BEACON Center for the Study of Evolution in Action

ANNUAL REPORT
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I. GENERAL INFORMATION

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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.

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.

SIGNIFICANT ACCOMPLISHMENTS

In this section, we will very briefly highlight just a few of the most important accomplishments and advances of the Center in this reporting period, including 1) successful recruitment of outstanding researchers at the faculty and postdoctoral level; 2) groundbreaking research discoveries, and 3) education/outreach activities with a high level of impact.

1. Personnel

Professor Kalyanmoy Deb is joining BEACON as the Herman Koenig Endowed Chair in MSU's College of Engineering. Prior to joining BEACON, Dr. Deb was a professor of Mechanical Engineering at the Indian Institute of Technology Kanpur. Dr. Deb is a pioneer in the field of multi-objective evolutionary algorithms, and his book Multi-Objective Optimization using Evolutionary Algorithms has become one of the most popular and highly cited books in the

field of evolutionary computation. Dr. Deb has received many honors and awards, including the Shanti Swarup Bhatnagar award in engineering sciences in 2005, the Thomson Citation Laureate award for his highly cited research in computer science during 1996-2005, and the MCDM Edgeworth-Pareto Award recognizing his major contributions to the field of Multiple Criteria Decision Making. Dr. Deb has been awarded the Infosys Prize in Engineering and Computer Science from the Infosys Science Foundation in Bangalore, India for his contributions to the emerging field of Evolutionary Multi-objective Optimization (EMO) that has led to advances in non-linear constraints, decision uncertainty, programming and numerical methods, computational efficiency of large-scale problems and optimization algorithms.

As a part of our NSF proposal, BEACON committed to identify potential new faculty participants, with an emphasis on increasing diversity. As a result, we created the BEACON Faculty Affiliates program to actively target early career, minority and/or women faculty at nonpartner universities that are interested in evolutionary science or evolutionary computation. Faculty Affiliates are awarded a mini-grant of up to $100,000 over a two-year period and are expected to conduct independent research that is multidisciplinary in nature, relevant to evolution in action, and will serve as the foundation for a future research grant proposal. BEACON successfully initiated its Faculty Affiliates program by appointing **Dr. Adriana Briscoe** at University of California, Irvine as the first BEACON Faculty Affiliate. Dr. Briscoe uses experimental evolution to examine how natural selection shapes the coding sequences and gene expression patterns of photoreceptor proteins in the eye and how this may lead to evolutionary changes in color vision and wing color in butterflies. The Briscoe lab also uses modeling and field experiments to understand how color vision impacts ecological interactions between butterflies and their predators, potential mates, host plants and the environment in the context of mimicry and species recognition. We will continue to appoint one Faculty Affiliate per year.

In another initiative to recruit outstanding researchers, BEACON has initiated the Distinguished Postdoctoral Scholars program. The successful applicant to this program receives a two-year postdoctoral fellowship (salary $50,000/year) and conducts interdisciplinary research with at least two BEACON faculty mentors. The first Distinguished Postdoctoral Fellowship was awarded to **Joshua Nahum**, who completed his doctoral degree at University of Washington with Ben Kerr. His work with Charles Ofria and Richard Lenski will involve the exploration of how and why organisms are evolvable. By combining the merits of digital and microbial systems, he seeks to understand how contingency loci (regions of the genome with an increased mutation rate) may allow organisms to more rapidly adapt to new and/or changing environments. Contingency loci are often associated with genes involved in pathogenicity and virulence in microbes, as well as neurological disorders in humans. As such, understanding their putative role in enabling more rapid adaptation would yield a more accurate understanding of the nature of mutations with possible implications for medicine. Should contingency loci and other forms of biased mutation rates prove beneficial to evolution, they may also offer another avenue to improve the performance of optimizing applied evolutionary algorithms.

2. Research

This reporting period has been extremely productive, with 162 publications submitted by BEACONites and 46 current research projects underway. Here we would like to highlight two recent research discoveries - one is a recently published experimental evolution study in *Nature*

that has received a great deal of media attention, and the other is a brand-new, world record-breaking evolutionary computation achievement that is not yet published.

The newest results from Richard Lenski's **Long Term Evolution Experiment** were published in *Nature* in September 2012. Previously, postdoc Zachary Blount (MSU) and Richard Lenski (MSU) described the **evolution of a novel trait**, aerobic citrate utilization (Cit+) in an experimental population of *E. coli* (Blount et al 2008, *PNAS* 105: 7899-7906). The *inability* to use citrate is actually one of the defining features of the species *E. coli*. Blount and Lenski have now used genomic analysis to document and describe the three-step process of specific mutations that evolved to allow these microbes to use citrate as an energy source (Blount et al 2012, *Nature* 489: 513-518). This study was featured on the NSF website, and was also covered by many media outlets including *The Washington Post*, *ABC News*, Salon.com, and Carl Zimmer's blog *The Loom.* The team is now working to determine **whether this lineage qualifies as a new species** based on various criteria that have been advanced over the years. They devised a method that allows them to revert citrate-using bacteria and thereby obtain otherwise isogenic Cit+ and Cit- genotypes. Using this approach, they find that the bacteria are becoming less fit in competition for glucose as they become progressively better adapted to using citrate, a result that provides support for the hypothesis that a maladaptive valley separates the adaptive peaks associated with growing on glucose and citrate. They have secured a new two-year grant from the Templeton Foundation that will support their continued research on this question.

