biology to non-scientists; (5) recognize what they do not know about evolutionary biology and develop strategies to complete their knowledge. These learning goals were achieved through a combination of lecture, individual and group exercises, computer simulations and independent study. The emphasis throughout the course was on active learning. The highest level of biological education among the students was sophomore biology, with most students having no exposure to biology after high school. Consequently, the class started from first principles, with description of DNA, RNA and proteins, building up to Mendelian, population and quantitative genetics, before moving on to evolutionary analysis, phylogenetics, sexual selection, etc. The class concluded with student-led presentations on topics of their own choosing that had not been covered in class.

The class was evaluated by the students in a formal survey administered by MSU and in an informal survey administered by the instructor. All surveys were completed anonymously. Students rated the instructor involvement as superior, their interest in the class as above average, their interaction with the instructor as superior, and the intellectual demands of the course and its organization as above average. All respondents agreed or strongly agreed that at the conclusion of the course they had a good understanding of evolutionary biology and were able to apply the evolutionary concepts presented. All the students subsequently participated in a second BEACON course where they collaborated with biology graduate students on projects addressing evolutionary hypotheses.

For Fall 2011 a total of eight students are enrolled. Additionally, the course is being improved upon based on student feedback. The long-term goal is for the class to be taught remotely at all four BEACON institutes. This presents some challenges, particularly with a course that involves a high level of student-instructor interaction. Nevertheless, the course will continue to be improved and serve as an example upon which similar courses can be developed.

Multidisciplinary Approaches to the Study of Evolution: This course provides an introduction to engaging in multi-disciplinary research collaborations involving biologists, computer scientists, and engineers by addressing fundamental questions about the dynamics of actively evolving systems (both biological and computational). Students work on these projects in multi-disciplinary and multi-institutional teams, with guidance to help them develop an understanding of the nature and challenges of such collaborative endeavors and how to overcome discipline-specific language and conceptual issues. Additionally, students are introduced to fundamental topics in experimental design and statistical analysis, critical to the success of any research project.

In Spring 2011 18 students (15 MSU, 3 UT) enrolled in the course. Final projects included a wide array of research on problems in evolutionary biology (for example The Evolution of Sexual Dimorphism; Signaling Loss; The Evolution of Evolvability).

At the end of the course, 61% agreed or strongly agreed they will pursue research that integrates evolution, engineering and computer science.

Game Theory and Adaptive Dynamics: Dr. Chris Klausmeier ran a 3-week workshop/class on game theory and adaptive dynamics. While the class was largely funded through a CAREER grant, BEACON supported five graduate students through assistantships. The course was co-instructed by Stefan Geritz (University of Helsinki). The first week (Mon-Fri, 9-5) was a combination of lectures, discussions, and computer lab exercises. Mon-Weds of week 2 was spent on a 'small project', where groups of 2-4 students recreated the results of published papers, extended them, and presented on Wednesday. On Thursday of week 2, the 15 students gave talks on their personal research interests. Friday of week 2 was spent on two more advanced lectures and on organizing into groups for week 3's “big project.” In the big project, students in groups of 2-4 worked on new research problems all week, and presented their findings Friday afternoon.

Activity Name	**Undergraduate Education in Computational Evolutionary Biology**
Led by	Claus Wilke and Art Covert (UT)
Intended Audience	Undergraduates
Approximate # of attendees	30

BEACON is also invested in training undergraduates in an effort to meet both our mission to (recruit and) train graduate students, as well as our mission to increase understanding of evolution and the nature of science. A number of educational projects are focused on undergraduate education.

Undergraduate Education in Computational Biology: Drs. Claus Wilke and Art Covert received funding to run the computational biology stream (now renamed the computational evolution stream) of the UT Freshman Research Initiative (FRI). An FRI stream is a year-long course designed to give freshman and sophomore students actual research experience. Twenty to thirty students spend one semester learning computational research methods, taught by a Research Educator (Dr. Art Covert) in an inquiry-based lab setting. Successful spring students then spend the summer and fall doing research on evolution in action in the Wilke lab.

In the first semester, students learn standard research techniques in computational evolution, including the basics of programming, running software-aided statistical analysis on large data sets, computer simulations of biological concepts, and basic scientific reasoning. In the second semester, students will participate in a variety of hands-on research projects organized by the Research Educator. Past students in the FRI program have made publishable contributions to their research projects and have been included as co-authors on subsequent publications.

The computational biology stream is currently in its third year, and in its first year with a full-time research educator funded 50% by BEACON and 50% by UT. Because there hasn't been a full-time research educator in the past, enrollment to the stream has been low. However, the students enrolled have been very successful. The majority of the students have been able to use the stream as an entryway to regular research work in a lab, and are on track to go to graduate school. Moreover, several of the students have co-authored research publications. The BEACON funding for this project has officially started in the fall of 2011, however we have already been actively training students over the summer and preparing materials for the fall course.

We are currently planning to restructure the course to draw more students from the computational sciences into biologically inspired research. Beginning in Spring 2012 students of the Computational Evolution stream will focus more on hands on research based on simulation of Evolution in Action. We will incorporate many of the useful techniques from earlier versions of the stream, such as programming in python and analyzing large data sets. However, these activities will take place in the context of inquiry-based laboratory exercises. Topics for the lab exercises will include simulation of population biology using self-replicating computer programs, and exploring the evolution of protein-protein interactions using a simulation of protein folding. Students will explore how to design experiments as well as how to analyze and interpret their results.

A typical project in our stream will involve original research exploring a followup question to a known result. A small group of students from FRI have already begun following this model for summer research. For example, the RE, Art Covert, has studied how the fitness effects of individual mutations have changed through time in asexual lineages of self-replicating computer programs. Art found that individual mutations of deleterious effect were occasionally not only compensated for, but even became critically important when joined with another mutation. A new FRI student, Lane Smith, is now recapitulating Art's earlier work, but in populations with haploid sexual reproduction. Lane's project is examining whether similar interactions among mutations take place in sexual populations. In order to accomplish this work, Lane must not only have an understanding of the biology involved, but also solve several computational problems, such as reconstructing a genealogy containing millions of genomes and then determining the evolutionary outcome of each mutation in it. Lane has been keeping a blog of his research experiences over the summer (http://knyon.com/summerfellow/).

Training and development: All students who complete the stream will have at least one year of programming experience with python, doing statistical analysis on large data sets. This includes not only obtaining data, either by simulation or from multiple online repositories, but also examining the data to address a specific scientific question. The students learn programming and statistical hypothesis testing. They also learn how to use parallel processing and high-performance computing. Finally, the students learn how to interpret the results of the statistical tests in light of the biological hypothesis they are interested in. Students are required to document their findings online using research blogs to describe what they are doing and what problems they have encountered.

Broader Impacts: Students from the computational biology stream gain a unique scientific insight from the nature of our cross-disciplinary work. The successful students from our stream will have learned how to synthesize concepts from computational and biological sciences to make new discoveries. In addition, the unique nature of the research in the stream should help draw from under-represented groups in both disciplines.

2b. Professional development activities

BEACON is actively engaged in professional development activities for center students, in line with our Optimal Outcome #1 of training and placing graduate students in multidisciplinary positions. BEACON provides support for students to travel to and present at scientific conferences. In the past year BEACON graduate students and postdocs have contributed over 30 presentations at conferences. BEACON faculty offer a grant-writing workshop, which has as a specific goal of students identifying and preparing a grant for submission.

BEACON has also recently created and provides support for a BEACON student/postdoc group. These students have met with the Education Director and are currently considering how best to use BEACON funds for a combined professional development/outreach project. BEACON is also joining with the Center for Academic and Future Faculty Excellence to provide additional BEACON-centered training sessions for graduate students and their mentors.

2c. External education activities

BEACON is currently funding a number of educational activities and programs, all which meet our EHRD goals and optimal outcomes. These projects range from evolutionary games for elementary students to software that engage undergraduate students in testing evolutionary hypotheses.

Activity Name	**BEACON High School Summer Residential Program**
Led by	Drew Kim (MSU)
Intended Audience	High School Students
Approximate # of attendees	30

BEACON High School Summer Institute: In July 2011 twenty-eight students participated in the weeklong program, learning about evolution in action. Seventeen students self-identified as female (61%) and 16 students identified as minorities (57%). The students were primarily entering their senior year of high school (57.7%), though matriculating college first year students (19.2%), high school juniors (15.4%) and high school sophomores (7.7%) also participated in the program. Students spent two full days at Kellogg Biological Station and three days on the MSU main campus. Morning sessions focused on activities highlighting evolution in action, including a study of fitness in milkweeds, selection in damselflies, and ecological interactions among strains of bacteria. Participants identified the classroom, laboratory, and field experiences as those they were most looking forward to (13 comments of the 34 received). When reflecting back on the program, students cited those activities 28 times in the 42 comments.

This program was evaluated with pre- and post-survey instruments. Students participating in the program made significant gains in their self-reported understanding of evolution in action,

moving from a mean of 2.19 (stdev = 0.49) on a scale of 1-4, to a mean of 3.54 (stdev = 0.58). The highest ranked educational session was the damselfly field experience in the stream (mean 1.14, stdev = 0.45, 1 = excellent, 4 = poor). Overall, students were pleased with their experience with the BEACON high school summer program (mean 1.64, stdev = 0.68, 1 = excellent, 4 = poor). When asked if students would recommend the BEACON summer program to others, 24 of the 28 participants said yes. Part of the program took place at the Kellogg Biological Station (KBS), including several lab/field experiences. Student feedback indicated a desire to remain at KBS for longer than two nights/two days, as the learning environment was more "fun," providing more opportunity for hands-on experiences, and the accommodations were more "homey" than what was experienced on the campus at MSU. The program next summer will held entirely at KBS.

Activity Name	**BEACON REU Field Experience**
Led by	Kay Gross (MSU) and Billie Swalla (UW)
Intended Audience	Undergraduate Students
Approximate # of attendees	25

BEACON REU Field Experiences: The primary goal of the BEACON REU program is to provide undergraduates with a research experience that will deepen their understanding of the importance and dynamics of evolution in action in natural systems and introduce them to various approaches and tools that are used in this research. The REU program broadens the diversity of students participating in BEACON research (and STEM disciplines more broadly), by coordinating recruitment efforts with the diversity programs at BEACON member institutions. The program also provides an opportunity to promote new cross-disciplinary research opportunities by enhancing relationships among disciplines and partner institutions.

BEACON REU experiences at both KBS and FHL for 2011 included: a mentored independent undergraduate research experience, BEACON research seminars throughout the summer, videoconference discussion of research projects and experience working at field stations with REUs at both sites, weekly professional development seminars (including RCR training), and student research presentations and final papers submitted at the end of the summer. This program structure gave students an opportunity not only to conduct research on contemporary topics in evolution with BEACON faculty, but also to be exposed to a variety of other BEACON projects at each of the participating BEACON partner institutions. Coinciding with this goal, students also learned common approaches and methodology to study questions with modern genetic and genomic tools. In addition, the ability to recruit and collaborate with multiple BEACON partner institutions (MSU, UW, and NC A&T) increased REU diversity, and gave the REUs a cross-disciplinary and cross-institutional research experience.

Activity Name	**Developing ribozyme evolution assay for undergraduate education and K-12 outreach**
Led by	Andrew Ellington
Intended Audience	K-12, undergraduates
Approximate # of attendees	

Ribozyme evolution assay: This project worked with the UT Freshman Research Initiative to develop, test and distribute a new hands-on inquiry activity for high school students, so they may gain a practical understanding of evolution and selection. The activity involved selecting for ribozyme catalytic function and rapidly evolving populations of ribozymes coding for faster catalysis. The Freshman Research Initiative (FRI) at UT recruits students from diverse backgrounds and underrepresented groups into a year-long authentic research experience. These activities or generated kits will be distributed to high schools, so they may provide students a practical understanding of evolution and selection. In essence, the students will show that they can do test tube evolution that results in a signal that everyone can see.

In the Summer of 2011, Gwen Stovall, under PI Dr. Andrew Ellington, led the Aptamer Stream as the Research Educator. The Ribozyme Stream began as a subset of the Aptamer Stream, containing Tony Hwang (GRA) and Michael Ledbetter (undergraduate researcher and mentor to FRI students). Using Gerald Joyce's molecular system, the students designed a couple of continuous ribozyme selection schemes, while building a control and a degenerative pool. The pool has been partially sequenced for verification. An initial ribozyme assay indicates a successful ligation.

Future work includes evaluation of the continuous evolution schemes: (1) a single ribozyme clone (i.e., b1-207 ligase ribozyme) repeatedly passaged using error prone polymerase; (2) the 15% degenerative ribozyme pool. The students will work on the adaptation of the system to a fluorescence or colorimetric reporter. Perhaps the most technical challenge of the project will involve adapting the system, such that it is economically feasible and practical, to the scale and setting of a modern high school science class. We have contacted high schools to distribute the kits once completed.

Activity Name	**Online Teacher Education Course**
Led by	Randall Hayes (NCAT)
Intended Audience	K-12 Teachers
Approximate # of attendees	

Teaching Evolution. This online course is being piloted with three master's students at NC A&T during the fall semester. Students are introduced to various online resources, including the National Association of Biology Teachers Evolution Symposium webcast, as well as topic-specific content such as Understanding Evolution. Students will learn to use Avida-ED, to test lessons developed at MSU, and to provide suggestions for integrating this new instructional tool into their classrooms. Following an introduction to the content of evolution, students will follow the PBS module, Teaching Evolution in the 21st century developed by the BEACON Education Director, Louise Mead. The course will run again during summer 2012 with full administration support.

Activity Name	**Engaging Educators with Evolution in Action**
Led by	Randall Hayes (NCAT) and Tom Getty (MSU)
Intended Audience	K-12 and Undergrads
Approximate # of attendees	~200 students, mostly African-American

Engaging Educators with Evolution in Action: Cutting-edge BEACON research will be incorporated into classroom modules for a Science, Technology, & Society class at the undergraduate level. English faculty have met with BEACON faculty at NC A&T. These English faculty will use their 4 sections of our STS course (96 students) to test and revise their lesson plans over the course of the academic year. We will then make the plans available through the BEACON website to any of the partner institutions who want to test them out. We will then begin looking for BEACON scientists to collaborate with at the partner institutions, with an eye towards summer travel during 2012.

Online curriculum guides for science fiction short stories dealing with evolution, targeted towards grades 9-16, will also be developed to encourage the reading skills necessary for success in graduate or medical school. Progress: Chad Rohrbacher has produced a draft of discussion questions focusing on social issues and writing process for 6/7 stories in the Origins: Tales of Human Evolution anthology. He has contacted the publisher, Hadley-Rille Books, about cross-promotion of the curriculum guide.

Finally simple, fun, scientifically responsible computational models of evolution are being developed for elementary school classrooms. Cathy Scott has produced drafts of two 45-minute fourth-grade lesson plans for EvoDots, focusing on graphing of data generated by the program. She has found a school (General Greene Elementary) and a teacher (Carrie Barrett) to partner with, and installed the program on the school's computers. She will begin testing those this fall, as we continue to develop other lesson plans around the keeping of records, the combination of data sets from replicated experiments, and the sequencing of events in evolutionary change (variation -> selection -> inheritance), which is a sticking point for college students, who tend to hold more Lamarckian views of evolution (selection -> variation -> inheritance). She has applied to present this work at a regional conference (SEPEEG) in October.

The goal for the part of this work done at MSU is to facilitate the achievement of the goals established at NCATSU and articulated above. Focus is on the design and testing of exciting, effective, standards-compliant lessons on evolution in action for use in K-12 classrooms, with an emphasis on computer simulations such as Ladybug and Aphids, EvoDots, and BoxCar2D. Progress: Melissa Kjelvik, a PhD student in Zoology at MSU, began work on the project in August, under the supervision of Tom Getty. Melissa has met with Terry Soule to begin developing plans for modifying and integrating Ladybug with classroom activities.

Activity Name	**Avida-ED Infrastructure Maintenance and Development**
Led by	Robert Pennock, Louise Mead, Charles Ofria, James Foster, Joseph Graves, James Smith, Billie Swalla, Claus Wilke
Intended Audience	Undergraduate, Graduate students
Approximate # of attendees	

Avida-ED: The goal of the project is to update the code base of Avida-ED, our digital evolution software designed for educational use in undergraduate and graduate courses, and then to provide training workshops to partner universities so that it can be used across BEACON. In the original proposal, the plan was to do workshops in the first year just with NCA&T and Univ. of Washington, but we expanded this to include UT-Austin and University of Idaho. So far we have given on-site presentations at all the partners except Idaho, and that last one is scheduled for November. We also gave a well-received tutorial at the BEACON Congress. Avida-ED will

be used in courses at all partner sites by Spring. Pennock and Ofria hold a weekly software development meeting with graduate student / programmer Dave Bryson. Specific coding progress has been made and we expect the alignment to be complete by January 2012.
As the full revision was not going to be ready for fall classroom use, we fixed a font display problem in the current version of Avida-ED that appears when it is run under Mac OS 10.6 so instructors can continue to use it now. We hope to have a beta of the full revision ready for use in the spring.

We submitted an NSF TUES Type 2 grant proposal to develop and distribute the next major release of Avida-ED, but were not funded. We are working to correct identified weaknesses in the proposal (e.g., need for evidence of classroom effectiveness) by beginning an assessment study with current users. This was not part of the original BEACON Avida-ED project, but starting this now will put us in a stronger position for the next TUES grant RFP. To accomplish this, we have added two science education graduate students to the project. Amy Lark will study implementation of Avida-ED and its effects on inquiry-based pedagogy as part of her PhD research project, and Wendy Johnson will study its effectiveness for student learning of evolutionary concepts as part of her Master's research project. We have also added faculty member Jim Smith to the project, who has volunteered to help with the design of the assessment questions.

We have also begun work on curriculum development. Peer-reviewed model exercises, aligned to the content and skill goals of the new national undergraduate biology standards, are being revised and supplemented with instructor support materials. Our goal is to have a set of example exercises and labs that instructors can use or modify for using Avida-ED in their own courses. Pennock and Mead hold a weekly curriculum development meeting with Lark, Smith and occasionally others. We are just in the early stages of this, but expect to have at least a core set ready for the spring.

Activity Name	**Teaching Evolution Through Action: The AVIDA Challenge**
Led by	James Foster, Terence Soule (UI)
Intended Audience	Undergraduates and high school students
Approximate # of attendees	

The Avida Challenge: The goal of this project is to develop a set of programming/evolutionary challenges to be addressed in AVIDA. These challenges will be designed to meet several specific objectives: (1) to encourage the learning and exploration of AVIDA; (2) to teach the essential concepts of evolutionary theory and artificial life; (3) to encourage the use of AVIDA at both BEACON partners and other institutions; (4) to encourage the use of AVIDA by undergraduates and high school students. In addition, the overall project also includes designing AVIDA documentation/training materials suitable for competition participants and evaluating the effectiveness of both the contest and the documentation in teaching and encouraging interest in evolution, artificial life, and AVIDA. **Progress:** Still in the preliminary stages of the project, a new team has been identified to pursue this project. The contest theme will be the evolution of cooperation and communication and planning for the organization and logistics of the contest, submission methods, judging, etc., has started. The next steps for this project include the following: (1) finalize the problem details; (2) coordinate with

Dr. Gerry Dozier at NC A&T to design appropriate evaluation tools; (3) develop AVIDA documentation and teaching materials appropriate to the skills required for the challenge; (4) design the 'advertising' material necessary to encourage participation in the challenge.

Activity Name	**Evolution Podcast "Variation, Selection, Inheritance"**
Led by	Randall Hayes (NCAT)
Intended Audience	General Public
Approximate # of attendees	Unknown

Evolution Podcast: As of October 2011, 22 episodes of VSI have been produced, ten in the spring (March-May), and four since August. Guests have ranged from scientists to an entrepreneur to an internet activist. A website was created (http://variationselectioninheritance.podbean.com) on the podcast hosting service Podbean.com. Podbean performs numerous useful services, including automatically cross-posting audio to the popular site iTunes and recording rudimentary download statistics. The podcast has been downloaded over 1000 times and the site visited by people from at least 15 countries on every continent except Antarctica. Traffic has grown slowly but steadily since March. BEACON is also currently reposting links to all blog posts and episodes. An undergraduate journalism major named Lauren Branch has been hired to edit audio and manage web pages. She will build a cross-posting Facebook page and manage the Twitter account. Additional plans are underway to cross-post the podcasts through the National Evolutionary Synthesis Center and advertise at public meetings such as Audubon Society meetings and at any professional meetings.

Activity Name	**Evolutionary Games**
Led by	Stephen Thomas, Louise Mead, Ethan Watrall (MSU)
Intended Audience	General public
Approximate # of attendees	Unknown

Evolutionary Games: Excellent progress is being made on the development of games that help to explain components of evolution and can be delivered on touchscreen kiosks in museums. Two games are currently in development, one on variation and the other on natural selection. The objectives of these games include: 1) visitors "watch" evolution in action as biological forms become better selected to their environment in the natural selection game; 2) visitors investigate changes in organisms through time as either caused by mutation or environmental factors as seen in the variation game; 3) visitors consider the relationship between evolution and engineering by reading about research being conducted by BEACON faculty in the "more information" section of each game. Designing games for a public audience includes a number of challenges including: 1) the average time a museum visitor spends at a display is only a couple minutes, requiring the games to be quick and engaging; 2) the recommended educational level for museum materials is approximately 8th grade level, requiring the games to be general enough for a middle school audience, while simultaneously teaching a complex topic; 3) flexibility to be put in any natural history exhibit. Upon completion of the games in

November, they will be incorporated into the BEACON exhibit in the MSU Museum. Our Education Advisory Board will be asked to provide feedback.

Activity Name	**Evolutionary Games for K-6th**
Led by	Terence Soule (UI)
Intended Audience	K-8, General Public
Approximate # of attendees	Unknown

Evolutionary Games for K-6th: The goal of this project is to develop and refine two simple games that illustrate evolution in action. The primary target is kindergarten – 6th grade. Based on suggestions and recommendations from a number of BEACON members with strong educational backgrounds, we are making the following modifications to The Ladybug Game, in which players use the mouse to guide a ladybug to capture aphids: 1) aphids can now sense and thereby learn to actively avoid the ladybug; 2) additional data displays have been created that allow more sophisticated players to trace the progress of evolution; 3) several autonomous ladybug behaviors have been added, allowing the player to observe how the aphids evolve in response to fixed behaviors on the part of the ladybug; 4) players can change the background color to study how that influences player behavior and in turn aphid evolution. We are developing educational materials that will allow the ladybug game to be brought into more formal classroom settings.

Activity Name	**Museum Exhibit: Relevance of Evolution to Our Daily Lives**
Led by	Christina Cid and Edward Theriot (UT)
Intended Audience	K-12, Undergrad, Grad, General Public
Approximate # of attendees	Unknown

Relevance of Evolution to Our Daily Lives: Under the supervision of the Director of Education at the Texas Natural Science Center, a graduate student is working with BEACON scientists, starting at UT Austin and then expanding the conversation to include all BEACON partner universities, to develop up to 10 narratives that can be used on interactive exhibit modules.

Once material is developed, collaborations with BEACON partner museums will ensue. We will identify representatives and diverse research occurring at the other institutions to highlight in exhibits at remote institutions.

As the graduate student hired for this project, Laura Crothers developed and distributed a template to scientists interested in having their research featured in the exhibit. The responses to the questions on this template will provide the foundation for the research narratives in the exhibit. Ms. Crothers attended the 2011 BEACON Congress and there began to forge collaborations with members of the Michigan State University museum and start conversations with researchers at both the University of Washington (Shou Lab) and North Carolina A&T State University (members of CASIS) to have their research featured in our exhibit. Ms. Crothers also intends to contact several BEACON researchers at UT-Austin and MSU for this purpose. We have also begun to contact companies (e.g., Snibbe Interactive) to get quotations for interactive

components of the exhibit, and are discussing general themes with which to organize the narratives of the exhibit.

Activity Name	**MSU Museum BEACON Education and Outreach**
Led by	Gary Morgan, Julie Fick (MSU)
Intended Audience	General Public
Approximate # of attendees	Unknown

MSU Museum BEACON Education and Outreach: The MSU Museum is working to deliver educational products that engage the broadest of audiences with the relevance and research of BEACON. Progress made to date on all of the MSU Museum BEACON educational products to date follows:

"Origins of Life: Experiment 1" Exhibit

Project goals:
1. To artistically reconstruct Urey-Miller's experiment in a museum exhibit.
2. To engage museum visitors with science and art in an interdisciplinary manner that was both visually stimulating and thought provoking.

Description and progress:

This exhibit re-interpreted the classic Urey-Miller experiment of the 1950s, where amino acids (the building blocks of life) were created using the three primary gases present in the primordial atmosphere of the Earth, together with electricity and water.

The project was a partnership between the MSU Museum and the three artistic curators – Adam Brown, Bob Root-Bernstein and Maxine Davis of MSU. The installation was set up in the MSU Museum's newly established art-science-creativity space from February through April 2011. This work of science-art asked the audience not only to think about the nature of research but also to ask where does practical science become art, and vice versa.

Following the display at the MSU Museum, the exhibit was presented at *Synth-ethic: Art and Synthetic Biology* exhibition at the BIO:FICTION science, art and film festival in Vienna. The exhibit is currently up in Linz, Germany as part of the Ars Electronica 2011 Festival for Art, Technology and Society. Outside funding is being sought to allow the exhibit to travel to at least two more venues. Eventually, a location at MSU will be identified where a version of the apparatus can be running continuously for both educational and experimental purposes.

"Evolution In Action" Exhibit area at MSU Museum

Project goals:
1. To create a small, portable or replicable exhibit describing BEACON's purpose and mission to the public and provides a cornerstone for additional BEACON exhibit components.
2. To present current "evolution in action" research in an accessible and understandable format to the general public.
3. To create a gallery space where evolution in action research could be highlighted through smaller exhibits that change periodically.

Description and progress:

This first installment of the "Evolution in Action" exhibit has three components, described below. It will visually and auditorily show visitors how scientists can actually SEE evolution happening in current populations of organisms and how evolutionary principles can help bring about advances in technology. The portions of the exhibit that are currently viewable or scheduled to be installed by September 30, 2011 include:

- **Introduction to BEACON** and the concept of "evolution in action".
- **"Hyenas Rule"** (exhibit): Featuring research on spotted hyenas in Kenya, what we can learn from them about the evolution of social behavior, and how research into the evolution of cooperation and intelligence can be applied to robotics.
- **"50,000":** Featuring Dr. Richard Lenski's long term evolution experiment, where researchers have followed the evolution of 12 lines of *E.coli* for over 23 years and 50,000 generations, exploring the mechanisms and repeatability of "evolution in action". The 50,000 generations theme is also presented in an articulated "Nariokotome Boy" (*Homo erectus*) specimen, to help visitors connect their understanding of generations and evolution over time in both *E. coli* and humans.
- **Specimens:** a fully mounted adult spotted hyena, a hyena skull with giraffe leg bone, and a *Homo erectus* skeleton.
- **Technology** in the exhibit area will include: two video touch screens, one interactive touch screen with evolution games, "QR" codes with additional online resources, and if possible, an example of augmented reality relating to at least one of the specimens.

Current and future pieces in this exhibit will be designed so that they can be used as portable, stand-alone exhibitions, or integrated together to provide a more comprehensive learning experience. Exhibit content is targeted to the middle school reading and comprehension level yet remaining interesting and thought provoking for adults.

"Hyenas Rule" (VOP)

A draft of a virtual outreach program (VOP) about hyena evolution research was started in early 2011 but not yet completed. This second year BEACON project is currently being reviewed by the MSU Museum education specialist and is scheduled for completion by spring of 2012. Products will include a 40-50 minute IVC (interactive video conferencing) program for secondary science students and accompanying teacher materials.

Activity Name	**Art & Evolution: Evolving Social Behavior of Liminal Machines**
Led by	Adam Brown, Philip McKinley, Xiaobo Tan
Intended Audience	General Public
Approximate # of attendees	

Art and Evolution: The Biolume project is a collaborative effort aimed towards creating an evolution-based art exhibit. Using the combined resources of artists, computer scientists, and electrical engineers, the project will bring the concept of evolution in action to the general public. The exhibit was designed to provide an easily approachable, hands-on experience to people of all ages. A population of Biolumes–immobile robotic agents–will be distributed throughout a provided space. Each unit will be capable of sensing the presence and proximity of

patrons and then interacting with patrons through the display of different evolved behaviors. The fitness of a Biolume is determined by how much interaction it is having with patrons. Thus, when a patron walks near, speaks to, or touches a Biolume, it will have a higher chance to pass its genes–and resulting behavior–to another Biolume. As a consequence, the exhibit's audience will dictate the behaviors that the Biolumes will express and maintain.

The first iteration of the prototype hardware for Biolume has been engineered. This first round of hardware is capable of sensing CO2, sound, video slip, touch and proximity. Actuation will be in the form of multi-colored lighting and pre-recorded sound delivered via a small embedded speaker. It is now being designed for surface mount application to prepare the circuit for mass production. Once the surface mount circuit has been fully prototyped, the exterior shell making the Biolume will be designed and fabricated. During the prototyping phase efforts are now being made to migrate software from simulated form to the new hardware.

To explore Biolume functionality in parallel with development of the hardware, we constructed an interactive Biolume simulator. Under this model, a human user interacts with virtual Biolumes through the cursor. Every movement and placement of the cursor provides feedback to all units in the vicinity. As in the actual exhibit, virtual Biolumes receive a fitness bonus for all interactions. The evolutionary model utilized in this system is that of linear genetic programming. Each Biolume behavior is expressed by executing a linear interpreted set of instructions. This set of instructions in encoded in the genes, which can then be passed from Biolume to Biolume during replication. The simulator is written in Java and uses the Processing toolkit for animations. Porting of this model re-implemented in the C programming language, is underway. Biolume is scheduled to be installed at the BEACON headquarters during the Spring 2012 semester.

The Biolume simulator was developed as part of a Research Experience for Teachers project. A local teacher, Adam Ford, developed the simulator in collaboration with two CSE graduate students, Daniel Couvertier and Tony Clark. Adam is a teacher at Wood Creek Magnet School in Lansing, Michigan, which serves a high percentage of students from underrepresented groups. Adam, who is African American, has been heavily involved in K-12 robotics activities and competitions for several years. Adam is currently developing corresponding lesson plans that integrate evolutionary robotics and basic engineering principles to create novel experiences for 4th-6th graders.

Activity Name	**BEACON – Michigan After-school Partnership**
Led by	Judi Brown Clarke
Intended Audience	K-12
Approximate # of attendees	

BEACON-MASP: Beacon is partnering with the Michigan After-school Partnership (MASP), a statewide network that provides statewide leadership to build and sustain high quality, after-school programs for children and youth in all communities throughout the state. MASP links stakeholders interested in improving outcomes for children and youth through school-based/school-linked and enrichment after-school programs. Stakeholders include policy-makers, educators, child care providers, youth development workers, program developers, advocates, parents, and others.

Diversity Director Judi Brown Clarke, a member of MASP's Executive Committee and STEM Education Committee, successfully co-wrote a funded $150,000 proposal to the NOYCE

Foundation called Project LIFTOFF, an initiative to build state systems for informal science education in the Midwest. Specifically, Project LIFTOFF SySTEM Grants are designed for the implementation of Statewide After-school Networks' visions and plans for statewide systems for informal science education. BEACON will collaborate and infuse *evolution in action* into the following goals:

- Quality Systems/Professional Development: Develop and implement professional development opportunities that incorporate informal STEM knowledge with youth development
- Communication/Awareness Building: Develop a communication plan to increase informal STEM education awareness among stakeholder groups, including constituents, funders, policy makers, providers, and the public
- Grow a body of research data to evaluate the provision of informal STEM experiences in after-school programs: Document evidence of quality indicators in professional development via surveys and observations

Other Outreach Activities

BEACONites are dedicated to our educational mission and goals, and have participated individually in many other education and outreach activities.

Teacher Training: Discovering the Art & Science of Tracking Dinosaurs. Christina Cid, Pamela Owen, John Maisano. April 2, 2011; July 20-21, 2011. An integrated art and science teacher training program in which 3-12 grade teachers worked with a paleontologist and an artist to: demonstrate how dinosaur tracks provide evidence for dinosaur anatomy, behavior and ecology; investigate characteristics shared by birds and extinct dinosaurs; learn how to draw birds and other dinosaurs; collect and analyze data from dinosaur trackways to hypothesize locomotory behavior; and evaluate artwork depicting dinosaurs and ancient environments. Teachers participated in inquiry-based activities aligned with Texas science and art curriculum standards using Texas Natural Science Center specimens and exhibits. Audience: K-12 teachers and program leaders from the Boys & Girls Club. Attendees: 55.

The joy of looking: recipes for discovery. Idelle Cooper, Thomas Getty. Plenary lecture for K-12 Partnership Workshop. Audience: Elementary and high school teachers. Attendees: 75.

Michigan's Most Deadly. Heather Eisthen**,** Jake Billhorn, Justin Schroeder. September 25, 2011. A public presentation about the toxic and venomous animals of Michigan, including information about the evolution and function of toxins/venoms and the mechanisms by which they work. Audience: public. Attendees: 30.

Training for interaction with public and press. James A Foster. September 15, 2011. The UI sponsored a limited workshop for faculty and staff on "Informing & Serving Society: Effective Communication & Engagement". All IBEST/BEACON personnel were invited by the local director. Audience: Faculty and staff. Attendees: unknown (from BEACON), 100 max.

Odyssey Camp. Patricia Hartzell**,** Jill Johnson, May 25-26 2011. I developed and taught 60 students, age 11-14 (and chaperones) for hands-on laboratory experience (two sessions: lecture and 2 hr interactive lab per session). Audience: junior high school students. Attendees: 67.

Palouse Discovery Science center. Patricia Hartzell, monthly. **M**ember of the board of directors; participate in fund-raising, planning displays, teaching. Attendees: 1000 annually.

Models: Reality, Simplified. Randall Hayes, July 16, 2011. He spoke to the North Carolina Governor's School West natural sciences students about his career as a researcher, educator, and podcaster. Audience: Gifted/talented high school juniors. Attendees: 45.

Some surprising results in the evolutionary race. Richard Lenski. March 22, 2011. Video interview for NSF website. Discussing recent research findings on evolvability from experiments with evolving bacteria. Audience: General public.

High School Tour of MSU. Philip McKinley**,** Chris Waters. Phil McKinley and Chris Waters hosted the DeWitt AP high school biology class during their visit to MSU. The students toured both laboratories and learned about the evolution of cooperative behavior in both virtual, robotic, and bacterial systems. The students were able to culture their own bioluminescent bacteria and observe robotic fish. Audience: high school students. Attendees: 22.

Evolution 101: Evolution and You. Louise S Mead, Kristin Jenkins. June 17, 2011. K-12 Evolution 101 Workshop at the Society for the Study of Evolution annual meeting. Audience: High school and college faculty. Attendees: 25.

SSE Education Workshop - Evolutionary Medicine. Louise S Mead**,** Kristin Jenkins. June 18, 2011. An outreach workshop for participants at the Society for the Study of Evolution Annual Meeting. Audience: College faculty. Attendees: 30.

Think Evolution III: Summer Institute for Science Educators. Louise S Mead**,** Judy Scotchmoor. August 1-5, 2011. Put on your evolution eyeglasses and your nature of science thinking cap and join us for (yet another) fun-filled five days of evolutionary explorations with biologists and educators from the University of California. Audience: High school and community college faculty. Attendees: 30.

Science Cafe Presentation. Robert T Pennock. February 8, 2011. He gave an invited Science Cafe organized by the Clemson University Sigma Xi chapter in Clemson, South Carolina. Held in a popular local bar, the informal presentation and open discussion attracted mostly members of the general public and some students. The lively discussion covered topics ranging from evolutionary computation to cultural factors affecting public acceptance of evolution to philosophical issues about the nature of science. Audience: General Public. Attendees: 25.

Darwin Discovery Day exhibit. Robert T Pennock**,** Rosangela Canino-Koenig, Louise Mead. February 13, 2011. Presented a hand-on exhibit on BEACON's evolutionary engineering and robotics work for the MSU Museum's Darwin Discovery Day. Visitors could observe and interact with E-Puck tabletop mobile robots whose behaviors had been evolved, talk with BEACON researchers, and learn how evolutionary computation is being applied to solve real world engineering problems. Audience: Middle school children and parents. Attendees: 150+.

Save the Frogs Day. Bree Rosenblum. April 2011. A day-long outreach activities to promote knowledge about biological diversity and conservation. Science and arts activities focusing on amphibians. Fun! Audience: Preschool children. Attendees: 20.

Lizard Camp. Bree Rosenblum. June 2011. Two daylong outreach activity for middle school students in New Mexico (at our field site) focused on understanding evolution in action in

White Sands lizards. Wild success - the students had a blast! Audience: middle school students. Attendees: 30.

Sturgeon Fisheries Education Teacher Workshop. Kim Scribner. August 11-12, 2011. Educating K-12 students and the general public about ecological and evolutionary questions developed in the context of Great Lakes ecosystems and inter-dependencies between fish communities and physical and biological stream processes is critical to increase awareness of evolutionary perspectives that can guide stewardship activities. The teacher workshop and associated grant will serve as a hub of information resources on Great Lakes-tributary ecosystems, emphasizing lake sturgeon, a large charismatic species of conservation, management, and public interest. Audience: K-12 teachers and science education professionals. Attendees: 22.

National Lab Day sponsored by HHMI. Billie J Swalla**,** Max Maliska, Char Konikoff, Lena Perry, Peter Wu. May 6, 2011. Two 30 min. sessions describing Swalla Lab Research with a group of sixth graders from Sacajawea Elementary School in Seattle Public School District. Audience: Sixth graders. Attendees: 20.

Public Lecture at UW FHL Open House. Billie J Swalla. May 14, 2011. Regeneration in Marine Animals. Audience: General Public. Attendees: 35.

Research Experiences for Teachers (RET). Xiaobo Tan**,** Drew Kim, Philip McKinley, Robert Pennock, Charles Ofria. June 19 - August 5, 2011. The RET Site on Bio-inspired Technology and Systems (BITS) supported three teachers working on BEACON-related research and curriculum development in summer 2011. Wendy Johnson, Jeff Farell, and Adam Ford worked under the guidance of Profs. Rob Pennock, Charles Ofria, and Philip McKinley, respectively, gained knowledge and experiences in evolution in action, and developed new curriculum materials that had been submitted to teachengineering.org, a nationally recognized repository for new course materials. Audience: School teachers. Attendees: 3.

Frontiers in Sciences Workshop. Xiaobo Tan. March 26, 2011. Tan conducted a five-hour workshop for the participants in the graduate program for science teachers, offered by the MSU College of Natural Resources, Division of Science and Mathematics Education. Activities included a presentation on robotic fish research, introduction to the Research Experiences for Teachers (RET) Site program, and lab tour. Audience: Science teachers. Attendees: 15.