Chris Adami (MSU) and Risto Miikkulainen (UT), with postdoc David Knoester (MSU), postdoc Arend Hintze (MSU), and graduate student Samuel Chapman (MSU), are evolving a **256-node neural controller** to recognize human handwriting in a project they named **Darwin vs. DARPA**. The goal of this project is to use evolution as a substitute for design in creating a computational structure that is brain-like, and not based on a von Neumann computer architecture. DARPA's SyNAPSE project, now using a silicon chip design, has as one of its stated goals to perform hand-written digit recognition on their neurochip. They have achieved an accuracy of 94% image recognition in the simulation of their design, and of 89% in the hardware implementation of it. **The BEACON team has not only beat DARPA's performance, but also the world record of machine performance, as well as outperformed the best human performance on this task.** The first part of this project is focused on evolving a Markov brain that recognizes the numerals 0-9 from the MNIST database. There are 60,000 different images in the training set, and 10,000 images in the test set. The accuracy of the algorithm is given by the percentage of test images that are classified incorrectly. The historically best classifier is a multi-layer neural network that was trained on a massively parallel GPU cluster, but not only with the 60,000 images, but a much larger set obtained by deforming the initial images. The current world record architecture misclassifies 23 images (Ciresan, D., U. Meier & J. Schmidhuber. 2012. Multi-column Deep Neural Networks for Image Classification, presented at Computer Vision and Pattern Recognition (CVPR 2012) Providence, Rhode Island). The BEACON team used a very different approach than what has been seen in the literature: Markov brain networks—that is, networks of hidden Markov gates whose connectivity and function are evolved. The team can evolve brains that have, on average, an error rate of 5% on the test set; that is, each brain misclassifies about 500 of the 10,000 test images (the best individual brains achieve an error rate of around 3.5%). The prediction accuracy can be increased further by taking "committees" of brains for the decision making process. For example, in each of 100 independent individual runs a different brain evolved, and therefore a different classifier. Interestingly, these classifiers make mistakes about different things, simply because evolution creates new classifiers every time. As

a consequence a committee of classifiers is provably better than the best brain in the set, and often the worst committee is better than the best individual classifier. A committee of the two best brains actually leads to a worse prediction, but a committee of just the six best gives an error rate of 0.017% (17 out of 10,000 test images misclassified). This performance beats the current world record of 23 misclassified images. A committee of just 12 members leads to only 2 misclassified images, and using the 20 best brains as a committee reduces the error rate further to zero. Given that humans misclassify 20 images on average, it is clear that **evolution has now achieved an improbable world record.** In fact, it is clear that evolution of digital logic automatically discovers all of the information in the data set, even when humans cannot achieve that feat. This capacity can be attributed to the differences in learned context for human recognition as opposed to automated recognition. The features that the evolved circuits use for classification include features that humans use, but also use additional features that are unintuitive for human image recognition. The team is now working on classifying a more ambitious set of images: the "Special Database 19" data set from NIST, comprising about 810,000 images of numerals and upper-case and lower-case letters, at 128x128 pixel resolution. Of those, 82,587 images are to be used as a test set. This project is described in greater detail in Section II. Research.

3. Education & Outreach

BEACON has several successful internal and external education and outreach projects that are described in subsequent sections of this report. The activity with arguably the greatest impact was our invited participation in the **USA Science and Engineering Festival Expo** in Washington D.C., April 2012. This event took place on the National Mall, featured over 500 US science organizations, 1,500 free interactive exhibits, and attracted about 500,000 people. BEACON's booth featured interactive computer and robotic activities, such as robots that evolved complex behaviors, online evolution games like the Ladybug & Aphids game described in the Education section of this report, and demonstrations of using genetic and evolutionary feature extraction for facial recognition.

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. The overall goals and optimal outcomes have not changed since the previous reporting period.

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. 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. 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. 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. 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. BEACON's **research output goal** is to disseminate widely an increasing quantity of original and highly regarded scientific research on evolution in action.

PROGRESS TOWARDS CENTER GOALS

The following sections summarize progress 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 toward the goals and metrics in our strategic plan.

GOAL	METRICS	PROGRESS
Integrative Research Goals		
New research collaborations and proposals	Number of interdisciplinary/multi-institutional research projects and publications	46 projects currently underway, 162 publications
	Service by members on doctoral research committees across disciplines and institutions	A recent inquiry revealed at least 18 faculty serving on at least 65 committees of this kind
New paradigms for research in organic and digital domains	Number of new sessions at scientific meetings or scientific meetings hosted at BEACON	BEACON hosted the Thirteenth Artificial Life conference in 2012
	Number of new journals and societies	None to report yet
	New or increased funding for biocomputational research	BEACON researchers submitted 52 proposals for ~$35M of external funding, and ~$10M in external funding has been granted in this reporting period
Increase in publications related to evolution in action	Number of BEACON faculty participants writing such publications and the number of citations of their work.	162 publications submitted

	High visibility science journalism about BEACON research	15 press releases and ~60 media pieces, including high profile pieces in New York Times, Washington Post, ABC News, USA Today, MSNBC, and Huffington Post
Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	Number of requests for information	~4700 downloads of Avida-ED, ~4,400 downloads of Avida; over 2,500 visits to BEACON website monthly
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.	No progress in the past year, but firm plans for the next year.
Respect for views and ideas "horizontally" and "vertically."	Number of Toolbox seminars and trials	Toolbox workshops temporarily on hold during the past year, as ToolBox PI moved to MSU, but firm plans for the next year.
	Number of BEACON participants who get cross-disciplinary training	Toolbox workshops temporarily on hold during the past year, but firm plans for the next year.
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	162 publications submitted, 143 conference or other presentations, 52 grant proposals submitted Feb. 1 - Oct. 31, 2012
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.

Some 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 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 22 projects are currently 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.

Thrust Group 2: Evolution of Behavior and Intelligence. Research in thrust group 2 focuses on the evolution of behavior of individuals, particularly in the context of social behavior, including cooperation, social coordination, and communication. 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 15 projects are funded in this thrust group.

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. This group also includes researchers exploring engineering applications inspired by biological studies of collective dynamics. Nine funded projects currently fall into this thrust group.

Education

The following table summarizes our progress towards the goals set in our strategic plan.

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	Multidisciplinary classes being taught across consortium. Mentoring programs established. BEACON postdoctoral fellowship established and first "Distinguished" postdoc appointed.
Increased public literacy in evolution and the nature of science	Development of educational materials	Testing of educational materials across audiences has started. Evaluation instruments have been developed.
	Frequency of public use of online materials or visits to exhibits	Cross-institutional dissemination of materials is underway.
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	Diversity surveys are being administered across education projects where appropriate. Data are presented in diversity section.
	Feedback from the External Advisory Committee	Positive feedback. See Appendix C

Recent science education reform recognizes that students learn better when information is organized around major unifying concepts (National Research Council, 2012), and all recent science education reform places evolution as a core idea within the biological sciences (Brewer and Smith, 2011; College Board, 2011). Yet, evolution is summarily rejected by nearly half of the general public living in the United States (Miller et al. 2005). Across all BEACON, our

educational projects aim to use BEACON research demonstrating evolution in action to reveal the power of evolution, showing (1) evolution is a historical ***AND*** ongoing dynamic process; (2) evolutionary biology is a good example of how science works; (3) evolutionary processes can help us solve complex biological and engineering problems.

Internal Education Activities. BEACON has instituted a series of courses specifically designed to train graduate students across disciplines. Courses include Computational Science for Evolutionary Biologists taught by Dr. Titus Brown; Evolutionary Biology for non-Life Scientists taught by Dr. Alex Shingleton; and Multidisciplinary Approaches to the Study of Evolution taught by Drs. Charles Ofria and Ian Dworkin. These courses are offered at MSU, but students at partner universities are also able to participate via videoconference and online technology. We initiated an evaluation of the course sequence, relative to our training objectives. 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.

External Education Activities. BEACON is currently funding a number of educational activities and programs, all of which help to meet our EHRD goals and optimal outcomes. Student-centered activities include the annual BEACON High School Summer Institute at MSU and Kellogg Biological Station and the BEACON REU Field Experience conducted jointly at Kellogg Biological Station (MSU) and Friday Harbor Laboratories (UW). BEACON is developing teacher training and educational materials including evolutionary games for elementary students and software that engages undergraduate students in testing evolutionary hypotheses. All such BEACON projects include an explicit evaluation component. We also have a number of educational activities that target the general public, including an evolution podcast and museum exhibits at MSU and UT.

Knowledge Transfer

The following table summarizes our knowledge transfer progress in the past year in the areas described in the strategic plan.

Knowledge Transfer Goals		
GOAL	**METRICS**	**PROGRESS**
Signed Intellectual Property agreements with Industrial Affiliates	Number of IP agreements signed	All 5 BEACON institutions have signed boilerplate agreement for industrial collaborations through BEACON and are actively recruiting industrial affiliates
Receiving industry-provided challenge problems and data with feedback	Number of instances that challenge problems, data, and feedback are received	At least six companies are providing challenge problems and feedback.
New collaborative research	Number of publications	At least 7

with Industry partners	Number and amount of joint grant proposals submitted	1
Dissemination and use of BEACON tools and data	Number of downloads of BEACON tools/data relative to baseline	~4700 downloads of Avida-ED; ~4400 downloads of Avida platform
Spinoffs formed	Number of spinoffs formed	1 in the previous reporting period, no new spinoffs this period
Adoption of new BEACON-developed technology by industry	Number of instances of BEACON projects, processes, and techniques adopted by industry	1

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.

Several companies are currently working with BEACON, including Ford Motor Company, Northrop Grumman, Continental Automotive, BAE Systems, General Motors, Secure Designs, Inc. and SCION, a Crown Research Corporation of New Zealand.

External Partnerships

BEACON aims to form external partnerships with other researchers and educators who are working in the area of evolution in action, with other centers that can broaden our impact, and with minority faculty members at non-BEACON institutions and/or faculty members at minority-serving universities to provide research opportunities for those faculty and their students.