Women in Evolution and Other Sciences. Emily G. Weigel, Jenny Boughman, members of Graduate Women in Science. February 13, 2011.At MSU's annual Darwin Discovery Day, we created an exhibit to highlight the role of women in evolution and other fields of research. The exhibit featured current women scientists at MSU, as well as a timeline of women in STEM fields. Younger audiences were also able to create and color their own scientist, which promoted the idea that scientists can be diverse in both their activities and as people. Audience: General Public. Attendees: 300.

Girl's Math and Science Conference (East Lansing, MI). Emily G. Weigel. February 12, 2011. Worked with the Ingham Intermediate School District Talent Development Office to develop eco-friendly alternative to the handouts given at the annual event. Created a take-home interactive page on USB drives for the girls to learn about evolutionary biology and other STEM subdisciplines. The page included links to interactive games, puzzles, archives, and homework websites, as well as dynamic, always-current links to the major science and technology journals

and news sources. For parents, this interactive page was combined with resource articles provided by the school district on encouraging girls in STEM. Audience: Middle-School Girls (grades 6-8) and Parents. Attendees: 150+.

Plainwell Science Day. Emily G. Weigel**,** Liliana Lettieri. March 31, 2011. Presented sticklebacks as a model of rapid evolution to elementary and middle school children. Highlighted sexual dimorphism in live fish and the global habitat distribution and incredible morph variety through a powerpoint. As members of Graduate Women in Science, also included presentation slides of photos of female scientists and short descriptions of their projects at MSU. Audience: Elementary and middle schoolers & their families. Attendees: 200.

Citizen Science. Danielle J. Whittaker. January 2011. This course is a new required 3-week winter intersession class for freshman at Bard College in New York, designed to increase scientific literacy in all of Bard's students. I taught one of 24 sections and focused on Evolution as a theme throughout all of the topics. Audience: College freshmen. Attendees: 20.

2d. Integrating research and education

The Michigan State Museum and the Texas Natural Science Center are both working on exhibits that highlight BEACON research. The MSU Museum Evolution in Action gallery features introductory information about BEACON, as well as the multidisciplinary approaches being taken by BEACON faculty like Dr. Kay Holekamp in her work on hyenas and the evolution of cooperation. The Evolution in Action gallery also includes a series of panels presenting the work of Dr. Richard Lenski and the 50,000 + generations of evolution in E. coli in his lab.

Researchers (faculty, postdocs, grad students) have also been working to adapt research for classroom use. For example, Anne Royer and Mike Wiser, two BEACON graduate students, developed a series of lessons and activities for high school students. Each lesson highlights evolution in action.

Many BEACON researchers maintain websites or contribute their research to databases that provide information to the general public. Charlotte Konikoff has updated the Hemichordata World Database, part of WoRMS (www.marinespecies.org/hemichordata/). New species have been added and extant information in the database has been corrected. Additional information on many species (distribution, etymology, type species, holotypes, etc.) has now been added, so that users may quickly find information on this poorly understood phylum.

2e. Progress towards metrics described above

Indicators and metrics for optimal outcome one (placing graduates in multidisciplinary positions) are long-range and we do not have data on these yet. We have collected preliminary data related to the initial BEACON Evolution in Action exhibit at the MSU Museum. While we used these preliminary surveys as formative assessment tools to evaluate the effectiveness of the initial panels, data indicate that students surveyed show an increase in their agreement with statements that evolutionary science can help research in fields other than biology and that evolutionary science is important to society. Data also indicate students moved in their agreement that evolutionary processes can create new structures, functions, and /or behaviors as well as their agreement that science is a collaborative process, with many kinds of scientists and

technologists working together. We also observed some minor shifts in student understanding of evolutionary process – specifically that evolution can be observed.

Progress: Multidisciplinary graduate training

- All three interdisciplinary graduate courses were offered in academic year 2010-2011, with participation from UT, UI, and UW.
- Offered again in 2011-2012, with improvements in technology to improve inter-institutional educational experience.
- NC A&T offering first upper-division undergraduate versions of courses in Fall 2011.
- UI offering Evolutionary Computation in Fall 2011
- BEACON is hosting International ALife 13 conference in summer 2012.
- Professional development through MSU's CAFFE (future faculty enrichment) and informal/formal active mentoring.
- We are creating a tiered mentoring system for training undergraduates through apprenticeships and research experiences.

Progress: Increased public literacy in evolution and the nature of science

- Ten percent of project funding is targeting education and outreach.
- "Evolution in Action" gallery set up at MSU Museum and first two exhibits are in place, third under development. MSU Museum Informal Learning Specialist Julie Fick is working closely with BEACON.
- Other interactive exhibits are in progress, including evolutionary computer games.
- Collaboration with BoxCar2D developer Ryan Weber; this program will be incorporated into the MSU museum exhibit.
- Creating BEACON Education Advisory Board
- Creating a BEACON Education Listserv
- Mead and Pennock conducted Avida-ED training workshops at partner universities.
- Merging of Avida and Avida-ED software is underway.
- Collecting baseline data on undergraduate attitudes toward evolutionary biology.
- We have identified at least one BEACON educational product for each of the following levels (K-4; 5-8; 9-12; Undergraduate) and are developing associated lessons, exercises, and resource material for educators and students.

Progress: Increased interest in STEM careers

- First BEACON High School Residential Program offered in summer 2011. Twenty-eight students from across Michigan and one student from Iowa attended the program.
- Thirty-two undergraduate students from underrepresented groups from across the country worked with BEACON faculty on evolutionary research. Students were funded through a variety of programs and initiatives.
- A total of six Education RAs were hired in BEACON to work on projects across campuses.
- Specific programs aimed at presenting STEM education and careers information to 6-12th graders (~250 participants).
- Student participation in the Freshman Research Initiative at UT Austin provided hands-on research opportunities in computational biology.
- Identification and mentoring of incoming freshmen for future placement in BEACON labs.
- STEAM (Science, Technology, Engineering, Art, and Math) teacher training workshops sponsored by BEACON were held at the Texas Natural Science Center.

- Adam Brown's science art installations appeared in the MSU Museum and are in development for BEACON headquarters.
- Partnered with Michigan Afterschool Partnership on a NOYCE Foundation STEM proposal, which was funded.
- Submitted proposal to NESCent for a Catalysis Meeting on K-12 Evolution Education to Underserved Minorities.
- Collected data on initial BEACON museum exhibits from a sample of community college students and high school students.

2f. Educational plans for next reporting period

First and foremost, we are in the process of establishing a BEACON Education Advisory Board. This board will include university and community college instructors and high school/middle school teachers. The BEACON Education Advisory Board will work with us to develop our educational materials and tools, helping to insure all instructional materials go through a peer review process and are fully tested for classroom use. Second we are also creating a BEACON Educator Listserv for the purpose of communicating important information related to educational outreach. BEACON will also join the National Evolutionary Synthesis Center and the American Institute of Biological Sciences in hosting the Evolution Symposium at the National Association of Biology Teachers in 2012.

Additionally, BEACON is working with CAFFE and the MSU Graduate School to plan more professional development activities for the coming year, including: 1) a College Teaching Certificate program for graduate students and postdocs who plan to pursue academic careers; 2) a Mentoring workshop and support program in the spring for graduate students and postdocs who will be mentoring undergraduates in research programs during the summer; and 3) a "Mini Institute" event that will feature a cluster of professional development workshops targeting both people who want to pursue academic careers and also those who are interested in industry or government careers.

IV. KNOWLEDGE TRANSFER

1a. Overall knowledge transfer goals

BEACON's **Knowledge Transfer goal** is to develop effective mechanisms and pathways to facilitate intellectual exchanges among BEACON partners and industrial affiliates that will support the sharing of knowledge and application of new technology. To facilitate technology exchange, we will establish an Industrial Affiliates Program (IAP) open to all companies.

1b. Goals, metrics, and progress

For each of the KT goals/objectives, we have concrete metrics for assessing our success. In the table below, we summarize the optimal outcomes from our Strategic Implementation Plan, the metrics to measure progress, and our progress to date. We report on our progress in greater detail in Section 2c.

Knowledge Transfer Goals		
GOAL	**METRICS**	**PROGRESS**
Signed Intellectual Property agreements with Industrial Affiliates	Number of IP agreements signed	IP agreements signed for collaboration among 5 member universities; 4 of 5 have signed boilerplate agreement for industrial collaborations through BEACON
Receiving industry-provided challenge problems and data with feedback	Number of instances that challenge problems, data, and feedback are received	2 instances
New collaborative research with Industry partners	Number of publications	1 paper and 1 software program so far
	Number and amount of joint grant proposals submitted	2 proposals submitted
Dissemination and use of BEACON tools and data	Number of downloads of BEACON tools/data relative to baseline	> 8,000 Avida downloads; developing software repository to track other programs
Spinoffs formed	Number of spinoffs formed	1
Adoption of new BEACON-developed technology by industry	Number of instances of BEACON projects, processes, and techniques adopted by industry	None to report.

1c. Problems encountered

No real problems have been encountered yet, with the exception of the boilerplate IP agreement taking longer than expected to finalize (see section 2c). While creating our strategic implementation plan, we anticipated several barriers to success and we are taking actions to avoid/overcome these barriers:

- *Company unwillingness to sign IP agreements*: BEACON will leverage its prior experience with IUCRC IP agreements.
- *Extra burdens imposed on researchers when working with industrial affiliates (e.g. deliverables, deadlines, publication constraints):* The Industrial Affiliates Manager will leverage BEACON participants' experience with contracts to negotiate an acceptable contract and remove some of these burdens from the researchers.
- *Skepticism by Industrial Affiliates about the benefits of providing challenge problems or data to BEACON researchers:* The Industrial Affiliates Manager will show demonstrable results from prior collaborations.
- *Lack of resources to support industry time for collaborative research:* The Industrial Affiliates Manager and the Managing Director will work to identify funding resources for industrial partners, such as NSF GOALI.
- *Tough economic times make resources scarce, limiting industry gifts or internships available for BEACON researchers:* BEACON can provide bridge funds to get collaborations started.
- *Lack of sufficient documentation for disseminating and tracking use of BEACON materials:* The Managing Director and Web Coordinator are working to produce quality online documentation tools.
- *Lack of knowledge about how to get started with forming a spinoff:* The Industrial Affiliates Manager, Managing Director, and Director will work to ensure that participants can easily find information and resources.
- *Faculty may be hesitant to take on the risk of commercializing a new technology:* The Management team will work with an industrial affiliate to demonstrate the benefits of BEACON research on one of their problems, and will help faculty to assess the potential value and impact of the technology.

2a. Organizations with which knowledge transfer occurs and the frequency and type of interactions

- **GENERTIA-II: A proactive vulnerability analysis, design & redesign.** Led by Gerry Dozier. Organizations involved: NC A&T and Secure Designs, Inc. In this endeavor, NCA&T is partnering with Secure Designs, Inc. to develop a system for vulnerability analysis of intrusion detection systems (and firewalls). The name of this proactive and self-healing system is GENERTIA-II (GENEtic inteRactive Teams for Information Assurance). GENERTIA-II is an extension of GENERTIA-I [Dozier et. al 2007; Dozier et. al 2004a; Dozier et. al 2004b; Dozier 2003; Hou & Dozier 2005; Hou & Dozier 2004]. GENERTIA-II will perform multi-packet vulnerability analysis, design, and redesign.
- **Marple: a genetic-algorithm based approach analyzes software models to detect unwanted latent properties.** Led by Betty Cheng. Organizations involved: Michigan State University and Ford Motor Company. Cheng is collaborating with researchers and developers at Ford Motor Company to analyze industrial-strength models to detect unwanted properties. The models are provided by Ford and have been sanitized to remove any proprietary information. This collaboration led to the publication of a full paper in the

International Conference on Model Driven Engineering and Languages (MODELS). In addition, the paper was nominated for Best Paper in the Applications Track.

- **Plato: a genetic-algorithm based approach to automatically generate system configurations that satisfy multiple functional and non-functional optimization criteria.** Led by Betty Cheng. Organizations involved: Michigan State University and Google, Inc. Cheng is working with a researcher at Google to analyze remote mirrors for data servers.

2b. Other outcomes or impacts of knowledge transfer activities not listed above

In parallel with the development of the general IP agreement to be used for the Industrial Affiliates, the BEACON's Industrial Affiliates Manager, Dr. Betty Cheng, has been engaging several industrial organizations to publicize BEACON's mission and provide an overview of evolution in action areas of expertise. She is also working with the PIs at the BEACON partner institutions to coordinate industrial contacts to avoid redundant efforts. Below are representative companies that are in KT discussions with the Industrial Affiliates Manager and the PIs at partner institutions:

- General Motors
- Ford Motor
- Continental Automotive
- Northrup Grummon
- IBM
- National Instruments
- Mechatron
- 41st Parameter
- V-Chain Solutions
- GE Aviation

A couple of activities from other sections of this Annual Report may also be considered KT activities.

- Epifire Software: Efficient and easy-to-use software plays a critical role in computational biology research. Contact network approaches in epidemiology provide sophisticated analytical and efficient computational methods, but currently no opensource toolkit is available for facilitating contact network epidemiology research. The Meyers lab developed the software **EpiFire**, an applications programming (BSD license) and graphical interface (GPL), available for Windows, OS X, and Linux, online at sourceforge.net/projects/epifire. EpiFire has been used extensively for research and teaching at the University of Texas at Austin and the Summer Institute for Statistics and Modeling in Infectious Diseases at the University of Washington. Status: EpiFire is freely available for download.
- Art & Evolution: Evolving Social Behavior of Liminal Machines: The Biolume project is a collaborative effort aimed towards creating an evolution-based art exhibit. Using the combined resources of artists, computer scientists, and electrical engineers, the project will bring the concept of evolution in action to the general public. This project is described in greater detail in the Education section of this report.

2c. Progress towards indicators/metrics listed above

In all of the key categories, except for signing up Industrial Affiliates, we have met or exceeded our target objectives over the past year.

1. Signed Intellectual Property agreements with Industrial Affiliates. IP agreements have been signed among all the BEACON partner universities to enable open collaborations among the universities within BEACON. However, it has taken longer than anticipated to negotiate a "boilerplate" IP agreement acceptable to all parties for signature by Industrial Affiliates. Significant progress has been made, as several drafts have been developed and considered, using the IUCRC IP agreement as a template. As of the end of October, 4 of the 5 universities have agreed to the current IP agreement. Due to personnel turnover at University of Idaho, we are waiting for their IP offices to approve the IP agreement. In parallel, we have already been lining up potential industrial collaborators to sign up as Industrial Affiliates. Given the level of review by university IP officers, we anticipate that industrial IP officers will take at least as long, if not longer, to approve of the IP agreement. As a result, we are amending our original goal of having 5 industrial affiliates signed by October 2011 to having at least 3 industrial affiliates signed by May 2012.

2. Industry-provided challenge problems (i.e. "Real World" problems) and data with feedback. Instead of working with "toy problems," BEACON aims to work on real problems with real data provided by industry. Rather than working with proprietary data, we will ask our industry partners to provide "sanitized" data that will allow us to provide a real solution to a real problem, without requiring companies to disclose any proprietary information.

- In August, 2011, Dr. Oliver Chikumbo, a researcher from Scion, a Crown Research Institute headquartered in Rotorua, NZ, brought to BEACON a problem in rural land use management, which had proved to be too difficult to optimize by conventional multi-objective evolutionary computation means. Erik Goodman and Kalyanmoy Deb, BEACON faculty members, worked with Dr. Chikumbo and developed an approach to solving the problem that included some elements modeled on epigenetic phenomena, while reshaping the 14-objective problem into one with 3 "super-objectives" subsuming those. Employment of different tools for evolutionary search for the Pareto front, combined with the other changes described, yielded a system providing excellent and understandable results using minimal computing resources (relative to the scale of the problem). Next steps anticipated include application for funds to support further joint work in New Zealand and working with researchers at the University of Auckland to develop graphical display tools allowing farmers and land use bodies to visualize alternative scenarios on maps.
- Dr. Betty HC Cheng received a challenge problem from her industrial collaborators from Ford Motor Research in December 2010. This challenge problem involved the model of several interacting automotive subsystems, including door locking, interior lighting, wipers, and power management. The objective of this challenge problem was to use an industrial standard modeling notation to capture the requirements and behavior of these subsystems and then use techniques that Dr. Cheng developed with her students to automatically identify errors in the models. The focus was looking for errors that occurred due to the interactions between the subsystems, including feature interactions. The techniques that they used involved a combination of those that harnesses evolutionary computation to detect hidden, unknown errors in the system, a tool known as Marple, and other tools developed by Dr. Cheng and her group, including Hydra and Cyclops. Hydra translates the graphical models

into a formal modeling language, and Cyclops identifies syntactic and semantic inconsistencies. With this toolchain, these errors are detected and corrected during the requirements phase (earliest part of the development process); otherwise, they would not have been detected until at least the testing phase of the development process, which would be much more expensive to the project.

3. New collaborative research with industry partners. BEACON will conduct collaborative research with partners in industry, and submit papers for peer review. To overcome lack of resources and enable such research, we will identify potential funding sources for industry partners and possibly provide bridge funds in order to get these collaborations started. To demonstrate our success and attract new partners, we will create a webpage describing BEACON's industrial affiliations and the resulting projects. Performance in 2011:

- The collaboration with Dr. Oliver Chikumbo, Scion, New Zealand, resulted in submission of two joint proposals to date, involving Dr. Chikumbo and Dr. Erik Goodman:
  - A proposal to the Marsden Fund, a major funder of research in New Zealand, in January, 2011, for funds to support this international collaboration between Scion and BEACON, was denied in April, 2011.
  - A proposal to New Zealand's International Mobility Fund, submitted in May, 2011, was funded, Contract Number IMF11A-66, in the amount of NZ$6,000, allowing Dr. Chikumbo to be resident in BEACON for one month, August, 2011. The major progress achieved during that visit is described above, and publications and further joint research proposals involving Ph.D. students are expected to follow.
- In the collaboration between Dr. Cheng and Ford, Dr. Cheng, her students, and her industrial collaborator summarized their findings in a technical paper that was submitted to MODELS, the international conference on model-driven engineering. The paper has been accepted for publication and presentation at MODELS to be held in New Zealand in October 2011.
- Dr. Philip McKinley and Dr. Charles Ofria have recently started collaborating with researchers at Northrup Grummon to explore how evolutionary computation can be used in the development of autonomous systems. In addition, Northrup Grummon, based on interactions with Drs. McKinley and Ofria, are actively investigating how Avida can be used to deal with cybersecurity.
- BEACON@A&T researchers have been working with NASA scientists and engineers on developing the eXploration Toolset for the Optimization Of Launch and Space Systems (X-TOOLSS). The software is being developed and maintained by BEACON@A&T. One may download a copy of X-TOOLSS at: http://nxt.ncat.edu.

4. Dissemination and use of BEACON tools and data:

- A one-page overhead describing the mission and scope of BEACON has been prepared and is being used by BEACON members to be included at the end of their presentations. The slide includes the names of the partner institutions and the key thrust areas covered by BEACON research and educational activities.
- Northrup Grummon has provided a gift of $25K to support Drs. McKinley and Ofria to explore how evolutionary computation can be used for the development of autonomous systems.
- For the Avida-ED system, we have the following statistics regarding downloads directly from MSU (since August 1, 2010:

Platform	No. of Downloads
Experimental Multi-Dish version for Mac	174
For Windows	3477
For Mac	1105
Manual	488

Here is a sample of schools that have downloaded Avida-ED: Cornell University, Grinnell College, Michigan State University, Harvard University, North Carolina A&T, University of Idaho, University of Massachusetts, University of Notre Dame, University of Texas at Austin, University of Toledo, University of Washington, University of Wyoming, Utah State University.