BEACON has recently been awarded a $200K supplemental grant from NSF to address the cyberinfrastructure needs of BIO centers and center-like institutions. This project, led by C. Titus Brown, will (1) extend existing online computational science training material to facilitate self-learning by biologists across a wide range of expertise; (2) run a number of focused workshops to teach the materials and train others in delivery; (3) develop reusable assessment strategies to study the effect of these materials on learning and help identify unmet learning needs; and (4) host several meetings across a number of centers to develop a list of shared educational needs. This project will be carried out in partnership with SESYNC (Socio-Environmental Synthesis Center) and NESCent (National Evolutionary Synthesis Center).

In July 2012, BEACON partnered with the International Society of Artificial Life to host the ALife 13 conference, overlapping the BEACON Congress on one day. By hosting the two events concurrently, we increased participation by BEACONites in the ALife conference, especially by biologists who might not normally attend this conference. About 300 people attended the conference. Keynote speakers included Steven Benner, Oron Catts, Benjamin Kerr, Radhika Nagpal, and 2009 Nobel Laureate Jack Szostak, who gave a public lecture titled “The origin of

life and the emergence of Darwinian evolution" that was attended by over 500 people. More information about the conference can be found online at http://alife13.org.

BEACON has submitted an NSF REU Site proposal to begin a new undergraduate research program, the BEACON Luminary Scholars Program, in partnership with Spelman College (a historically black college) and UT Pan Am (a Hispanic-serving institution). This program would bring undergraduate students from these two colleges to BEACON institutions for summer research, and would provide resources for faculty to conduct research during the academic year with these students. This program is described in more detail in the Diversity section.

Education Director Louise Mead is working directly with the National Association of Biology Teachers to find ways to develop and introduce BEACON materials for high school and college biology classes. This activity includes teacher training sessions, and is described in more detail in the Education section.

Diversity

BEACON's overall goal is to exceed national norms for diversity at all levels in the Center. In 2011, 18% of BEACON participants self-reported as underrepresented minorities. In 2012, this proportion has increased to 30.3%, including 25% of BEACON's graduate student participants. The increase is due partly to better reporting, but also to active recruitment of minorities for our undergraduate and graduate programs. Participation of underrepresented minorities at BEACON exceeds national norms at all levels (undergraduates, graduate students, and faculty) based on figures from the National Science Foundation.

Participation of women is overall comparable to national norms (32.8% compared to 33.4%, weighted by field), but at some levels is below the norms. In general, participation within the biological sciences is at or above national levels, but within BEACON, there are fewer women in computer science and engineering than are found at the national elvel. Participation of women at the undergraduate level (41.2%) is well above national norms (36.5%) due to increased summer research opportunities for undergraduates. At the graduate level, participation of women at BEACON (30.6%) is somewhat below national norms (34.5%), due primarily to the lower participation of women in computer science and engineering disciplines. We plan to actively recruit female participants both internally (current graduate students in these disciplines at partner universities who are not currently part of BEACON) and externally (by recruiting students through the REU program and graduate recruitment conferences). The particpation of women at the postdoc level at BEACON (26.9%) is well below national norms (45.7%), due to very low proportions of women in the computer science (16.7%) and engineering (0%) disciplines. We will actively recruit women at the postdoc level, particularly in these disciplines. Finally, though the proportion of women in the biological sciences at BEACON exceeds national norms, there are very few BEACON women faculty in computer science (6.3%) and engineering (0%). We will actively recruit women faculty in these areas from participating BEACON institutions.

One of our biggest successes is the high proportion of underrepresented groups in our summer undergraduate research opportunity programs. This success is due partly to active recruitment, but also to our mentor training programs for the graduate students and postdocs who mentor these students. This training improves the experience both for participating undergrads

and for the mentors, and as a result many students have indicated their desire to participate again in the following year. Ultimately, this strategy will result in increased recruitment of students from undergraduate programs into BEACON graduate programs.

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	The number of cross-disciplinary submissions (using a strict definition) increased 125% from last reporting period
	Number of new courses	One new course offered at MSU in Fall 2011
	Number of students enrolled in cross-disciplinary courses	Fall 2011: 32; Spring 2012: 19
	Number of funding proposals submitted	Number of cross-disciplinary grants submitted since last reporting period is the same as the previous period.
Increase in cross-institutional research and education	Number of paper/conference submissions	Increase of 150% since last reporting period.
	Number of new courses	One new course offered at MSU in Fall 2011
	Number of students in cross-institutional courses	Fall 2011: 23; Spring 2012: 19
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	52 grant proposals submitted in this funding period; 5 can be considered cross-disciplinary and/or cross-institutional by a strict definition
	Award dollars	BEACONites have been awarded over $10.6M in this funding period, exceeding goal of $5M/year
Increase in new participants	Number of faculty, post-docs, and students	Since baseline (Nov 2010): No change in faculty; postdocs increased from 21 to 28 (33% increase); grad students

		increased from 86 to 98 (14% increase). At Affiliate level, much larger increases.
Effective support of Center operations by Management team	Survey for participants about management team	Year 2 evaluation was positive but revealed areas for improvement, which we are addressing
	Feedback from External Advisory Committee	Feedback is very positive (Appendix C)
Center is perceived by NSF as exemplary	Renewal of NSF funding	Renewal was approved for our third funding increment, and we have received positive feedback from NSF
	Number of public mentions made by NSF about BEACON	7 mentions of BEACON on nsf.gov during this reporting period; BEACON also selected as one of the NSF projects represented in US Science and Engineering Festival

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). Details about this process are provided in section VII. Management. The competitive internal funding process at BEACON rewards interdisciplinary and inter-institutional collaboration, and has resulted in a significant increase in such collaboration (between 2010 and 2011, one-way ANOVA, $p<0.001$). Of the 41 research, education, and diversity projects funded in Project Year 3, 51% are cross-disciplinary, 63% are cross-institutional, and 41% are both cross-disciplinary and cross-institutional. We anticipate that these newer collaborations will lead to a spike in number of cross-disciplinary and cross-institutional paper, conference, and proposal submissions.

BEACON Student/Postdoc Association. The only other major change in this reporting period is that the BEACON Student/Postdoc Association is now fully functional. The group uses the main BEACON student and postdoc email lists for their communication needs, so that they are able to reach all of the students and postdocs that participate in or are affiliated with BEACON. They also maintain a Facebook group that currently has 83 members. The group holds monthly meetings at MSU and organizes activities such as lab visits, data science seminars, and other professional development activities, which are be described in greater detail in the Education section of the annual report. In addition to these lunch seminars, the group also negotiated “mini-sabbaticals” for members. These include a limited amount of funding for a student/postdoc to travel to a partner institution and visit outside the scope of other funding opportunities provided by BEACON. The group also organized a student/postdoc retreat day as part of the BEACON Congress that included presentations on communicating science to the public and how to get grants. The evening ended with a picnic at a local park that brought together students and other

researchers from all partner universities. Overall, more than 100 individuals signed up to attend this retreat.

BEACON Organizational Formative Evaluation Report. Drs. Patricia Farrell and Marilyn Amey are conducting an on-going process of data collection focused on factors affecting the organizational development of five institutions into an inter-institutional, interdisciplinary collaboration. The 2012 Organizational Formative Evaluation Report (October, 2012) made several recommendations for improvement. Nearly all of these recommendations are items that BEACON management was either already planning to implement, or was aware of as needing attention, but the availability of these data help to reinforce that the right targets for change are being addressed. Over the next year, we will be working to address these recommendations in many ways.

Center-Wide Outputs

Publications submitted: 162 reported January 31, 2012 – October 31, 2012

Conference presentations and other dissemination activities (including lectures, seminars): 143

Awards and Honors: 28 awards and honors reported

Students that graduated (reported): 5 Master's, 6 PhD's

General outputs of knowledge transfer activities: 1 patent, 1 invention disclosure

Participants: 295 participants, plus another 326 affiliates (under 160 hours/year in Center activities), for a total of 621 BEACONites

Media publicity: In 2012, we put out 15 press releases. At least 60 features on BEACON research appeared in the mainstream and online media in the current reporting period (nearly triple the number in the previous period), including *The New York Times*, *The Washington Post*, *USA Today*, ABC News, MSNBC, and the Huffington Post.

Indirect/Other Impacts

International activities: Four faculty members from outside the US (Korea and China) had extended visits in BEACON in 2012, each funded primarily by the visitor's host institution or a grant from their government. They engaged in collaborative research with Director Erik Goodman and other BEACON participants in four projects described under Research. Two additional visiting scholars from China (one pre-doctoral and one post-doctoral) also collaborated in BEACON on two of those projects. One student from China became a BEACON graduate student with support from one of those projects. All of the collaborations are continuing.

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. The Center's overall goals and objectives have not changed since the last reporting period.

In the current reporting period, a total of 46 research projects were supported by BEACON, including 16 projects that just began in summer/fall 2012. 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	46 projects currently underway, 162 publications
	Service by members on doctoral research committees across disciplines and institutions	A recent inquiry revealed at least 18 faculty serving on at least 65 committees of this kind
New paradigms for research in organic and digital domains	Number of new sessions at scientific meetings or scientific meetings hosted at BEACON	BEACON hosted the Thirteenth Artificial Life conference in 2012
	Number of new journals and societies	None to report yet
	New or increased funding for biocomputational research	BEACON researchers submitted 52 proposals for >$35M of external funding,

		and ~$10M 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.	162 publications submitted. System for tracking citations through Google Scholar is under development. (Available method under Web of Science drastically underreports articles and citations)
	High visibility science journalism about BEACON research	15 press releases and ~60 media pieces, including high profile pieces in *New York Times*, *Washington Post*, ABC News, *USA Today*, MSNBC, and Huffington Post
Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	Number of requests for information	~4700 downloads of Avida-ED, ~4,400 downloads of Avida, over 2,500 visits to BEACON website monthly
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.	No progress in the past year, but firm plans for the next year.
Respect for views and ideas "horizontally" and "vertically."	Number of Toolbox seminars and trials	Toolbox workshops temporarily on hold during the past year as the ToolBox PI (M. O'Rourke) moved to MSU, but there are firm plans for the next year.
	Number of BEACON participants who get cross-disciplinary training	Toolbox workshops temporarily on hold during the past year, but firm plans for the next year.