- The Digital Evolution platform, Avida, is available for download from SourceForge.net. And since August 2010, we have a record of 8,230 downloads through that site.
- BEACON@A&T have developed the eXploration Toolset for the Optimization Of Launch and Space Systems (X-TOOLSS). The tool is available for download at http://nxt.ncat.edu

5. Spinoffs formed. While no spinoffs were originally anticipated in the first five years of the Center, we have a successful establishment of a spinoff facilitated by the activities of the Center and the initiative of the PI.

- Based on KT seminars presented at the BEACON Congress in August 2010 and followup discussions with other BEACON members, Prof. Risto Miikkulainen (BEACON lead at UT Austin), started a spin-off company, Digital Certainty, Inc., focusing on applications of neuroevolution, and the company is working on executing its first contract in October 2011.

6. Adoption of new BEACON-developed technology by industry. No progress to report this early.

2d. Knowledge Transfer plans for the next reporting period

1. Finalize Industrial Affiliates IP agreement to be used by BEACON and their industrial affiliates
2. Continue to collect additional challenge problems
3. Develop a web-based repository of evolutionary computation techniques/tools developed by BEACON members to be made available to the community. One key feature of this centralized repository is to include a tool for collecting metrics about downloads and usage.
4. Sign up at least 3 industrial affiliates by May 2012
5. While the repository is under development, have all BEACON partners add mechanisms to track access to their respective tools and techniques
6. Explore how citations to papers written by BEACON members can be tracked.
7. Put together a resume repository for BEACON students that can be accessed by faculty members receiving requests from industrial organizations with available internships or permanent jobs. Many students indicated at the last BEACON Congress their interest in gaining industrial experience in the form of internships.

V. EXTERNAL PARTNERSHIPS

1a. Describe the Center's overall goals and/or objectives for developing external partnerships.

BEACON aims to form external partnerships with other researchers who are working in the area of evolution in action. Most of these partnerships take the form of visiting researchers on sabbatical.

In its third project year, BEACON is initiating a program aimed at creating external partnerships with minority faculty members and/or faculty members at minority-serving universities. BEACON is also collaborating directly with NESCent, the National Evolutionary Synthesis Center, in many projects involved in education and outreach. BEACON has also begun working with the National Association of Biology Teachers to introduce BEACON-developed educational materials into high school and college biology courses.

1b. Performance metrics

We are keeping track of the number of researchers who come to BEACON for sabbaticals, and the number of resulting published papers and submitted grant proposals.

1c. Problems encountered

None to report. We are pleased by the enthusiastic response we have already received from members of the research community.

2a. Partnership activities

Activity: Sabbatical visit to BEACON by Professor Christoph Adami (August 2010 – July 2011)

Organizations involved: MSU, where Adami was in residence for the length of his sabbatical, and Keck Graduate Institute, Adami's home institute at the time.

Narrative: Adami's sabbatical at BEACON was extremely productive, resulting in numerous publications, press releases, and research collaborations. As noted in the Management section of this report, in the summer of 2011 Adami was hired at MSU as a tenured full professor in the department of Microbiology and Molecular Genetics as an "Excellence Hire." Adami continues to be closely involved in BEACON activities and is a great asset.

Activity: Solving a land use, multi-objective optimisation problem: competitive co-evolutionary genetic algorithms

Organizations/people involved: Dr. Oliver Chikumbo, Scion (a NZ Crown Research Corp.); Dr. Erik Goodman, BEACON Director; Prof. Kalyanmoy Deb, Koenig Endowed Chair, Michigan State University; BEACON Center, Michigan State University; Scion, a New Zealand Crown Research Corporation

Narrative: Goodman and Deb collaborated with Dr. Oliver Chikumbo, of SCION, a Crown Research Corporation of New Zealand, on using multi-objective evolutionary computation methods to provide sets of alternative solutions for problems of agricultural land management in the environmentally sensitive Rotorua region of New Zealand. They applied for and received a

grant from Scion's International Mobility Fund for Dr. Chikumbo to visit BEACON for one month, August, 2011, to collaborate with Goodman and Deb. Dr. Chikumbo has since received indications that financial support to continue the work will be made available through DairyNZ and other agencies. Progress made during the visit included identification of a small set of "superobjectives" that users could understand, replacement of the multi-objective optimization code earlier used unsuccessfully by Dr. Chikumbo, with a new code that worked very well, and discovering that the resulting land use plans could be effectively displayed for practitioners using GIS-based display techniques. A proposal to put a University of New Zealand Auckland student to work on developing the needed graphical user interface, and Chikumbo's time to supervise the student, has already been approved by DairyNZ. Goodman and Deb plan to continue this BEACON collaboration.

Current visiting researchers: Professor Robert Heckendorn (from BEACON at UI), Professor Zhun Fan (Technical University of Denmark), Professor Kisung Seo (Seokyeong University, Seoul, Korea), Ling Wang (Shanghai University) and Professor Lihong Xu (Tongji University), Chenwen Zhu (Tongji University), Dr. Chengju Liu (Tongji University), Professor Meng Yao (East China Normal University).

2b. Other outcomes or impacts of partnership activities not listed elsewhere

None to report.

2c. Progress towards goals

Number of researchers visiting BEACON for sabbatical: 1 in 2010-2011, 5 in 2011-2012
Number of publications resulting from sabbaticals: 9
Number of submitted external grant proposals: none to report

2d. Plans for partnership activities for the next reporting period

BEACON is issuing a Faculty Affiliates Request for Proposals with the goal of recruiting diverse faculty from non-BEACON institutions to visit BEACON and collaborate with BEACON researchers. See the Diversity section for more details.

VI. DIVERSITY

1a. Overall goals for increasing diversity at the Center

BEACON's overall goal is to ***exceed national norms for diversity at all levels in the Center.*** The table below shows the current diversity statistics for the Center. Note that many categories, including Hispanic and Disability, are known to be underreported. The proportion of BEACON graduate students that are women or minorities is currently at the national norms for women and Hispanics, and exceeds the national norms for Black Non-Hispanic graduate students, according to 2009 figures from the National Science Foundation. Our goal is to increase the diversity at the Center above our starting baseline. Many of the Center's participants have a positive history of mentoring women and minority students.

	N	Male	Female	Dis-ability	White	Black	Asian	American Indian	Pacific Islander	Hispanic	Race/ Ethnicity Not Reported
Participants											
Undergrads	20	12 (60%)	8 (40%)	0 (0%)	11 (55%)	1 (5%)	4 (20%)	0 (0%)	0 (0%)	0 (0%)	5 (25%)
Graduate Students	86	56 (65%)	30 (35%)	1 (1.2%)	51 (59%)	15 (17%)	10 (12%)	1 (1%)	0 (0%)	8 (9%)	10 (12%)
Postdocs	22	16 (73%)	6 (27%)	0 (0%)	18 (82%)	0 (0%)	2 (9%)	0 (0%)	0 (0%)	0 (0%)	2 (9%)
Faculty	76	60 (79%)	16 (21%)	2 (2.7%)	52 (68%)	6 (8%)	10 (13%)	1 (1%)	0 (0%)	2 (3%)	8 (11%)
Other	18	5 (28%)	13 (72%)	0 (0%)	15 (83%)	2 (11%)	1 (6%)	0 (0%)	0 (0%)	1 (6%)	0 (0%)
TOTAL Participants	**222**	**149 (67%)**	**73 (33%)**	**3 (1.4%)**	**147 (66%)**	**24 (11%)**	**27 (12%)**	**2 (1%)**	**0 (0%)**	**11 (5%)**	**25 (11%)**
Affiliates											
Undergrads	13	8 (62%)	5 (38%)	0 (0%)	7 (54%)	1 (8%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	5 (38%)
Graduate Students	66	47 (71%)	19 (29%)	1 (1.5%)	21 (32%)	4 (6%)	3 (5%)	0 (0%)	0 (0%)	1 (2%)	38 (58%)
Postdocs	10	8 (80%)	2 (20%)	0 (0%)	3 (30%)	0 (0%)	1 (10%)	0 (0%)	0 (0%)	0 (0%)	6 (60%)
Faculty	43	34 (79%)	9 (21%)	0 (0%)	21 (49%)	1 (2%)	2 (5%)	0 (0%)	0 (0%)	0 (0%)	19 (44%)
Other	22	10 (45%)	12 (55%)	0 (0%)	6 (27%)	1 (5%)	3 (14%)	0 (0%)	1 (5%)	0 (0%)	12 (55%)
TOTAL Participants & Affiliates	**376**	**256 (68%)**	**120 (32%)**	**4 (1.2%)**	**205 (55%)**	**31 (8%)**	**36 (10%)**	**2 (1%)**	**1 (0.3%)**	**12 (3%)**	**105 (28%)**

Percentages may not sum to 100% due to individuals reporting multiple ethnicities/races.

1b. Performance and management indicators

Our first goal was to collect the baseline data for our diversity measure. Diversity Director Brown Clarke has collected baseline data across the consortium and is establishing mechanisms to ensure its accuracy. To measure future progress, we will collect data on the numbers or percentages of faculty, post-docs, graduate students, undergraduate participants, that are from underrepresented demographic groups, including women, underrepresented ethnic groups, and

people with disabilities. Our target is to achieve a 5% increase by October 2013, and a 10% increase by October 2015 over a baseline set by current national STC statistics.

We are also working to develop a database to identify and track prospective graduate students, which will assist our efforts to increase the pool of women and minority participants. Additionally, we will solicit feedback from the External Advisory Committee to get an objective assessment of our progress towards this goal.

1c. Problems encountered

One challenge we face is that diversity and inclusion efforts are typically thought to be limited to programming and recruiting. At BEACON we are working to change the culture to ensure that diversity and inclusion are woven into all aspects of BEACON. We are addressing this challenge with the following actions:

- Budget requests must address a diversity component, with opportunities for cultural competency awareness
- Ensuring that diversity is represented as a connecting thread through all aspects of BEACON; e.g., representation on website, cultural competency training, adaptive environments information and support
- Creating welcoming, accommodating environments and support for individuals with disabilities

2a. Center activities which contribute to the development of US human resources in science and engineering at the postdoc, grad, undergrad and pre-college levels

Ongoing activities include:

- Emphasis on recruiting diverse students to summer undergraduate research students
  - Seven underrepresented minority NC A&T students participated in summer undergraduate research programs at MSU and KBS in summer 2011
  - Another three diverse undergraduate students participated in the REU program at Friday Harbor Laboratories (UW), and all three have expressed a strong desire to return next summer to continue their research
  - BEACON partnered with MSU's Graduate School to host five underrepresented students (in addition to the NC A&T students) for the Summer Research Opportunity Program (SROP), where they conducted evolutionary research
- Brown Clarke is actively recruiting undergraduates, graduates, and post-docs at regional and national conferences; and identifying/securing partnerships for future pipelines/pathways of talent.
- While BEACON is drawing on its relationship with historically black member institution NC A&T to recruit diverse undergraduates into summer research programs and Ph.D. programs, BEACON is also actively working with several other HBCUs: Tuskegee University (Alabama), Spelman College (Georgia), Morehouse College (Georgia), Jackson State University (Mississippi) and Bennett College (North Carolina).

As part of BEACON's annual budget allocation process, and in addition to many education projects that had major diversity components, three projects that specifically aimed to increase diversity in BEACON and in STEM fields in general were funded.

Activity Name	**Enhancing Diversity through Evolution in Action at the Molecular Level**
Led by	Barry Williams (MSU)
Intended Audience	Underrepresented minority undergraduate students
Approximate # of attendees	4

Barry Williams led a summer program for diverse students, recruited from NC A&T and Notre Dame, which included a 10-week course designed to teach students the basics of evolution, genetics, molecular biology and microbiology. The group held daily and weekly discussion of techniques, projects and primary literature. Students worked at least 40 hours per week at the bench on independent projects, which they helped develop. Students also generated presentations in the form of talks and posters describing each of their independent research projects and presented their posters at an undergraduate research meetings at the Ohio State University and MSU, and one of the students also presented at the locally held professional meeting "MSU Summer Symposium on Transcriptional Dynamics." This course was also integrated with the MSU SROP program for undergraduate research, which included programming on issues like professional development, preparation for graduate school, and research ethics.

Williams is currently in process of restructuring the course to iron out all of the initial kinks identified in the first run of the course, but there was quite positive input from the students who attended this summer. Three of the undergraduates have asked if they can come back and do it again next year and the fourth student is graduating next spring (and may be applying to MSU). In the future, Williams would like to add more students to the course and to integrate underrepresented minorities from the additional BEACON institutions of UT Austin (primarily Hispanic students) and UW (primarily Native American students). Williams is in the process of working with faculty at both institutions to recruit students for next year.

This course directly impacts training and recruitment of underrepresented minorities. Williams introduces these students into the research lab (usually their first exposure). Furthermore, interaction with undergraduate and graduate students in BEACON and the Williams lab (as well as collaborator labs) introduces them into "graduate student life." Williams provided mentoring on how to apply to graduate school as well as the details of income, classes, research and personal dynamics when in graduate school, contrasting this experience with typical experiences found in medical school and working in private industry, in order to provide them with a fair representation of life as a grad student at MSU.

Activity Name	**BEACON Day at NC A&T**
Led by	Gerry Dozier
Intended Audience	Undergraduates, university administration
Approximate # of attendees	100

BEACON Day at NC A&T (Gerry Dozier, NCAT): BEACON@A&T will host a BEACON-wide day in celebration of the accomplishments of the NSF BEACON Science and Technology Center. It will help introduce and/or educate NCAT administration about BEACON, provide a forum for discussion of BEACON research across the Center, provide an opportunity for faculty across the Center to come to NCAT and discuss possible collaborations, and provide a showcase for getting NCAT students excited about research at BEACON institutions or other universities.

This event is scheduled for November 4, 2011, and will include:

- Welcome & introduction from the Chancellor's office, Provost's office, and the Dean of the College of Engineering
- An introduction to the vision of BEACON, presented by Director Erik Goodman
- An introduction to ongoing BEACON research at NC A&T
- Presentations on BEACON research by students and faculty from the other four BEACON institutions
- Presentations on diversity and education efforts by BEACON
- Orientations and discussion designed to increase collaboration with partner institutions

Activity Name	**Increase BEACON-UW Diversity**
Led by	Wenying Shou
Intended Audience	High school seniors and undergraduates
Approximate # of attendees	100

A new website (http://beaconuw.org/) will facilitate dissemination of research and education opportunities at BEACON-UW. This website has a content-management system, and Shou is in the process of writing up a protocol so that individual investigators can update the website.

They have designed a brochure that will be distributed to schools with high representation of minority students. The BEACON group at UW has decided to join forces with the UW GenOM (genomics for minorities) program to recruit minority students to engage in summer research.

The GenOM-BEACON program will advertise to high school science teachers and expect to get about 200~300 applications from graduating seniors. The program administrators will hand-pick several dozen students who are minorities and who have had a good track record in science and math. Each student will be interviewed by two faculty members on the phone. Once accepted, the student will go through training before entering a lab. S/he will take math classes (pre-calculus or calculus, depending on student level), receive lab training (pipetting, molar conversions, gel electrophoresis, PCR, pouring plates, streaking bacteria, restriction digest, bacteria transformation, DNA extraction, protein purification, laboratory notebook-keeping), and join ethics discussions (laws, research ethics, history of human testing in America and around the world, laws on animal testing, what is ethical, etc.). The student will work in a BEACON laboratory to carry out a project that will end in a poster presentation at the end of fellowship. These students are usually incoming freshmen to UW, which means that they can continue their training in interdisciplinary evolution research. They generally have a high probability of getting the Gates scholarship or HHMI scholarship from UW for subsequent quarters of research.

2b. Impact of these activities on enhancing diversity at the center

The underrepresented graduate students listed above are actively pursuing degrees and research in some type of evolutionary science. Their activities include representing BEACON at national and international conferences and events. These students have also acted as peer-to-peer recruits and are recommending our programs and research opportunities to other students. In August 2011 at the BEACON congress, the graduate students formed a formal student group. This group will have a student representative on the Diversity Committee, with the same rights as the current members. BEACON has weekly presentations from students and faculty in the various research thrust groups. Education and diversity have been added to that rotation, and on October 27, 2011 Judi Brown Clarke gave the first presentation in that area.

2c. Progress towards goals

It is too early to measure an increase in recruiting underrepresented students, post-docs, and faculty. However, we did evaluate the summer research programs to measure whether these students' interest in pursuing STEM careers increased.

A short pre-/post- survey on understanding of evolution was administered to 13 participants in the summer REU programs at Michigan State University, Kellogg Biological Station, and Friday Harbor Biological Station. Here are highlights of the findings:

1. To what extent do you anticipate your BEACON undergraduate experience will introduce you to cutting-edge research?
   - Pre-Survey: 55% of students anticipated that they would be introduced to cutting-edge research
   - Post-Survey: 87% of students reported that their research experience was cutting-edge
2. To what extent do you expect your experience to include or integrate a multidisciplinary approach (specifically: biology, computational science, and engineering)?
   - Pre-Survey: 63% of students anticipated a multidisciplinary approach
   - Post-Survey: 97% of students experienced a multidisciplinary approach
3. What is your current interest in a STEM (Science, Technology, Engineering, and Mathematics) career?
   - Pre-Survey: 90% of students reported an interest in a STEM career
   - Post-Survey: 94% of students reported an interest in a STEM career
4. To what extent has your previous coursework included multidisciplinary training (specifically: biology, computational science, and engineering)?
   - Results: 43% of students report having multidisciplinary courses, and only 23% reported having a multidisciplinary curriculum and/or being in a multidisciplinary department
5. What does "evolution in action" mean to you?
   - Pre-Survey: 74% of students gave literal descriptions of *evolution in action*, as a theoretical foundation for looking at things historically
   - Post-Survey: 93% of students described *evolution in action* as dynamic and constant; and reported a broadening of their understanding of its application beyond the field of biology

2d. Plans for the next reporting period

- We found that many of underrepresented students were underprepared for the REU experience, and we are creating a two-tiered program for next summer. We will combine REUs (for students with strong lab/research backgrounds), with Undergraduate Research Apprenticeships (for student with little to no lab/research background. We are writing a

collaborative proposal, blending multiple funding sources, to create summer research opportunities at MSU, Friday Harbor, KBS, and UT Austin's Freshman Research Initiative (FRI) program.

- We are hiring an evaluator to formally assess the summer research programs. Our evaluator is a Ph.D. student at University of Illinois, and will be mentored by Dr. Lizanne DeStefano, the primary evaluator for the Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS), a peer NSF STC.
- BEACON initiated a conference call for the diversity and education directors in all the STCs. This will become a bi-monthly event and opportunity for problem solving and sharing of best/promising practices among colleagues.
- We are auditing our website to ensure it meets the standards for accessibility for people with disabilities. We are also working with our MSU Resource Center for Persons with Disabilities and UW's Disability Resources for Students' adaptive lab space for guidance.
- BEACON continues to work closely with the Sloan Program, which now refers to itself as Sloan/Beacon. The BEACON students have access to all the same programming as the Sloan scholars, with a weekly informational meeting on Fridays.
- The BEACON High School Camp will continue to target underrepresented students, thereby exposing them to evolutionary science and research methods/skills. This pipeline will continue to cultivate relationships, with the aim of recruiting participants into any of the BEACON schools.
- Brown Clarke has drafted the Faculty Affiliate FRP to recruit diverse faculty from non-BEACON universities (Oct 2011). BEACONites will submit recommendations to the executive committee for selection (Dec 2011).

VII. MANAGEMENT

1a. Center's organizational strategy and its underlying rationale

Management Team. BEACON is headquartered at Michigan State University, and has members at North Carolina A&T State University, University of Idaho, The University of Texas at Austin, and University of Washington. The central management team is located at MSU, and consists of the Director (Prof. Erik Goodman), the Deputy Director (Prof. Charles Ofria), the Managing Director (Dr. Danielle Whittaker), the Education Director (Dr. Louise Mead), the Diversity Director (Dr. Judi Brown Clarke), the Industrial Affiliates Manager (Prof. Betty Cheng) the Administrative Coordinator (Connie James), the Accounts Manager (Darcie Zubek), and two Information Technology specialists (Brian Baer and David Bryson). The lead contacts at each member institution are: Profs. Gerry Dozier and Joseph Graves at NC A&T, Prof. James Foster at UI, Prof. Risto Miikkulainen at UT, and Prof. Ben Kerr at UW.

The Managing Director, Education Director, Diversity Director, Administrative Coordinator and Accounts Manager are full time positions, paid entirely from BEACON funds. The two Technology Specialists each spend 50% of their effort on BEACON support work and 50% on center-sponsored research projects. No faculty members are paid full time from BEACON funds. The Director devotes full time to BEACON administration and research, but is paid 50% AY from NSF funds, which buys out his teaching, 50% AY from departmental funds, plus 2 months of summer from NSF funds. The Deputy Director is part time, paid one month of summer from NSF funds. The Industrial Affiliates Manager is paid from BEACON funds for 1.35 months of AY effort plus one month of summer.

Executive Committee. While BEACON is centrally administered, we aim to ensure that all member institutions are active participants in the decision-making process. There are 13 members of the Executive Committee: Erik Goodman (Director and PI), Charles Ofria (Deputy Director, co-PI, and Digital Evolution cross-cutting theme leader), Kay Holekamp (co-PI), Richard Lenski (co-PI and Biological Evolution cross-cutting theme leader), Robert Pennock (co-PI), Thomas Getty (Education Steering Committee chair), Percy Pierre (Diversity Steering Committee chair), Betty Cheng (Industrial Affiliates Manager), Bill Punch (Evolutionary Applications cross-cutting theme leader), Gerry Dozier (NC A&T co-lead), Joseph Graves (NC A&T co-lead), James Foster (UI lead), Risto Miikkulainen (UT lead), and Ben Kerr (UW lead). The Executive Committee will soon have a fourteenth member, representing BEACON students and postdocs.

Research leads. BEACON research falls into three Thrust Groups, discussed in more detail in Section II, each with two leaders: Genomes, Networks & Evolvability, led by Tom Schmidt and Titus Brown; Behavior & Intelligence, led by Kay Holekamp and Robert Pennock; and Ecological Communities & Collective Dynamics, led by Fred Dyer and Phil McKinley. These thrust groups are united by three Cross-Cutting Themes, each with one leader: Biological Evolution (Richard Lenski), Digital Evolution (Charles Ofria), and Evolutionary Applications (Bill Punch).

Education and Diversity leads. Education and Diversity are important goals of BEACON, and to that aim we have Education and Diversity Steering Committees who work closely with our Education and Diversity Directors. The Education Steering Committee is chaired by Tom

Getty at MSU, and includes the Education Director (Mead) and one coordinator from each member university (Joseph Graves at NC A&T, Terence Soule at UI, Claus Wilke at UT, and Billie Swalla at UW), plus the RCR and Mentoring Lead (Julius Jackon), the Outreach Lead (Drew Kim), the Multidisciplinary Graduate Education coordinators (Charles Ofria, Titus Brown, Alexander Shingleton and Ian Dworkin), and the BEACON Fellowships coordinators (Eric Torng and Tom Schmidt). The Diversity Steering Committee is organized in a similar manner, chaired by Percy Pierre at MSU and including the Diversity Director (Brown Clarke) and Diversity Coordinators from each member institution (Greg Goins at NC A&T, Mark Edwards at UI, Lauren Meyers at UT, and Wenying Shou at UW).

Assessment. BEACON has multiple external assessment teams. One team is led by Drs. Patricia Farrell and Marilyn Amey, who evaluate the organization, management structure and leadership of the Center. Michael O'Rourke of the Toolbox Project at University of Idaho leads a multidisciplinary training and communication workshop that we have piloted at BEACON and plan to incorporate in the future, which provides feedback to training and feedback to multidisciplinary teams being formed. During the last reporting period, our educational evaluation was led by MSU's Institute for Research on Math and Science Education, which helped to establish general instruments and tools for use by BEACON faculty and staff. Due to a recent reorganization of the institute, it will no longer be involved in direct evaluation of BEACON education/outreach projects. Given the breadth of our educational projects, we are working with each project leader to identify appropriate external evaluators and/or an assessment team who have more specific content and assessment experience.

Budget Request Process. Projects at BEACON are chosen through an annual selection process, in which BEACON members submit budget requests in January under one of six categories: Thrust Group 1, 2, or 3; Education; Diversity; or Other (which can include infrastructure requests). Research projects are evaluated by the two leads for the respective thrust group, as well as 4 ad hoc reviewers from within the thrust group chosen by the leads, including faculty members from any of the five BEACON universities. Projects focused on education and outreach are evaluated by the Education Steering Committee while those focused on increasing diversity are evaluated by the Diversity Steering Committee. Projects designated "other" are reviewed by the Management team. Each budget request is evaluated on the basis of 8 criteria, each of which is rated on a scale from 1-5. There are four intellectual merit criteria (1-4) and four broader impact criteria (5-8):

- Scientific strength of the proposed project
- Centrality of project to BEACON's mission
- Probability of leading to external funding
- Degree of multidisciplinarity
- Impact on education and human resource development
- Knowledge transfer to industry
- Impact on achieving the diversity goals of BEACON
- Multi-institutionality

Funds granted for BEACON projects are considered "seed money": researchers are encouraged to use these funds to generate preliminary results that will lead to increased external funding. Faculty members are discouraged from putting faculty summer salaries in these seed grants, in order that as many projects as possible may be supported, although an exception is made for projects involving direct delivery of summer education and outreach projects and for

faculty members at our non-Research I partners, whose teaching loads are elevated and who may lack other sources of summer support. Although the budget requests are evaluated centrally, each member institution is guaranteed a funding floor— a minimum amount for their subcontract. Member institutions may receive a subcontract that is greater than the minimum amount if projects are selected at those institutions that require greater amounts of funding. The floor decreases each year, so that it will become increasingly important for the member institutions to participate actively in the Center-wide project-based budget request process. In the first two years [note this refers to "project years" and not "NSF funding periods"; see explanation in next paragraph], the floor is $500,000; this decreases to $350,000 in the third year, $250,000 in the fourth year, and $150,000 in the fifth year of BEACON's operation.

There is a disconnect between the Academic Year at universities, which makes it natural to start projects in the August-September timeframe, and BEACON's NSF-mandated February 1 – January 31 budget year. The BEACON project budget request process, for projects starting May or August, 2011 and continuing through May or August, 2012, will accept applications until January 10, 2011, and decisions will be completed by February 14, 2011, so that the decisions will allow faculty to recruit students and postdocs to projects and to make commitments to returning students well in advance of the project start date. That means that most BEACON projects will span two BEACON budget years. For example, projects begun in August, 2011, are funded in part from the budget period beginning February 1, 2011, and partially from the budget period to begin in February, 2012. BEACON's annual reports are due November 1 of each year (three months before the end of the budget year), so will typically describe startup of new projects and final results of projects completed the previous May - August.

This process was successfully implemented across all 5 BEACON member institutions in BEACON's "Project Year 2," which is currently underway. These projects, as well as the completed projects from "Project Year 1," are described in Section II. Application instructions for the third round of requests have been distributed to all BEACON members and the requests will be evaluated beginning January 10, 2012.

1b-1c. Performance and management indicators and progress towards goals

BEACON's overall Leadership and Management goals are to envision and enable the Center's mission through inclusive and transparent decision-making as well as effective and responsible implementation; to inspire Center participants; and to facilitate collaborative efforts within and beyond the Center. In the table below, we list specific optimal outcomes and indicators we have developed, and report our progress for each one.

Management Goals		
GOAL	**METRICS**	**PROGRESS**
Increase in cross-disciplinary research and education	Number of paper/conference submissions by BEACON authors	Goal was 20 cross-disciplinary submissions in first year: ~45 reported for first 15 months
	Number of new courses	Three BEACON graduate courses at MSU, with participation from UT/UI/UW. Two courses have also been

		modified and are being offered in Fall 2011 at NCAT.
	Number of students enrolled in cross-disciplinary courses	Grad courses at MSU/UI/UT/UW: Fall 2010: 43; Spring 2011: 22, Fall 2011: 33. At NCAT: 6 in Bio, 30 in CS
	Number of funding proposals submitted	Goal: 10 per year. 17 submitted Aug 2010-Jan 2011; 31 submitted Feb – Nov 2011.
Increase in cross-institutional research and education	Number of paper/conference submissions	Too soon to measure, as cross-institutional research teams enabled by BEACON still new
	Number of new courses	The three above-mentioned MSU courses are successfully cross-institutional.
	Number of students in cross-institutional courses	Fall 2010: 43; Spring 2011: 22, Fall 2011: 23.
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	42 grant proposals submitted by August 2011 (baseline)
	Award dollars	Target of $1 million by Oct 2011: over $8 million awarded by Oct 2011
Increase in new participants	Number of faculty, post-docs, and students	Number involved in August 2010-August 2011 will serve as our baseline: 156 grad students, 124 faculty, 31 postdocs, 25 undergrads
Effective support of Center operations by Management team	Survey for participants about management team	Baseline survey administered October-November 2010, and we have implemented changes in areas identified as needing improvement. Year 2 evaluation plans are currently being finalized.
	Feedback from External Advisory Committee	Feedback is largely positive (Appendix C)
Center is perceived by NSF as exemplary	Renewal of NSF funding	Renewal was approved for our second funding increment
	Number of public mentions made by NSF about BEACON	In 2011, NSF issued one press release about BEACON-related research, and 3 stories were featured on the NSF-sponsored webpage Live Science.

BEACON Organizational Baseline Evaluation Report. In fall 2010, Drs. Patricia Farrell and Marilyn Amey conducted a survey to evaluate the performance of BEACON management, and to set a baseline by which to judge our future improvement. The evaluators sent out a survey to 270 BEACONites in November 2010 by email; 138 responded to the survey (51% response rate). Respondents were categorized by role (BEACON leadership, faculty, post-doc, graduate student, undergraduate student, and support staff) and institution (MSU, NC A&T, UI, UT, UW, Other). A report to BEACON management was provided in spring, 2011. As a followup, additional focus groups and individual interviews were conducted by the evaluators with graduate students and post-docs in Spring 2011.

In general, respondents expressed high levels of satisfaction with BEACON's mission, and felt connected and committed to the center. However, some respondents expressed concerns about communications and about how the center would actually carry out its mission. Respondents were satisfied by BEACON's leadership, their ability to provide input into decisions, and transparency of the management, though a number of respondents felt there was room for improvement. Management was generally viewed as promoting collaboration, inclusiveness, and collegiality. Trust and respect among BEACONites were also rated highly.

The evaluation helped us to identify challenges in the organization. In particular, in the early months as we were still developing our web-based systems, communication among participants needed improvement. In response to these concerns, we have created BEACON email lists that are continuously maintained, a BEACON website and blog, and Facebook and Twitter feeds so that BEACONites can receive information in a variety of formats.

Another challenge is that participants at partner (non-MSU) universities may feel less connected. We are continually working to ensure that these participants are included in weekly research seminars, blog coverage, emails, etc., and making sure that their voices are heard. Graduate students and post-docs, especially those whose advisors are not closely connected to BEACON, are particularly at risk for feeling unconnected. BEACON is forming a Graduate Student/Post-Doc Association, to be run by grad students and post-docs, that we hope will begin to address this problem. Students and post-docs are also concerned about future career opportunities, and we are planning to hold career workshops in the coming academic year.

Some respondents expressed dissatisfaction at the difficulties involved in beginning new collaborations across disciplines and institutions. We are putting greater efforts into facilitating communication among interested parties at weekly seminars, and into setting up collaborative planning sessions at the annual BEACON Congress.

Finally, we continually strive to communicate our research and education efforts to all of our members, as well as to ensure continued transparency in our decision-making processes. We will use these survey results as a baseline, and will survey our members again in Fall 2012 to examine our progress in these challenging areas, and identify any new areas that need attention.

Formation of BEACON Student/Postdoc Association. The first goal of the BEACON undergraduate, graduate, and postdoc association is to promote communication, both within- and among BEACON institutions. Towards this goal, we have chosen liaisons at 4 out of the 5 partner universities, each of whom is planning to build a strong network among students and postdocs at their home institution. These groups will have regular social interactions such as

"lunches and lab tours" to learn about different BEACON-related activities at their institutions. The group of liaisons communicate regularly in order to share successes and keep each of the sites connected. We also plan to elect representatives to the various committees within BEACON so that students and postdocs have a voice in the directions of BEACON. These representatives will receive feedback from and communicate to the entire body of BEACON students and postdocs about the activities of these committees. Additionally, the organization aims to use some of its funds to support between-institution travel outside that of funded projects in order to foster new collaborations and maintain a cohesive body of students and postdocs.

This collaboration both within- and among partner institutions is a major priority of the student and postdoc association. Through events such as a student and postdoc retreat, scheduled to take place before BEACON congresses and all-hands meetings, students and postdocs can learn about work being done at other institutions as well as form new collaborations. To support potential collaborations, students and postdocs can submit requests for small, fixed-amount awards that are provided by the association in order to help begin new or maintain existing cross-discipline and cross-institution collaboration.

Another major component of the BEACON student and postdoc association is to prepare BEACON alumni for wherever their career takes them. This training is accomplished through the interaction of undergraduates and graduate students as well as graduate students and postdocs, so that each of these groups can learn from those in the next phase of their academic careers. This training is extended through planned local outreach programs funded by the student and postdoc organization, in which high school students are invited to meet with and observe researchers in BEACON. By interacting with BEACON members, these students can gain a greater understanding of science in action, and how students are educated. Additionally, the small awards available can be used to fund personal development and/or outreach activities such as invited speakers during the student and postdoc retreat preceding the BEACON all-hands meetings. By these means, we hope this organization will cater directly to the needs of its constituents, since the activities are created and dictated by them.

New faculty hires. BEACON has been directly involved in hiring two new faculty members at MSU so far, and is discussing the possibility of several new tenure-stream lines being added in the near future. For academic year 2010-2011, Dr. Christoph Adami, formerly of Keck Graduate Institute, spent his sabbatical at BEACON at MSU. In the summer of 2011, MSU hired Adami as a tenured full professor in the department of Microbiology and Molecular Genetics as an "Excellence Hire." BEACON also took the lead in conducting the search for a faculty member to fill the Koenig Endowed Chair in Electrical and Computer Engineering. The search was successful, and a recognized leader in evolutionary computation is being hired, but the name of the person has not yet been released to the public. We will report this hire in next year's annual report. Finally, we are seeking to strengthen our faculty in the area of bioinformatics.

1d. Problems encountered

Our primary problems revolve around communication – between disciplines and across institutions, within BEACON and between BEACON and the general public. We continue to work through these problems and to build a greater sense of community within the Center.

Current lack of communication between disciplines: We are developing tools and information to inform BEACON participants of opportunities across disciplines, including email

lists and a central website, which includes a very extensive "BEACON Intranet" accessible only to BEACON's participants and affiliates. We held the second annual Congress at BEACON in August 2011, where sessions were set up for participants to brainstorm around research problems ("Sandbox sessions"). We will continue to have similar sessions every year. In the original proposal, the BEACON meetings in odd-numbered years (2011, 2013) were planned to be much smaller, but the need for more cross-institutional communication led to their expansion to being full "all-BEACON" meetings, as in even-numbered years.

Long-distance communication hampers joint activity: We are establishing a culture in which partners collaborate in person, via videoconference, and via shared center resources. We are making great progress in this area, and have resolved most of the technical difficulties associated with videoconferencing that we experienced early on. In the BEACON classrooms, graduate instruction in BEACON's transdisciplinary courses in computational methods for new biology graduate students is making use of iPADs purchased to allow small groups of students to collaborate electronically during the class, and that is working well.

Integrating new participants into the Center: We provide travel funding for new participants.

Partners [at NCA&T, UI, UTA, and UW] may feel isolated: We have established an online system for submitting and tracking data from all partners (details below). We also continue to work on reaching out to partners and ensuring that they are made aware of and encouraged to participate in weekly seminars, blog posts, interinstitutional classes, and interinstitutional research collaborations.

NSF is unaware of BEACON accomplishments: We are working to ensure that NSF remains informed of significant BEACON accomplishments through frequent communication with our technical coordinator, George Gilchrist.

2. Management and communications systems

Management systems. Our central management "engine" is our intranet system, the structure of which we purchased from the Center for Materials and Devices for Information Technology Research (CMDITR) in November 2010. After some modifications for our own center, this system was up and running by mid-December 2010, and improvements have continued on a regular basis by BEACON's IT specialists. This system is used for many applications:

- Individual personnel profiles, where we collect demographic information
- Generation of specific email lists based on status (student, postdoc, faculty, etc) and home institution
- Collecting information on outputs and activities and progress reports on ongoing projects
- Submission and peer reviewing of budget requests
- Collection of suggestions for the annual BEACON Congress in a wiki format
- Sharing of files, such as powerpoint presentations for BEACON-wide Friday seminars
- Tracking of compliance with Responsible Conduct of Research requirements
- Providing shared data storage areas for collaborating teams

Central website. Our website is located at www.beacon-center.org. The front page of this website is in a blog format. The primary feature is "BEACON Researchers at Work," a blog written by BEACON students, postdocs, and faculty describing their research at a level accessible to the scientific public. The managing director solicits, schedules, and edits these

posts. In addition, we also post news stories about BEACON research in that space. Other pages in the website describe BEACON mission, research, and education and diversity efforts, and we maintain an archive of BEACON press releases and media coverage. Access to BEACON's members-only Intranet is through these pages.

Social media. We also connect with our members and the general public via Facebook (120 "likes" as of 10/28/11) and Twitter (95 followers as of 10/28/11). We use these networking tools to announce blog posts and media coverage, to send reminders about Center-wide activities, and to help maintain a sense of community. These pages are updated at least 3 times a week.

Videocommunications systems. For our weekly Friday all-location meetings we using Polycom and Tandberg dedicated videoconferencing equipment, augmented by a central "bridge" at MSU (outside BEACON). With the update of equipment at Universities of Texas and Idaho (both with new Tandberg units) presenters are now able to speak and show slides at any of the partner schools and have them viewed at high quality at the other universities. The University of Washington also has members regularly attending from two remote sites (Friday Harbor Laboratories and Fred Hutchinson Cancer Research Center). The audience at all these sites can be seen and heard by the speakers to allow cross-campus interactions. A limited number of individuals can view/hear these meetings from their personal computers and even interact by telephone. For multiple-campus classes (two in the fall and one in the spring) we use the same video-conferencing equipment, but controlled by the local Polycom unit at the BEACON center at MSU. Also, this term we have purchased a set of iPads with video chat and "whiteboard" software to allow students to work in cross-campus small groups -- so far this experiment seems to be working well. For smaller and informal meetings across campuses we are using either Skype or a combination of Acrobat Connect (for video and content sharing) and an "800" conference phone system (for audio).