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	162 publications submitted, 143 conference or other presentations, 52 grant proposals submitted during this reporting period
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: We held our third annual BEACON Congress in July 2012. We added a graduate student/postdoc retreat day, which was received well and will be repeated in the future. Feedback from participants suggests the need for more structured interaction opportunities in addition to the Sandbox Sessions we introduced in 2011 for discussing research topics, so we will add some new types of sessions in 2013. In 2013 we will also lengthen the Congress by one more day, for a total of 4 days (one is student/postdoc only).
- **BEACON Intranet profiles**. We are currently upgrading our intranet system for increased functionality, and are creating a more searchable database that will allow BEACONites to discover other members with similar research interests, and to browse their work.
- **Weekly seminars**. We hold weekly meetings, which rotate through five themes (the three research thrust groups, plus education/outreach and "All-BEACON"), in which members present the results of ongoing activities. These seminars have more than once successfully sparked interest and led to new collaborations. At MSU and UT, we follow the seminar with a "social hour," providing refreshments and an opportunity for casual interaction. At UI and UW, the seminar occurs during the lunch hour due to time zone differences, and lunch is either provided or brought by the attendees.

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

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. Many projects could be assigned to two or more research groups,

but for convenience we only report each project as belonging to a single thrust group below. The overall themes pursued in BEACON research are roughly the same as the last reporting period. Below, we describe progress on 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 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 22 projects are currently 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).

MSU postdoc Zachary Blount and Lenski are studying an experimental *E. coli* lineage that evolved the novel ability to use citrate for energy (phenotype Cit+). They seek to understand whether that lineage qualifies as a new species based on various criteria that have been advanced over the years. They have made substantial progress on several fronts. First, they have a long-format article in Nature that describes the genomic changes responsible for the emergence of that trait (Blount et al, 2012), information that will be essential for examining some of the species criteria. Second, they secured a new two-year grant from the Templeton Foundation that will support their continued research on this question. Third, they devised a method that allows them to revert citrate-using bacteria and thereby obtain otherwise isogenic Cit+ and Cit- genotypes. Using this approach, they find that the bacteria are becoming less fit in competition for glucose as they become progressively better adapted to using citrate, a result that provides support for the hypothesis that a maladaptive valley separates the adaptive peaks associated with growing on glucose and citrate.

Dr. Boughman's lab has made substantial progress on collecting phenotypic data for mapping fitness and sexual isolation loci in stickleback fish. Over the past year they doubled our sample size for behavioral and morphological data (and now have about 350 males phenotyped), spending the spring and summer at Kellogg Biological Station conducting the field experiments. They will be genotyping the fish this fall, using RADseq, and expect to build the map over the winter. They have produced some exciting results on how selection through both female choice and male competition are generating divergent selection. The Boughman lab is in the process of analyzing data on sexual isolation at the phenotypic level.

Williams and MSU graduate student Carlos Anderson have examined the rate at which intrinsic postzygotic reproductive isolation evolves. In the first project, they showed deleterious mutations that are evolutionarily suppressed by compensatory adaptation lead to more rapid and stronger postzygotic isolation than that caused by genetic drift in digital organisms. The second project determined the rate at which pairwise genetic incompatibilities evolve relative to the rate at which hybrid fitness deteriorates. While they found support for the popular 'snowball' theory of speciation (pairwise incompatibilities accumulate quadratically), they also found that more complex genetic interactions buffer simple, pairwise incompatibilities and lead to the previously observed pattern of a linear decline in hybrid fitness over time—'the missing snowball.' These results validate recent work on snowball theory, but also point to the relative importance of complex incompatibilities in speciation. Luke Harmon and Anderson examined the relative influence of parallel adaptation, gene flow, and genetic drift in the evolution of speciation in digital organisms.

Barry Williams (MSU) and Paul Hohenlohe (UI) are developing **an experimental evolution model for genomic islands of speciation.** A central concept in the population genomics of adaptation and speciation is the genomic island – a chromosomal region of elevated differentiation between populations, caused by divergent selection, that can facilitate the evolution of reproductive isolation and speciation. Despite some support from modeling and comparative genomic work, we still do not understand the evolutionary processes that can lead to the formation of genomic islands and their dynamic behavior over time. This new collaboration between labs at two BEACON institutions explores the feasibility of two experimental evolution systems for directly studying genomic island dynamics, *in vivo* (yeast) and *in silico* (AVIDA).

The process of divergence in the presence of gene flow is the 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, UI

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 UT 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. To date, 52 mtDNA genomes have been assembled by Sarver. Preliminary phylogenetic analyses of the complete genomes confirm the mtDNA introgression that has been detected using a single mtDNA gene.

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." There has been progress in two areas: *(1) Evolution in a network of populations connected by migration.* Felsenstein has extended the mathematical theory of geographic differentiation by neutral mutation and genetic drift in the presence of migration between populations. He has discovered a new way to describe migration among populations using the eigenvectors and eigenvalues in a migration matrix, extending the work of Maruyama (1970, 1971) in a way that requires fewer approximations. A paper has been submitted and is now under revision for Theoretical Population Biology. *(2) Expanding the suite of models that can be fit to phylogenetic comparative data.* Optimum selection within species is well-modeled by an Ornstein-Uhlenbeck process (a Brownian motion with a linear force of return to an optimum). Progress has been made by Felsenstein in expressing the multivariate Ornstein-Uhlenbeck process in terms of the additive genetic covariances and the shape of the phenotypic optimum peak in multivariate character space. It is also possible to use these formulations to carry out the computations for a known phylogeny of species and compute likelihoods. There are still a few computational steps to be worked out but this should constitute a noticeable advance in treatment of multivariate OU models with phylogenetic data. Felsenstein has also now completed the mathematics deriving the distribution of traits when populations that are subject to optimum selection track a moving optimum, when this optimum is itself wandering according to a Brownian Motion process. An R package or programs in the PHYLIP phylogeny inference package will ultimately make these methods available to the community. Harmon has implemented three new comparative methods. One uses a statistical model related to Levy walks to identify evolutionary "jumps" on trees. A second carries out analyses that include both intra- and interspecific data, thus bridging the gap between "micro" and "macro" evolution in a single analysis. Finally, a third project allows fitting

of models that include genetic drift, stabilizing selection, and species interactions to be fit to comparative data.