3. Names and affiliations of the Center's external advisors

External Advisory Board	
Name	**Affiliation**
Scott Edwards	Harvard University
John Koza	Stanford University
Hod Lipson	Cornell University
Una-May O'Reilly	Massachusetts Institute of Technology
Judy Scotchmoor	University of California, Berkeley
Kathleen Smith	NESCent, Duke University
Joan Strassman	Rice University

The first meeting of BEACON's External Advisory Board was held August 12-13, 2011, at Michigan State University. The summary report from that meeting is in Appendix C.

4. Changes to the Center's strategic plan

The strategic plan has been updated to reflect progress already made, and to adjust targets that have turned out to be unrealistic. The goals and optimal outcomes remain the same.

VIII. Center-Wide Outputs and Issues

1a. Center publications

Abbot P, Getty T, et al, "Inclusive fitness theory and eusociality," *Nature*, Vol 471, E1 - E4 (2011). [DOI: 10.1038/nature09831]

Abdulsadda AT, Tan X, "Artificial lateral line-based localization of a dipole source with unknown vibration amplitude and direction," *The 15th International Conference on Advanced Robotics*, (2011).

Abdulsadda AT, Zhang F, Tan X, "Localization of source with unknown amplitude using IPMC sensor arrays," *Electroactive Polymer Actuators and Devices (EAPAD) XIII*, (2011).

Abegaz T, Dozier G, Bryant K, Adams J, Shelton J, Ricanek K, Woodard D, "SSGA and EDA Based Feature Selection and Weighting for Face Recognition," *2011 IEEE Congress on Evolutionary Computation (CEC)*, (2011).

Abegaz T, Dozier G, Bryant K, Adams J, Baker B, Shelton J, Ricanek K, Woodard D, "Genetic-Based Selection and Weighting for LBP, oLBP, and Eigenface Feature Extraction," *2011 Midwest Artificial Intelligence and Cognitive Science Conference (MAICS)*, (2011).

Adami C, Qian J, Rupp M, Hintze A, "Information content of colored motifs in complex networks," *Artificial Life*, Vol 17, Iss 4, 375 - 390 (2011). [DOI: doi:10.1162/artl_a_00045]

Adami C, "The use of information theory in evolutionary biology," *Annals of the New York Academy of Sciences*, Vol 1232, (2011). *In Press*.

Adams J, Dozier G, Bryant K, Moore K, "A IDEA for Computational Hip-Hop," *2011 ADMI Conference*, (2011).

Alford A, Popplewell K, Dozier G, Bryant K, Kelly J, Adams J, Woodard D, Ricanek K, "A Comparison of GEC-Based Feature Selection and Weighting for Multimodal Biometric Recognition," *2011 IEEE Congress on Evolutionary Computation (CEC)*, (2011).

Alford A, Hansen C, Dozier G, Bryant K, Kelly J, Woodard D, Ricanek K, "GEC-Based Multi-Biometric Fusion," *2011 IEEE Congress on Evolutionary Computation (CEC)*, (2011).

Alford A, Popplewell K, Dozier G, Bryant K, Kelly J, Adams J, Abegaz T, Shelton J, "GEFeWS: A Hybrid Genetic-Based Feature Weighting and Selection Algorithm for Multi-Biometric Recognition," *2011 Midwest Artificial Intelligence and Cognitive Science Conference (MAICS)*, (2011).

Avegaz TM, Adams JM, Popplewell KM, Shelton JM, Bryant KM, Dozier GM, Woodard DL, Ricanek KM, "Hybrid GAs for Eigen-Based Facial Recognition," *The 2011 IEEE Workshop on Computational Intelligence in Biometrics and Identity Management,* (2011). *Submitted*.

Bailey GL, Han J, Wright DC, Graves JL, "Religiously Expressed Fatalism and the Perceived Need for Science and Scientific Process to Empower Agency," *Science in Society*, Vol 2, Iss 3, 55 - 88 (2011).

Baker BM, Bryant KM, Dozier GM, "GESLIC: Genetic and Evolutionary-Based Short-Length Iris Codes," *The 2011 IEEE Workshop on Computational Intelligence in Biometrics and Identity Management,* (2011).

Beck D, Settles M, Foster JA, "OTUBase: an R infrastructure package for taxonomic unit data," *Bioinformatics*, (2011). *In Press*.

Byers CM, Cheng BH, McKinley PK, "Digital Enzymes: Agents of Reaction Inside Robotic Controllers for the Foraging Problem," *Proceedings of the ACM Genetic and Evolutionary Computation Conference*, (2011).

Chandler CH, Chadderdon G, Phillips P, Dworkin I, Janzen F, "Experimental evolution of the Caenorhabditis elegans sex determination pathway," *Evolution*, (2011). *In Press*.

Clune J, Stanley KO, Pennock RT, Ofria C, "On the Performance of Indirect Encoding Across the Continuum of Regularity," *IEEE Transactions On Evolutionary Computation*, Vol 15, Iss 3, 346 - 367 (2011).

Connelly BD, Zaman L, Ofria C, McKinley PK, "Modeling the Evolutionary Dynamics of Plasmids in Spatial Populations," *2011 Genetic and Evolutionary Computation Conference*, (2011).

Connelly BD, Zaman L, McKinley PK, Ofria C, "Modeling the Evolutionary Dynamics of Plasmids in Spatial Populations," *Proceedings of the ACM Genetic and Evolutionary Computation Conference*, (2011).

Conner JK, Karoly K, Stewart C, Koelling VA, Sahli HF, Shaw FH, "Rapid Independent Trait Evolution Despite a Strong Pleiotropic Genetic Correlation," *American Naturalist*, Vol 178, 429 - 441 (2011).

Cooper IA, Gilman RT, Boughman JW, "Sexual dimorphism and speciation on two ecological coins: patterns from nature and theoretical predictions," *Evolution*, Vol online, (2011). Note: This work predates Beacon support, but is related to my Beacon project "Mystery of Mysteries"

Couvertier D, McKinley PK, "Effects of Biased Group Selection on Cooperative Predation in Digital Organisms (poster summary)," *Proceedings of the ACM Genetic and Evolutionary Computa- tion Conference*, (2011).

Crowley S, Eigenbrode SD, O'Rourke M, Wulfhorst JD, "Localization in Cross-Disciplinary Research: A Philosophical Approach," *Multilingual*, Vol 114, (2011).

Day M, Beck D, Foster JA, "Microbial Communities as Experimental Units," *Bioscience*, (2011). *In Press*.

DesRoches S, Harmon L, Rosenblum EB, "Ecological release in White Sands lizards," *Ecology and Evolution*, (2011). *In Press*.

Dorn ED, Nealson KH, Adami C, "Monomer abundance distribution patterns as a universal biosignature: Examples from terrestrial and digital life," *Journal of Molecular Evolution*, Vol 72, 283 - 295 (2011). [DOI: 10.1007/s00239-011-9429-4]

Dorn ED, Adami C, "Robust Monomer-Distribution Biosignatures in Evolving Digital Biota," *Astrobiology*, Vol 11, Iss 9, (2011). *In Press*.

Dozier GM, Purrington KM, Popplewell KM, Shelton JM, Bryant KM, Adams J, Woodard DL, Miller PM, "GEFeS: Genetic & Evolutionary Feature Selection for Periocular Biometric Recognition," *The 2011 IEEE Workshop on Computational Intelligence in Biometrics and Identity Management,* (2011). *Submitted*.

Dupuis J, Fan Z, Goodman ED, "Evolutionary Design of Both Topologies and Parameters of a Hybrid Dynamical System," *IEEE Transactions on Evolutionary Computation*, (2011). *In Press*. [DOI: ISSN: 1089-77BX]

Dziuk AC, Mikkulainen R, "Creating Intelligent Agents through Shaping of Coevolution," *IEEE Congress on Evolutionary Computation*, (2011).

Eastman JM, Harmon LJ, La H, Joyce P, Forney L, "The onion model, a simple neutral model for the evolution of diversity in bacterial biofilms," *Journal of Evolutionary Biology*, (2011). *In Press*.

Edlund JA, Chaumont N, Hintze A, Koch C, Tononi G, Adami C, "Integrated information increases with fitness in the simulated evolution of autonomous agents," *PLoS Comp. Bio,* Vol 7, (2011). *In Press*.

Evans J, Sullivan J, "Approximating model probabilities in BIC and DT approaches to model selection in phylogenetics," *Molecular Biology and Evolution*, Vol 28, 343 - 349 (2010). [DOI: 10.1093/molbev/msq195.]

Evans J, Sullivan J, "Generalized mixture models for molecular phylogenetic estimation," *Systematic Biology*, (2011). *In Press*. [DOI: 10.1093/sysbio/syr093]

Ferguson AA, Jiang N, "Pack-MULEs: recycling and reshaping genes through GC-biased acquisition," *Mobile Genetic Elements*, Vol 1, 135 - 138 (2011).

Furusawa GM, Dziewanowska KM, Stone HM, Settles MM, Patricia HL, "Global analysis of phase variation in Myxococcus xanthus," *Molecular Microbiology*, Vol 81, Iss 3, 784 - 804 (2011).

Grabowski LM, Bryson DM, Dyer FC, Pennock RT, Ofria C, "Clever Creatures: Case Studies of Evolved Digital Organisms," *European Conference on Artificial Life 11,* (2011).

Book Chapter: Graves JL, "Evolutionary versus Racial Medicine: Why it Matters?," *Race and the Genetic Revolution: Science, Myth and Culture*, (2011).

Han Z, Tan Z, Yao M, Fleet B, Goodman ED, Deller JR, "BRATUMASS Antenna Positioning Optimization with Genetic Algorithm," *2011 International Conference on Bioinformatics and Computational Biology*, (2011).

Han Z, Tao Z, Yao M, Fleet B, Goodman ED, Deller JR, "The Application of the Genetic Algorithm Tool Box at Target Enhancement Processing in Breast Cancer Microwave Imaging," *2011 International Conference on Bioinformatics and Computational Biology*, (2011).

Hayes RD, "Variation Selection Inheritance: a Public Outreach Podcast on Evolution by the NSF BEACON Consortium," *North Carlolina Academy of Sciences Annual Meeting*, (2011).

Holekamp KE, Smith JE, Strelioff CC, Van Horn RC, Watts HE, "Society, demography and genetic structure in the spotted hyena," *Molecular Ecology*, (2011). [DOI: 10.1111/j.1365-294X.2011.05240.x]

Jensen AC, Cheng BH, Goldsby HJ, Nelson EC, "A Toolchain for the Detection of Structural and Behavioral Latent System Properties," *Model Driven Engineering Languages and Systems*, (2011).

Joneson S, Stajich J, Shiu S, Rosenblum EB, "Genomic transition to pathogenicity in chytrid fungi," *PLoS Pathogens*, (2011). *In Press*.

Kahn AI, Dinh DM, Schneider D, Lenski RE, Cooper TF, "Negative epistasis between beneficial mutations in an evolving bacterial population," *Science*, Vol 332, 1193 - 1196 (2011).

Karpov IV, Valsalam VK, Miikkulainen R, "Human-Assisted Neuroevolution Through Shaping, Advice and Examples," *Genetic and Evolutionary Computation Conference (GECCO'11)*, (2011).

Karpov I, Valsalam V, Miikkulainen R, "Assisting Machine Learning via Shaping, Advice and Examples," *Proceedings of the 2011 IJCAI Workshop on Agents Learning Interactively from Human Teachers*, (2011).

Knoester DB, McKinley PK, "Neuroevolution of Controllers for Self-Organizing Mobile Ad Hoc Networks," *Proceedings of the Fifth IEEE International Conference on Self-Adaptive and Self-Organizing Systems*, (2011).

Knoester DB, McKinley PK, "Evolution of Synchronization and Desynchronization in Digital Organisms," *Artificial Life*, Vol 17, Iss 1, 1 - 20 (2011).

Kohl N, Miikkulainen R, "An Integrated Neuroevolutionary Approach to Reactive Control and High-level Strategy," *IEEE Transactions on Evolutionary Computation*, (2011). *In Press*.

Lenski RE, "Evolution in action: a 50,000-generation salute to Charles Darwin," *Microbe*, Vol 6, 30 - 33 (2011).

Lenski RE, "Chance and necessity in the evolution of a bacterial pathogen (News and Views)," *Nature Genetics*, (2011). *In Press*.

Lockett A, Miikkulainen R, "Real-Space Evolutionary Annealing," *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO-2011, Dublin, Ireland)*, (2011).

Lockett A, Miikkulainen R, "Measure-Theoretic Evolutionary Annealing," *Proceedings of the IEEE Congress on Evolutionary Computation*, (2011).

Massie JP, Koestler BJ, Cong J, Waters CM, "Quantification of High-Specificity Cyclic di-GMP Signaling," *PNAS*, (2011). *Submitted*.

Magazine: Mead LS, "Review: What Mr. Darwin Saw; Darwin: Glimpses into his Private Journal," *Reports of the National Center for Science Education*, (2011).

Magazine: Mead LS, "Review: The Big Picture Book; Evolution Revolution," *Reports of the National Center for Science Education*, (2011).

Meyer JR, "Statistical structure of host-phage interactions," *PNAS*, Vol 108, Iss 28, 11309 - 11310 (2011). [DOI: 10.1073/pnas.1101595108]

Meyer JR, "Repeatability and Contingency in the Evolution of a Key Innovation in Lambda Phage," *Science*, (2011). *Submitted*.

Book Chapter: Miikkulainen R, "Neuroevolution," *Encyclopedia of Machine Learning*, (2011).

Mirmomeni M, Punch W, "Co-evolving Data Driven Models and Test Data Sets with the Application to Forecast Chaotic Time Series," *IEEE Congress on Evolutionary Computation (IEEE CEC 2011)*, (2011).

Momeni BM, Chen CM, Hillesland KL, Waite AM, Shou WM, "Using artificial systems to explore the ecology and evolution of symbioses," *Cell Mol Life Sci,* Vol 68, Iss 8, 1353 - 1368 (2011).

Nahum JR, Harding BN, Kerr B, "Evolution of restraint in a structured rock–paper–scissors community," *Proceedings of the National Academy of Sciences of the United States of America*, (2011). *In Press*.

Norris V, Zemirline A, Amar P, Jean AN, Ballet P, Ben Jacob E, Bernot G, Beslen G, Cabin A, Fanchon E, Giavitto J, Glade N, Greussay P, Grodin Y, Foster JA, et al. F, "Computing with bacterial constituents, cells and populations: from bioputing to bactoputing," *Theory in Biosciences*, (2011).

Østman B, Hintze A, Adami C, "Impact of epistasis and pleiotropy on evolutionary adaptation," *Proceedings of the Royal Society B: Biological Sciences*, Vol 278, (2011). [DOI: 10.1098/rspb.2011.0870]

Popplewell K, Dozier G, Bryant K, Alford A, Adams J, Abegaz T, Purrington K, Shelton J, "A Comparison of Genetic Feature Selection and Weighting Techniques for Multi-Biometric Recognition," *2011 ACM Southeast Conference*, (2011).

Qian J, Hintze A, Adami C, "Colored motifs reveal computational building blocks in the C. elegans brain," *PLoS One*, Vol 6, Iss 3, e17013 (2011).

Rajagopalan P, Rawal A, Miikkulainen R, Wiseman MA, Holekamp KE, "The Role of Reward Structure, Coordination Mechanism and Net Return in the Evolution of Cooperation," *IEEE Conference on Computational Intelligence and Games (CIG 2011)*, (2011).

Ramirez AJ, Cheng BH, "Automatic Derivation of Utility Functions for Monitoring Software Requirements," *Fourteenth International Conference on Model Driven Engineering Languages and Systems (MODELS'11)*, (2011).

Ramirez AJ, Cheng BH, McKinley PK, "An Evolutionary Approach to Network Self-Organization and Resilient Data Difussion," *Fifth International Conference on Self-Adaptive and Self-Organizing Systems (SASO'11)*, (2011).

Ramirez AJ, Jensen AC, Cheng BH, Knoester DB, "Automatically Exploring How Uncertainty Impacts The Behavior of Dynamically Adaptive Systems," *26th International Conference on Automated Software Engineering (ASE'11)*, (2011).

Ramirez AJ, Cheng BH, McKinley PK, "An Evolutionary Approach to Network Self-Organization and Resilient Data Diffusion," *Proceedings of the Fifth IEEE International Conference on Self-Adaptive and Self-Organizing Systems*, (2011).

Ramirez AJ, Knoester DB, Cheng BH, McKinley PK, "Plato: A Genetic Algorithm Approach to Run-Time Reconfiguration in Autonomic Computing Systems," *Cluster Computing*, Vol 14, Iss 3, 229 - 244 (2011).

Ramsey DC, Scherrer MP, Zhou T, Wilke CO, "The Relationship Between Relative Solvent Accessibility and Evolutionary Rate in Protein Evolution," *Genetics*, Vol 188, Iss 2, 479 - 488 (2011). [DOI: 10.1534/genetics.111.128025]

Reid N, Demboski J, Sullivan J, "Phylogeny estimation of the radiation western American chipmunk (Tamias) in the face of introgression using reproductive protein genes," *Systematic Biology*, (2011). *In Press*. [DOI: 10.1093/sysbio/syr094]

Ripplinger J, Sullivan J, "Assessment of substitution-model adequacy using frequentist and Bayesian methods," *Molecular Biology and Evolution*, Vol 27, 2790 - 2803 (2010). [DOI: doi:10.1093/molbev/msq168]

Roles AM, Fenster CM, Rutter MM, Conner JM, "Field measurements of GEI for spontaneous mutations in Arabidopsis thaliana," *Society for the Study of Evolution Annual Meeting. Portland, OR,* (2011).

Rosenblum EB, Settles M, Murdoch G, Poorten T, "Only skin deep: the genetics of death by the chytrid fungus in endangered frogs," *Molecular Ecology*, (2011). *Submitted*.

Sahli HF, Conner JK, "Testing for conflicting and non-additive selection: floral adaptation to multiple pollinators through male and female fitness," *Evolution*, Vol 65, 1457 - 1473 (2011).

Sambanthamoorthy K, Gokhale AA, Lao W, Parashar V, Neiditch MB, Semmelhack MF, Lee I, Waters CM, "Identification of a Novel Benzimidazole that Inhibits Bacterial Biofilm Formation in a Broad Spectrum Manner," *Antimicrobials Agents and Chemotherapy*, Vol 55, Iss 9, 4369 - 78 (2011). Note: This work was supported by NIH grant 1K22AI080937-01 and support from the Region V "Great Lakes" RCE (NIH award 2-U54-AI-057153) to C.M.W. K.S. was supported by a postdoctoral research fellowship from the Michigan State University Center for Waters Sciences.

Schossau J, Hintze A, Adami C, "Evolution of stochastic altruist strategies in microbial games," *Physical Review E*, (2011). *Submitted*.

Schrum J, Miikkulainen R, "Evolving Multimodal Networks for Multitask Games," *IEEE Symposium on Computational Intelligence and Games,* (2011).

Schrum J, Karpov IV, Miikkulainen R, "UT^2: Human-like Behavior via Neuroevolution of Combat Behavior and Replay of Human Traces," *IEEE Symposium on Computational Intelligence and Games,* (2011).

Sen D, Van Der Auwera GA, Rogres LM, Thomas CM, Brown CJ, Top EM, "Broad-host-range plasmids from agricultural soils have IncP-1 backbones with diverse accessory genes," *Appl. Environ. Microbiol,* (2011). *In Press*.

Shelton J, Dozier G, Bryant K, Smalls L, Adams J, Popplewell K, Abegaz T, Woodard D, Ricanek K, "Comparison of Genetic-based Feature Extraction Methods for Facial Recognition," *2011 Midwest Artificial Intelligence and Cognitive Science Conference (MAICS)*, (2011).

Shelton JM, Bryant KM, Adams JM, Popplewell KM, Abegaz TM, Purrington KM, Woodard DL, Ricanek KM, Dozier GM, "Genetic-Based LBP Feature Extraction and Selection for Facial Recognition," *The 2011 IEEE Workshop on Computational Intelligence in Biometrics and Identity Management,* (2011). *Submitted*.

Sleight SC, Bartley BA, Lieviant JA, Sauro HM, "Improving mutational robustness in genetic circuits and metabolic pathways," *Synthetic Biology 5.0*, (2011). Note: University of Washington, Dept. of Bioengineering

Sleight SC, Bartley BA, Sauro HM, "Synthetic systems as microbial threats: Predictability of loss-of-function mutations in engineered systems," *IOM Forum on Microbial Threats report, The Science and Applications of Synthetic and Systems Biology,* (2011).

Small L, Shelton J, Alford A, Dozier G, Bryant K, Washington K, "Landmark-Based Local Binary Patterns for Face Recognition," *2011 ADMI Conference*, (2011).

Small L, Shelton J, Dozier G, Bryant K, Adams J, "Biased Initialized Genetic & Evolutionary Feature Selection for Face Recognition," *2011 ADMI Conference,* (2011).

Smith JE, Powning KS, Dawes SE, Estrada JR, Hopper AL, Piotrowsky SL, Holekamp KE, "Greetings promote cooperation and reinforce social bonds among spotted hyaenas," *Animal Behaviour*, Vol 81, Iss 2, 401 - 415 (2011). [DOI: 10.1016/j.anbehav.2010.11.007]

Smith JE, Swanson EM, Holekamp KE, "Evolution and mechanisms of cooperation among mammalian carnivores," *Current Anthropology*, (2011). *In Press*.

Srivastava D, Harris RC, Waters CM, "Integration of Cyclic di-GMP and Quorum Sensing in the Control of vpsT and aphA in Vibrio cholerae," *Journal of Bacteriology*, (2011). *In Press*. Note: This work was supported by funding from NIH grant 1 K22 AI 080937-01, NSF sponsored BEACON Science and Technology 630 Center Cooperative Agreement No. DBI-0939454, and Michigan State University to C.M.W.

Subbiah MM, Shah DM, Top EM, Call DM, "The long-term persistence of blaCMY-2 positive, IncA/C plasmids requires selection pressure," *Appl. Environ. Microbiol*, Vol 77, 4486 - 4493 (2011).

Swanson EM, Dworkin IM, Holekamp KE, "Lifetime selection on a hypoallometric size trait in the spotted hyaena," *Proceedings of the Royal Society B*, (2011). [DOI: doi:10.1098/rspb.2010.2512]

Tan X, "Autonomous robotic fish as mobile sensor platforms: Challenges and potential solutions," *Marine Technology Society Journal*, (2011). *In Press*.

Tao Z, Han Z, Yao M, Fleet B, Goodman ED, Deller JR, "Application of Quarter Iteration of FRFT in BRATUMASS for Weak Signal Extraction," *2011 International Conference on Bioinformatics and Computational Biology*, (2011).
Book Chapter: Till R, Durak M, Goodman E, Groner N, "Modeling Critical Incidents to Improve Response," *Handbook of Critical Incident Analysis*, (2011). Note: (forthcoming, Dec, 2011)
Valsalam V, Miikkulainen R, "Evolving Symmetry for Modular System Design," *IEEE Transactions on Evolutionary Computation*, Vol 15, 368 - 386 (2011).
Wang J, Alequin-Ramos F, Tan X, "Dynamic modeling of robotic fish and its experimental validation," *The 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, (2011).
Whittaker DJ, Richmond KM, Miller AK, Kiley R, Bergeon Burns C, Atwell JW, Ketterson ED, "Intraspecific preen oil odor preferences in dark-eyed juncos (Junco hyemalis)," *Behavioral Ecology*, Vol 22, 1256 - 1263 (2011). [DOI: doi: 10.1093/beheco/arr122]
Whittaker DJ, Dapper AL, Peterson MP, Atwell JW, Ketterson ED, "Maintenance of MHC Class IIB diversity in a recently established songbird population," *Journal of Avian Biology*, (2011). *Submitted*.
Whittaker DJ, Soini HA, Gerlach NM, Posto AL, Novotny MV, Ketterson ED, "Role of testosterone in stimulating seasonal changes in a potential avian chemosignal," *Journal of Chemical Ecology*, (2011). *Submitted*.
Woods RJ, Barrick JE, Cooper TF, Shrestha U, Kauth MR, Lenski RE, "Second-order selection for evolvability predicts winners in a large E. coli population," *Science*, Vol 331, 1433 - 1436 (2011).
Workineh AM, Homaifar AM, "A New Bidding Strategy in LCS Using a Decentralized Loaning and Bid History," *IEEE Aerospace conference*, (2011).
Workineh AM, Dugda MM, Homaifar AM, Lebby GM, "GMDH and RBFGRNN Networks –A Comparative Study for Multi-Class Data Classification," *The 8th International Conference & Expo on Emerging Technologies for a Smarter World (CEWIT2011)*, (2011).
Zaman L, Devangam S, Ofria C, "Rapid Host-Parasite Co-Evolution Drives the Production and Maintenance of Diversity in Digital Organisms," *2011 Genetic and Evolutionary Computation Conference*, (2011).

1b. Conference presentations

Conference(Poster) -- July 17, 2011 - July 22, 2011 **Carlos Anderson**, Microbial Population Biology Gordon Research Conference , Andover, NH, "The rate of compensatory adaptation."

Conference -- July 17, 2011 - July 22, 2011 **Zachary Blount**, Gordon Research Conference on Microbial Population Biology, Andover, New Hampshire, "Proposed Test of Speciation in an Experimental Population of E. coli Following the Evolution of a Key Innovation."

Conference -- 7-3-11 - 7-7-11 **C. T Brown**, Invited Talk, Sixth International Tunicate Meetings, Montreal, CA, "Tail loss: investigating the Molgula."

Conference -- Aug 10, 2011 - Aug 12, 2011 **Chi-Chun Chen**, Beacon Congress, MSU, "Incipient evolution of a synthetic cooperative system."

Conference -- Jeffrey Conner, Society for the Study of Evolution Annual Meeting, Norman, OK, "Spontaneous mutations and fitness."

Conference -- May 26, 2011 - May 30, 2011 **Idelle Cooper**, Evolution of life on Pacific Islands and reefs, Honolulu, HI, "Ecology of sexual dimorphism in Hawaiian damselflies."

Conference -- August 10, 2011 - August 12, 2011 **Idelle Cooper**, All-BEACON Congress, MSU, "Poster: Recent range shifts and the role of sexual signals in premating isolation of sympatric Calopteryx damselflies."

Conference -- 6/17/2011 - 6/21/2011 **Arthur W Covert**, Evolution 2011, Norma, OK, "Navigating the Royal Road with Forks to High Fitness."

Conference -- 7/17/2011 - 7/22/2011 **Arthur W Covert**, GRC: Microbial Population Biology, Andover NH, "Tests of Shifitng Balance Theory in Digital Organisms."

Conference -- Aug 1, 2011 - Aug 4, 2011 **Patricia Hartzell**, Invited Talk, INBRE-NIH Conference, Moscow, Idaho, "Population heterogeneity: how it arises and why it matters."

Conference -- 3/25/2011 - 3/26/2011 **Randall Hayes**, North Carolina Academy of Sciences Annual Meeting, Elon, NC, "Variation Selection Inheritance: A Public Outreach Podcast on Evolution by the NSF BEACON Consortium."

Conference -- 7/25/2011 - 7/29/2011 **Randall Hayes**, Conference Board of Mathematical Sciences Lecture Series on Mathematical Epidemiology, Johnson City, TN, "VSI: A public outreach podcast on evolution."

Conference -- 25 July 2011 - 29 July 2011 **Kay E Holekamp**, Invited Talk, International Ethological Congress/Animal Behavior Society joint meeting, Bloomington, IN, "Social and other forms of environmental complexity in the evolution of intelligence."

Conference -- August 28 - September 1 **John P Jerome**, International Workshop on Campylobacter, Helicobacter and Related Organisms, Vancouver, Canada, "Campylobacter jejuni: What's in a strain? That which is not a clone."

Conference(Talk) -- 7-3-2011 - 7-7-2011 **Charlotte Konikoff**, Invited Talk, Sixth International Tunicate Meetings, Montreal, CA, "Deuterostome Hippo pathway proteins show different evolutionary trajectories."

Conference -- April 1,2011 - April 3,2011 **Megan Larsen**, Midwest Ecology and Evolution Conference, Carbondale, IL, "Eco-evolutionary dynamics of bacteria and virus in nitrogen- and phosphorus-limited environments."

Conference -- 5/2/11 - 5/5/11 **Richard Lenski**, Invited Talk, Great Lakes Bioinformatics Conference, Athens, Ohio, "Dynamics of Genome Evolution During a Long-Term Experiment with E. coli."

Conference -- 8/26/11 - 9/1/11 **Richard Lenski**, Invited Talk, FQXi: Setting Time Aright, Bergen, Norway, "Time - Forward and Reverse - in Experimental Evolution."

Conference -- 8/20/11 - 8/25/11 **Richard Lenski**, Invited Talk, European Society for Evolutionary Biology, Tubingen, Germany, "Phenotypic and Genomic Evolution in a 50,000-Generation Experiment with Bacteria."

Conference -- 7/17/11 - 7/20/11 **Richard Lenski**, Invited Talk, Gordon Research Conference on Microbial Populations, Andover, NH, "Dynamics of phenotypic and genomic evolution during a 50,000-generation experiment with E. coli."

Conference -- 6/27/11 - 6/30/11 **Richard Lenski**, Invited Talk, FEMS, Geneva, Switzerland, "Pathways of phenotypic and genomic evolution in a 50,000 generation experiment."

Conference -- 2/27/11 - 3/3/11 **Richard Lenski**, Invited Talk, Keystone Symposium on Evolutionary Developmental Biology, Tahoe City, CA, "Dynamics of Phenotypic and Genomic Evolution in a 50,000-Generation Experiment with Bacteria."

Conference(Poster) -- 7/3/11 - 7/7/11 **Elijah K Lowe**, Sixth International Tunicate meeting, Montreal, Quebec Canada, "I have my notochord cell, but where did I leave my tail?"

Conference -- May 16, 2011 - June 2, 2011 **Emily Jane McTavish**, Quantitative Evolutionary and Comparative Genomics Workshop, Okinawa, Japan, "Genomic Patterns of Population Structure in New World Cattle Breeds."

Conference -- June 18, 2011 - June 21, 2011 **Emily Jane McTavish**, Evolution, Norman, OK, "Tracking introgression between cattle subspecies using genomic SNP data."

Conference -- 7/17/11 - 7/22/11 **Justin Meyer**, Microbial Population Biology Gordon Conference, Andover NH, "Evolution of phage lambda to exploit a novel receptor; the origins of a key innovation."

Conference -- Risto Miikkulainen, Invited Talk, Genetic and Evolutionary Computation Conference, "Tutorial on Evolving Neural Networks."

Conference -- 7/31/2011 **Risto Miikkulainen**, Invited Talk, International Joint Conference on Artificial Neural Networks, San Jose, CA, "Tutorial on Evolving Neural Networks."

Conference -- June 5 2011 - June 8 2011 **Masoud Mirmomeni**, Invited Talk, IEEE Congress on Evolutionary Computation, New Orleans, "Co-evolving Data Driven Models and Test Data Sets with the Application to Forecast Chaotic Time Series."

Conference -- July 12, 2011 - July 16, 2011 **James J Morris**, Phycological Society of America Annual Meeting, Seattle, WA, "The Black Queen Hypothesis and the evolution of algal-bacterial mutualisms."

Conference -- July 17, 2011 - July 22, 2011 **James J Morris**, Gordon Conference: Microbial Population Biology, Andover, NH, "The Black Queen Hypothesis: Evolution of mutualism through adaptive gene loss."

Conference -- 6/17/11 - 6/21/11 **Bjørn Østman**, Evolution 2011, Norman, OK, "Applying evolutionary metagenomics to greenhouse gas-emitting microbial communities."

Conference -- 8/20/11 - 8/25/11 **Bjørn Østman**, ESEB 2011, Tübingen, Germany, "Epistatic modules: Does size matter?"

Conference -- 4/16/2011 **Robert T Pennock**, Invited Talk, Midwest Cognitive Science Conference, East Lansing, MI, "From AI to EI: Modeling the Evolution of Intelligence from the Bottom Up."

Conference -- 4/27/2011 - 4/29/2011 **Robert T Pennock**, Invited Talk, IRMSE Biology Forum, Chicago, IL, "Where is the research field of biology headed over the next ten years: What are the implications for biology education."

Conference -- 7/8/2011 - 7/11/2011 **Robert T Pennock**, The Evolution of Morality and the Morality of Evolution, Oxford University, UK, "Altruism Evolving: Empirical and Philosophical Tests."

Conference -- 8/24/2011 **Robert T Pennock**, Invited Talk, Santa Fe Institute Business Network Meeting: Innovation: Adventures in Possibility Space, Santa Clara, CA, "Innovation by Evolutionary Computation."

Conference(Poster) -- 7-3-11 - 7-7-11 **Lena J Perry**, Sixth International Tunicate Meetings, Montreal, CA, "Investigating Ptychodera flava Hox Gene Organization."

Conference -- 10/21/2011 - 10/23/2011 **Catherine M Scott**, SEPEEG Southeastern Population Ecology & Evolutionary Genetics meeting, Reidsville, NC, "Engaging Teachers (and Students) With Evolution in Action."

Conference -- 9/5/11 - 9/9/11 **Kim Scribner**, American Fisheries Society Annual Meeting, Seattle, WA, "Plastic Responses to Altered Selection Regimes in Larval Lake sturgeon."

Conference -- 06/15/11 - 06/17/11 **Sean Sleight**, Invited Talk, Synthetic Biology 5.0, Palo Alto, CA, "Improving mutational robustness in genetic circuits and metabolic pathways."

Conference(Talk) -- 7-3-11 - 7-7-11 **Billie J Swalla**, Invited Talk, Sixth International Tunicate Meetings, Montreal, CA, "Chordate Origins & Evolution."

Conference(Talk) -- 4-26-11 - 4-30-11 **Billie J Swalla**, Invited Talk, Developmental Biology of the Sea Urchin XX, Woods Hole, MA, "Central Nervous System Development in Hemichordates."

Conference(Poster) -- July 25, 2011 - July 30, 2011 **Robin Tinghitella**, Behavior 2011, Bloomington, IN, "Mate availability and hybridization in the threespine stickleback."

Conference(Talk) -- June 30, 2011 - July 1, 2011 **Eva Top**, First International Symposium on Microbial Resource Management in biotechnology: Concepts & applications, Ghent, Belgium,, "Bacterial plasmids from environment to clinic: Predicting their host reservoirs and promiscuity based on genomic signatures. ."

Conference(Talk) -- November 29, 2011 **Eva Top**, Invited Talk, Departmental Seminar, University of Florida, Department of Biology, "Evolutionary Patterns of Plasmid-host adaptation."

Conference(Poster) -- July 17, 2011 - July 21, 2011 **Caroline Turner**, Microbial Population Biology Gordon Conference, Andover, NH, "One new niche begets another: Cross-feeding specialists evolve to co-exist with citrate metabolizing E. coli."

Conference(Poster) -- October 18 - October 20, 2011 **Brian Wade**, European Science Foundation CAREX Conference on Life in Extreme Environments, Dublin, Ireland, "Experimentally evolved desiccation and ultraviolet radiation tolerance in the bacterium Escherichia coli."

Conference -- May 22, 2011 - May 25, 2011. **Patrick Wanko**, 2011 Industrial Engineering Research Conference (IERC), Reno, NV, May 2011, Reno, Nevada, "Using Social Networks to Devise Distance-Based Genetic Algorithms Clusters."

Conference -- May 22, 2011 - May 25, 2011. **Patrick Wanko**, 2011 Industrial Engineering Research Conference (IERC), Reno, NV, May 2011, Reno, Nevada, "Assessing the Suitability of Schooling Behavior to Search Heuristics."

Conference -- 4/3/1011 - 4/5/2011 **Chris Waters**, Invited Talk, 7th National RCE Meeting, Denver, CO, "Identification and Characterization of anti-Biofilm Compounds."

Conference -- 5/22/2011 **Chris Waters**, Invited Talk, American Society for Microbiology 2011 General Meeting, New Orleans, "Systems Biology Approach to Quantify Cyclic di-GMP Signaling Specificity."

Conference -- August 23, 2011 - August 24, 2011 **Chris Waters**, Invited Talk, GLRCE Annual Meeting, Chicago, IL, "Identification and Characterization of anti-Biofilm Compounds."

Conference -- 3/7/2011 - 3/11/2011 **Emily G Weigel**, FroSpects Winter School for Eco-evolutionary Modeling of Speciation, Abisko, Sweden, "Sexual signaling loss."

Conference(Poster) -- August 10, 2011 - August 12, 2011 **Emily G Weigel**, BEACON Congress, East Lansing, MI, "Mate availability and hybridization in the threespine stickleback."

Conference -- April 13, 2011 - April 16, 2011 **Danielle J Whittaker**, Invited Talk, American Association of Physical Anthropologists, Minneapolis, MN, "Chemical communication without a vomeronasal organ: parallel evolution in primates and birds."

Conference -- July 25, 2011 - July 30, 2011 **Danielle J Whittaker**, Animal Behavior Society/International Ethological Conference, Bloomington, IN, "Is bill-wiping a form of avian scent marking."

Conference(Poster) -- 7/17/2011 - 7/21/2011 **Michael Wiser**, Gordon Research Conference, Microbial Population Biology, Andover, NH, "The view from 50,000 generations: Analaysis of fitness trajectories in a Long Term Evolution Experiment in E. coli."

Conference(Poster) -- 7-3-11 - 7-7-11 **Peter X Wu**, Sixth International Tunicate Meetings, Montreal, CA, "Molgulid Ascidians Share a Unique Gene Complex."

Conference(Poster) -- July 17 - July 22 **Luis Zaman**, Gordon Conference - Microbial Population Biology, Andover, NH, "Investigating Parasite Driven Diversity in Digital Organisms."

1c. Other dissemination activities

Lecture -- August 24, 2011 **Zachary Blount**, Invited Talk, Santa Fe Institute Business Network Meeting: Innovation: Adventures in Possibility Space, National Semiconductor University, Santa Clara, California, "Watching Evolution Innovate in the Lab."

Seminar -- February 11, 2011 **Erik D Goodman**, Invited Talk, Computer Science and Engineering Seminar Series, Michigan State University, "Unifying Biology, Computation and Engineering in BEACON Center for the Study of Evolution in Action."

High School Class -- June 10, 2011 - June 16, 2011 **Erik D Goodman**, Invited Talk, BEACON H.S. Summer Institute, MSU, East Lansing, "Introduction to BEACON."