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, contingency loci, and the role of population structure, as well as the factors influencing the evolution of virulence and biomechanical traits.

Benjamin Kerr (UW), Eric Klavins (UW), Richard Lenski (MSU), Lauren Meyers (UT) and Charles Ofria (MSU) are studying the **evolution of evolvability**. As the ultimate source of variation, genetic mutation is necessary for biological adaptation. However the majority of mutations are not beneficial. Organisms must always trade the cost of deleterious mutation for the potential of evolutionary innovation. When the environment changes, genomic regions will differ in the fraction of potential mutations that enable adaptation. That is, certain regions will contain a greater proportion of beneficial mutations relative to all possible mutations in that region. Given constant environmental change, one way to alleviate the aforementioned trade-off is to elevate mutation rate at genomic regions most likely to produce adaptive change. Contingency loci, which are genomic locations subject to a higher mutation rate, may harness the spontaneity of mutations where they can do the most good. Contingency loci can cause rapid genotype switching in populations. One ubiquitous form of a contingency locus is a tandemly repeated, short nucleotide sequence. Due to the repeats, such regions are subject to length changes by strand-slippage replication events and recombination errors. Such mistakes yield mutations that extend the region (by insertion of the repeated unit) or contract it (by deletion). Tandem repeats mutate 10 to 100 times more frequently than other parts of the genome. Unlike some other forms of mutation, such length changes are highly reversible as extensions can be countered by contractions and vice versa. Variable number tandem repeats (VNTRs) are tandem repeats differing in length between individuals. VNTRs have been implicated as contingency loci with potentially adaptive consequences. For instance, VNTR length variation can diversify cell surface antigens in bacteria and fungi, allowing pathogens to rapidly evade their host's immune system. This project will use an engineered contingency system (in *E. coli*) and build contingency loci into a digital system (AVIDA) to explore the environmental conditions that favor the evolution of evolvability through contingency loci (with a focus on the role of environmental change). This experimental work is complemented by theoretical modeling.

Jenny Boughman (MSU), Luke Harmon (UI), Paul Hohenlohe (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. The team is employing computationally intensive analyses to link phenotype, genotype, and fitness, and reveal the nature of evolutionary change at the genetic level. This project also includes a cross-institutional graduate seminar on multidimensional adaptation and outreach efforts to increase public understanding of evolution.

It is easy to be struck by the range in diversity of organisms that inhabit nature. Upon closer inspection, however, it is equally impressive to observe the constancy of form within any particular species. An organism's ability to generate consistent phenotypes during development in the face of environmental and genetic perturbations is known as canalization. By hiding the phenotypic effects of new mutations, genetic canalization allows populations to accumulate cryptic genetic variation, which may be subsequently available to natural selection. Despite the importance of canalization to evolution, the mechanisms that underlie canalization and how they evolve are poorly understood, thus Jeffrey Barrick (UT) and Alexander Shingleton (MSU) are studying the **evolution of canalization mechanisms**. Until recently, the few examples of canalizing mechanisms suggest that canalization occurs by imposing external control on the processes being canalized, like training wheels on a child's bike. Examples include Hsp90, a molecular chaperone that canalizes by stabilizing proteins in a wide variety of developmental pathways. Research in the Shingleton lab, however, suggests that canalization mechanisms may also be part of the developmental pathway being canalized, rather than an addition to the pathway. They found that reducing the expression of FOXO, a gene that codes for an insulin-signaling transcription factor, environmentally canalizes organ growth in Drosophila. Importantly, FOXO is also a signaling component of the developmental pathway that it canalizes (the insulin-signaling pathway). They hypothesize that there are two broad classes of canalization mechanisms: (i) extrinsic mechanisms that result from the introduction of external controls (e.g., Hsp90) and (ii) intrinsic mechanisms that result from modifications of the pathways they canalize (e.g., changes in FOXO expression). The first has been established biologically, but the second remains untested, at least with reference to genetic canalization. The goal of this project is to determine under what conditions and the extent to which each class of mechanism is likely to evolve. To achieve this goal, the team is taking a multifaceted approach to explore the regulation and evolution of genetic and environmental canalization using *Drosophila* and the Avida system.

Scott Harrison (NCAT), Julius Jackson (MSU), and Justin Zhan (NCAT) are testing hypotheses about **coevolution in genome sections in Gram-negative bacteria**. Recombinational change is associated with how bacterial populations succeed in switching between non-host and host environments. To investigate the impact on physiologic function and

association with microbial habitat, they are examining the arrangement of genes associated with the biosynthesis of the cytoplasmic membrane, cell wall and outer membrane in all fully sequenced Gram-negative bacteria. They are constructing a generative model for simulating the rearrangement of these genes based on site-specific and homologous recombination events. As a case scenario, lambda and lambdoid phages have been identified as a primary cause of recombinational change in some emergent disease-causing enteric bacteria. The team seeks to specifically address the likelihood by which lambda and lambdoid phage types distinctively mediate rearrangement.