Seminar -- 10/21/11 **Erik D Goodman**, Invited Talk, MSU CSE Strategic Partners Meeting, Engineering Building, "Overview of BEACON (20 minutes)."

Seminar -- 9/13/2011 - 9/15/2011 **Erik D Goodman**, Invited Talk, NSF STC Directors' Meeting, Lawrence, Kansas, "BEACON Progress in Year One."

Seminar -- May 10, 2011 **Patricia Hartzell**, Invited Talk, Joseph G. Galusha Lecture Series, Walla Walla University, "Impact of phase variation on survival of Myxococcus xanthus,."

Seminar -- Aug 30, 2011 **Patricia Hartzell**, Invited Talk, Biological Sciences seminar series, Moscow Idaho, "Population heterogeneity in bacteria: the evolution of co-dependent cell types."

Lecture -- 9/15/2011 **Richard Lenski**, Invited Talk, University of Illinois, "Dynamics of Evolution in a 50,000 Generation Experiment with E. coli."

Lecture -- 5/17/11 **Richard Lenski**, Invited Talk, University of Washington, "Dynamics of Phenotypic and Genomic Evolution in a 50,000-Generation Experiment with Bacteria."

Seminar -- 11/14/11 **Richard Lenski**, Invited Talk, NASA Goddard Space Flight Center, "Evolutionary Dynamics in a 50,000 Generations Experiment with Bacteria."

Seminar -- 4/15/11 **Richard Lenski**, Invited Talk, Santa Fe Institute, "Evolution in Action: A 50,000 Generation Experiment."

Seminar -- February 2011 **Philip McKinley**, Invited Talk, Microbiology and Molecular Genetics Seminar, East Lansing, Michigan, "Evolution of Cooperation in Digital Organisms."

Seminar -- October 2010 **Philip McKinley**, Invited Talk, MSU Gifted and Talented Advisory Committee Annual Luncheon, East Lansing, Michigan, "Evolution in Action."

Seminar -- 10/6/11 **Justin Meyer**, Invited Talk, EEPB Dept, Washinton University St. Louis, "Viral genomic and experimental evolution studies reveal processes underlying a key innovation."

Seminar -- 2/16/2011 **Bjørn Østman**, Invited Talk, EEBB Colloquium, 203C Natural Sciences, Michigan State University, "Evolutionary Metagenomics, Adaptation, and Blogging."

Seminar -- 2/8/11 **Robert T Pennock**, Invited Talk, Clemson University, "Evolution in Action: Observing Evolutionary Processes in Real Time."

Seminar -- 2/11/11 **Robert T Pennock**, Invited Talk, College of Charleston, "A new LENS tool: Learning Evolution and the Nature of Science using Avida-ED Digital Evolution Software."

Seminar -- 2/11/11 **Robert T Pennock**, Invited Talk, The Citadel, "Evolution in Action: Observing Evolutionary Processes in Real Time."

Seminar -- 2/17/11 **Robert T Pennock**, Invited Talk, MSU Faculty Emeriti Association, East Lansing, "Evolution in Action: Observing Evolutionary Processes in Real Time."

Seminar -- 2/11/2011 **Robert T Pennock**, Invited Talk, Biology Dept. Colloquium, The College of Charleston, "A new LENS tool: Learning Evolution and the Nature of Science using Avida-ED Digital Evolution Software."

Seminar -- 3/24/2011 **Robert T Pennock**, Avida-ED workshop, North Carolina A&T University, "A new LENS tool: Learning Evolution and the Nature of Science using Avida-ED Digital Evolution Software."

University Class -- 3/31/2011 **Robert T Pennock**, Invited Talk, Computational Biology class, Univ. of Texas at Austin, "Modeling Evolution in a Computer."

Seminar -- 3/31/2011 - 4/1/2011 **Robert T Pennock**, Avida-ED workshop, Univ. of Texas at Austin, "A new LENS tool: Learning Evolution and the Nature of Science using Avida-ED Digital Evolution Software."

Seminar -- 9/15/2011 **Robert T Pennock**, Invited Talk, Biology department colloquium, Utah State University, "Learning Evolution and the Nature of Science using Digital Organisms."

Seminar -- 4-14-11 - 4-17-11 **Billie J Swalla**, Invited Talk, Michigan State University, "Evolution of the Chordates: Evidence from Fossils, Phylogenies and Gene Networks."

Seminar -- 10-7-11 - 10-9-11 **Billie J Swalla**, Invited Talk, Auburn University, Auburn, AL, "Origin, Evolution & Development of the Chordates."

Seminar -- April 22, 2011 **Xiaobo Tan**, Invited Talk, CSE Lecture Series, Michigan State University, East Lansing, MI, "Toward autonomous robotic fish schools: Challenges and potential solutions."

Conference(Poster) -- July 25, 2011 - July 30, 2011 **Robin Tinghitella**, Behavior 2011, Bloomington, IN, "Mate availability and hybridization in the threespine stickleback."

Seminar -- October 3, 2011. **Eva Top**, Invited Talk, Departmental Seminar, Gene and Linda Voiland School of Chemical Engineering and Bioengineering, Washington Sate University, Pullman, WA,, "Shifts in Bacterial Host Range of Drug Resistance Plasmids: What Does It Take?"

Seminar -- 10/31/11 **Caroline Turner**, Invited Talk, Biology Department, Wright State University, Dayton, OH, "Interactions between ecology and evolution in a 50,000 generation experiment with E. coli."

Seminar -- September 18, 2011 **Patrick Wanko**, Invited Talk, BEACON Seminar Series, Teleconference, "Schooling Genetic Algorithms."

Seminar -- February - 2011 **Chris Waters**, Invited Talk, invited seminar speaker, University of Kentucky, "Targeting Cyclic di-GMP to Prevent Infection."

2. Awards and Honors

	Recipient	Reason for Award	Award Name and Sponsor	Date	Award Type
1	Zachary Blount	Distinguished graduate research	Ronald M. and Sharon Rogowski Fellowship	4/13/2011	Fellowship
2	Chad Byers	Best Paper Nomination	2011 ACM Genetic and Evolutionary Computation Conference	July 2011	Scientific
3	Mairin Chesney	Best Poster	MICWIC (Michigan Women in Computing)	4/2/11	Scientific
4	Kari Dammerman		Norman S. Baldwin Fishery Science Scholarship, IAGLR and GLFC	April 2011	Scientific
5	Kari Dammerman	Student Travel Grant to AFS Meeting in Seattle, WA	Michigan Chapter of the American Fisheries Society	July 2011	Other
6	Gerry Dozier		Team Research Award, NC A&T Division of Research and Economic Development	2/25/11	Scientific
7	Carrie Glenney		NSF Graduate Research Fellowship Honorable Mention	2011	Fellowship
8	Heather Goldsby	Postdoctoral Fellowship	NSF, CI TraCS Fellowship for Transformative Computational Science	July 2011	Fellowship
9	Erik D Goodman	Nationally recognized distinguished professional scholarship and	Distinguished Faculty Award, MSU	February 8, 2011	Other, Education-related

		teaching			
10	Patricia Hartzell	Service and mentoring	Decade of excellence award, INBRE-NIH	Aug 3, 2011	Education-Related
11	Benjamin Kerr	Recognition of outstanding work of scientists and engineers in early stages of their careers	PECASE, NSF and OSTP	10/14/11	Scientific, Education-related
12	Dave Knoester	Postdoctoral Fellowship	NSF, CI TraCS Fellowship for Transformative Computational Science	July 2011	Scientific
13	James M Kremer		NSF Graduate Research Fellowship (honorable mention)	4/2011	Fellowship
14	Alycia Lackey	Support for Thesis Research	Sigma Delta Epsilon - Graduate Women in Science Fellowship	June, 2011	Fellowship
15	Elena Litchman	Recognition of outstanding work of scientists and engineers in early stages of their careers	PECASE, NSF and OSTP	10/14/11	Scientific, Education-related
16	Justin Meyer	Excellence as senior graduate student	MSU College of Natural Science, Barnett Rosenberg Fellowship	2011-05-17	Fellowship
17	Justin Meyer	Postdoctoral Fellow	McDonnell Foundation, Postdoctoral Fellowship Awards in Studying Complex Systems	Oct. 2011	Fellowship
18	Justin Meyer	Outstanding research in environmental sciences	College of Natural Sciences, MSU, Hensley Fellowship	May 2011	Fellowship
19	Justin Meyer	Outstanding research	Department of Zoology, MSU, Shaver Fellowship	May 2011	Fellowship
20	Babak Momeni	Postdoctoral Fellowship	Gordon and Betty Moore Foundation,	8/1/2011	Fellowship

			Life Science Research Foundation Fellowship		
21	Robert T Pennock	Nationally recognized distinguished professional scholarship and teaching	Distinguished Faculty Award, MSU	February 8, 2011	Other, Education-related
22	Tasneem Pierce	Best Poster	MICWIC (Michigan Women in Computing)	4/2/11	Scientific
23	Tasneem Pierce		NSF Graduate Research Fellowship	04/05/2011	Fellowship
24	Bree Rosenblum		University of Idaho College of Science, Early-Career Faculty Award	2011	Scientific
25	Jacob Schrum	Best-Paper Award to J. Schrum and R. Miikkulainen for "Evolving Multimodal Networks for Multitask Games"	2011 IEEE Conference on Computational Intelligence and Games	2011	Scientific
26	Robin Tinghitella	Travel to Animal Behavior Society Conference	Animal Behavior Society, Education Travel Award	July 25, 2011	Education-Related
27	Emily G Weigel	Graduate Student Award to Support Thesis Research	MSU Zoology, John. R. Shaver Award	April 21, 2011	Scientific
28	Peter X Wu	Undergraduate research on NA14/bobcat/man x gene complex in tailed and tailless ascidian species	Library Research Award, University of Washington	6/7/2011	Scientific
29	Peter X Wu	Undergraduate research to be presented at Sixth International Tunicate Meetings in Montreal	Casey Award, University of Washington Biology Department	6/7/11	Scientific

3. Undergraduate, M.S. and Ph.D. students who graduated during the reporting period

	Student Name	Degree	Years to Degree	Placement
1	Joshua Adams, NCAT	B.S., Computer Science		
2	Matthew de Wet, UT	B.S., Computer Science		
3	Owen Pierce, MSU	B.S., Economics and Computer Science		
4	Tasneem Pierce, MSU	B.S., Genomics and Molecular Genetics	4	Graduate school, UW
5	Peter X. Wu, UW	B.S., Biology		Graduate school
6	Tamirat Abegaz, NCAT	M.S., Computer Science		
7	Freddie Alequin-Ramos, MSU	M.S., Electrical & Computer Engineering		
8	Julie M. Hughes, UI	M.S., Biological Sciences	2.8	Applying for jobs
9	Zachary Blount, MSU	PhD, Microbiology & Molecular Genetics	8	Postdoc, MSU
10	Heather Goldsby, MSU	PhD, Computer Science & Engineering		Postdoc, UW
11	David Knoester, MSU	PhD, Computer Science & Engineering		Postdoc, UW
12	Matt Rupp, MSU	PhD, Computer Science & Engineering		
13	Vinod Valsalam, UT	PhD, Computer Science	8	Industry: TwoSigma, Inc

4a. General outputs of knowledge transfer activities

	Patent Name and Inventors/Authors	Number	Application Date	Receipt Date
1	Benzimidazole Inhibition of Biofilm Formation, Chris Waters, MB Neiditch, MF Semmelhack, and K Sambanthamoorthy	3000.038PRV	2/18/2011	

	Name of Start-Up Company	Main Product(s)
1	Digital Certainty	Neuroevolution software

4b. Other outputs of knowledge transfer activities

Primary Person Involved: Erkin Bahceci
Other People Involved: Risto Miikkulainen
Type of Activity: Software Package
Description: NKVIS: A visualization tool for NK fitness landscapes
Location: http://nn.cs.utexas.edu/?nkvis
Date: May 2011

Primary Person Involved: Vinod Valsalam
Other People Involved: Risto Miikkulainen
Type of Activity: Software Package
Description: ENSO: Software for evolution of symmetric modular neural networks
Location: http://nn.cs.utexas.edu/?enso-code
Date: November, 2010

Primary Person Involved: Vinod Valsalam
Other People Involved: Risto Miikkulainen
Type of Activity: Software Package
Description: Sorting Networks: Software for minimizing the number of comparators in sorting networks
Location: http://nn.cs.utexas.edu/?sorting-code
Date: November, 2010

6. Summary listing of all the Center's research, education, knowledge and other institutional partners

	Organization Name	Organization Type	Address	Contact Name	Type of Partner	160 hours or more?
	Secure Designs, Inc.	Company	301 North Elm Street Suite 201 Greensboro, NC 27401		KT	N
	Ford Motor Company	Company			KT	N
	Google, Inc.	Company	1600 Amphitheatre Parkway Mountain View, CA 94043		KT	N

7. Summary table

	The number of participating institutions (all academic institutions that participate in activities at the Center) This value should match the number of institutions listed in Section I, Item 1 of the report plus other additional academic institutions that participate in Center activities as listed in the table above.	5
	The number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at the Center) This value should match the number of partners listed in the table in Section VIII, Item 6 (above)	3
	The total leveraged support for the current year (sum of funding for the Center from all sources *other* than NSF-STC) [Leveraged funding should include both cash and in-kind support that are related to Center activities, but not funds awarded to individual PIs.] This value should match the total of funds in Section X, Item 4 of "Total" minus "NSF-STC" for cash and in-kind support	$500,000
	The number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF). Please EXCLUDE affiliates (click for definition) This value should match the total number of participants listed in Section VIII, Item 5 (above)	222

8. Media publicity

2011 Press Releases

9/9/11 MSU Press release: Evolution keeps sex determination flexible.
http://ns.msu.edu/index.php/2011/09/evolution-keeps-sex-determination-flexible/
8/22/11 MSU Press release: Hyenas' ability to count helps them decide to fight or flee.
http://news.msu.edu/story/9680/
7/19/11 MSU Press release: Avian 'Axe effect' attracts attention of females and males.
http://news.msu.edu/story/9579/
6/30/11 MSU Press release: Mutations help organisms become kings of the mountain.
http://news.msu.edu/mutations-help-organisms-become-kings
4/14/11 MSU Press release: MSU Museum explores evolution in action.
http://news.msu.edu/story/9213/&topic_id=3
3/24/11 KGI Press release: Allen Foundation awards grant to KGI professor to study brain complexity. http://www.kgi.edu/news-and-events/news-story-allen-foundation-awards-grant-to-kgi-professor-to-study-brain-complexity.html
3/23/11 MSU Press release: Miller-Urey experiment recreated in art-science exhibit.
http://news.msu.edu/story/9108/
3/23/11 MSU Press release: Larger female hyenas produce more offspring.
http://news.msu.edu/story/9106/
3/22/11 MSU Press release: In the race of life, better an adaptable tortoise than a fit hare.
http://news.msu.edu/story/9096/
3/22/11 NSF Press release: Some outcomes of the evolutionary race buck conventional wisdom.
http://www.nsf.gov/news/news_summ.jsp?cntn_id=119029&org=NSF&from=news

2011 Media Coverage

10/4/11 TED.com: "Christoph Adami: Finding life we can't imagine." (Video)
http://www.ted.com/talks/christophe_adami_finding_life_we_can_t_imagine.html
9/23/11 *State News*: New robotic fish detect harmful pollutants.
http://statenews.com/index.php/article/2011/09/new_robotic_fish_detect_harmful_pollutants
9/19/11 Geek.com: Robotic schools of fish made from 3D printers will patrol for water pollution.
http://www.geek.com/articles/geek-cetera/robotic-schools-of-fish-made-from-3d-printers-will-patrol-for-water-pollution-20110919/
9/19/11 *Scientific American blogs*: Synchronized swimming: patrolling for pollution with robotic fish. http://blogs.scientificamerican.com/guest-blog/2011/09/19/synchronized-swimming-patrolling-for-pollution-with-robotic-fish/
9/12/11 ScienceDaily: Evolution keeps sex determination flexible.
http://www.sciencedaily.com/releases/2011/09/110912143447.htm
8/22/11 ScienceDaily: Hyenas' ability to count helps them decide to fight or flee.
http://www.sciencedaily.com/releases/2011/08/110822131809.htm
8/17/11 *Nature* News: Hyenas can count like monkeys.
http://www.nature.com/news/2011/110817/full/news.2011.484.html
7/22/11 Futurity.org: Songbird 'cologne' drives females wild. http://www.futurity.org/science-technology/songbird-%E2%80%98cologne%E2%80%99-drives-females-wild/

7/19/11 ScienceDaily: Avian 'Axe effect' attracts attention of females and males.
http://www.sciencedaily.com/releases/2011/07/110719151906.htm
7/8/11 NPR's Science Friday: The Story of Texas Longhorns, as Told by Their DNA.
http://www.sciencefriday.com/program/archives/201107082
6/20/11-7/11/11 *New York Times* "Scientist At Work" blog posts by Kay Holekamp.
http://scientistatwork.blogs.nytimes.com/author/kay-e-holekamp/
6/1/11 Ars Technica: Evolving bacteria through a game of rock-paper-scissors.
http://arstechnica.com/science/news/2011/06/evolving-bacteria-through-a-game-of-rock-paper-scissors.ars
4/8/11 LiveScience Behind the Scenes: Understanding the brain as a computational network.
http://www.livescience.com/13639-understanding-brain-computational-network-bts-110408.html
3/24/11 artdaily.org: Classic experiment from 1952 on the origin of life recreated in art-science exhibit. http://artdaily.com/index.asp?int_sec=2&int_new=45974
3/24/11 ScienceDaily: Larger female hyenas produce more offspring.
http://www.sciencedaily.com/releases/2011/03/110323140251.htm
3/23/11 ScienceDaily: In the race of life, better an adaptable tortoise than a fit hare.
http://www.sciencedaily.com/releases/2011/03/110322105304.htm
3/21/11 Carl Zimmer, *New York Times*: Tortoise and Hare, in a Laboratory Flask.
http://www.nytimes.com/2011/03/22/science/22evolve.html?_r=2&ref=science
3/18/11 *Science* Podcast: Interview with Jeff Barrick and Rich Lenski.
http://www.sciencemag.org/content/331/6023/1433/suppl/DC2
3/18/11 Cosmic Log: In evolution, slow and steady wins.
http://cosmiclog.msnbc.msn.com/_news/2011/03/18/6294783-in-evolution-slow-and-steady-wins
3/17/11 ScienceNews: In evolution, last really can be first.
http://www.sciencenews.org/view/generic/id/71318/title/In_evolution,_last_really_can_be_first
3/17/11 *Nature* News: Slow evolvers win in the end:
http://www.nature.com/news/2011/110317/full/news.2011.166.html
3/15/11 LiveScience: Large lady hyenas throw their weight into cub-making.
http://www.livescience.com/13257-large-hyena-females-cubs.html
1/21/11 *New Scientist*: Telltale chemistry could betray ET.
http://www.newscientist.com/article/mg20927962.700-telltale-chemistry-could-betray-et.html

IX. INDIRECT/OTHER IMPACTS

1. Please describe any international activities in which the Center has engaged. If they are described elsewhere in the report, highlight them without going into great detail.

Four faculty members from outside the US (Denmark, Korea and China) will have extended visits in BEACON in 2011, each funded primarily by the visitor's host institution or a grant from their government. They will engage in collaborative research with Director Erik Goodman and other BEACON participants.

2. Please use this space to describe other goals, impacts, or influences related to the Center's progress and achievement during the current reporting period that may not have been captured in another section of the report. (optional)