Using biological and computational techniques, Larry Forney (UI), Benjamin Kerr (UW), Charles Ofria (MSU), Robert T. Pennock (MSU), Eva Top (UI), and Claus Wilke (UT) are examining **adaptation in structured worlds**. The adaptive landscape is a visual metaphor depicting the relationship between an organism's genotype and its fitness. Imagine placing all possible genotypes of an organism on a plane, where the distance between two genotypes gives the number of mutations needed to generate one genotype from the other. Each genotype is assigned a height proportional to its fitness. An evolving population is represented as a cloud of points on the resulting landscape (one point for each individual). Novel alleles arise in the population via mutations, expanding the range of the cloud. In contrast, natural selection reduces the cloud's range, shifting its weight uphill as less fit genotypes are culled. The combination of mutation and selection enables a population to 'climb' hills to their 'peaks,' which are genotypes from which all mutations are deleterious. On a smooth landscape, a population will always converge to the global optimum, as it is the only fitness peak. In contrast, if the landscape is rugged (i.e., multiple peaks) a population may become trapped at a local, suboptimal fitness peak, which limits future evolutionary potential. As evolution can be constrained by landscape topography, elucidating the topographical features of landscapes will provide a better understanding of adaptation. When organisms disperse and interact locally, their population is considered "spatially structured." Given structure, different portions of the evolving population are exploring the adaptive landscape semi-independently, permitting a more thorough search. If the adaptive landscape is smooth, structured populations reach the global optimum more slowly than unstructured populations. However, a more expansive search on rugged landscapes may lead to the discovery of a higher peak. Also, given structure, a population residing on one peak is more likely to shift off, as mildly detrimental mutants persist longer. If the landscape is rugged, such deleterious mutants can occupy valleys between multiple peaks. Thus, more peaks are likely to be found in a structured population. A rugged landscape can produce a 'tortoise-hare' pattern in the trajectories of average fitness, where the unstructured population rises quickly (hare), but is overtaken eventually by the structured population (tortoise). In summary, spatial structure allows for improved long-term adaptation on a rugged landscape, but only slows the rate of adaptation on a smooth landscape. The team has explored these predictions using multiple study systems. First, simulations of NK landscapes are consistent with the general predictions. Second, they evolved *Escherichia coli* as metapopulations of 96 wells within a microtiter plate and manipulated population structure by controlling the migration pattern between wells over 36 transfers. The fitness trajectories of the Structured treatment (where migration was restricted to adjacent wells) relative to the Unstructured treatment (where migration could occur between any wells) display the 'tortoise-hare' pattern consistent with a rugged landscape topography. Third, they have evolved digital organisms under varying degrees of population structure; the fitness pattern is again consistent with a rugged topography. The group is now extending these studies to

plasmid evolution and will elucidate the effect of population structure on genome evolution in all our digital and organic experimental systems.

Jeffrey Conner (MSU) and graduate students at MSU and UI are investigating **rapid adaptation in natural settings** using the evolution of weedy traits as a model system. The goal is to uncover the molecular genetic basis of the rapid evolution of early flowering in weedy radish. The group is taking a multi-pronged approach, combining molecular population genetic, genomic, and phylogenetic studies of multiple weed, native, and crop populations with characterization of the key weedy phenotypes in the field. To generate sufficient pilot data for an NSF Plant Genome grant, they have used a panel of 21 SNP and SSR markers to genotype multiple native, weedy and crop populations from the four species in the radish genus *Raphanus*. The results show that the weeds appear to be genetically intermediate between native *R. raphanistrum* and the crop species *R. sativus*. MSU graduate student Amanda Charbonneau has also done a spring field planting, and is currently doing a fall planting, of individuals from multiple weed, native and crop populations (as well as F2s from a weedy X native cross) to generate clearer data with respect to several key weedy traits, particularly the loss of the requirement for vernalization, which leads to rapid flowering so the plants can set seed before being plowed under in agricultural fields. These data should elucidate how much variation is present among the native plants (including multiple species and sub-species) and how they differ from the weed and crop plants. The team is also in the final planning stages to examine a small set of individuals (48) for genome wide markers (using reduced representation genomic libraries) to look for regions that may be strongly differentiated between a population of weeds and the native population that are phenotypically distinct but quite similar genetically based on the genome-wide markers described above, which should maximize the ability to identify regions showing strong genetic differentiation as candidate genomic loci undergoing natural selection.

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 insertions 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. In contrast, clinical isolates of *C. jejuni* strains did not evolve increased virulence during mouse passage. This project is the first to study bacterial evolution in action through rapid alteration of contingency loci.

Craig McGowan (UI) and Phil McKinley (MSU) are studying the roles of **morphology, mechanics, and natural selection in the evolution of bipedal hopping**. The overall goal is to understand why animals as diverse as kangaroos, wallabies, and kangaroo rats all hop. To

achieve this goal the team is using an interdisciplinary approach that integrates biomechanics, computation, and physics-based simulation to understand how selective pressures shape the evolution of leg design and gait in these animals. They are simultaneously using an established evolutionary environment and physics-based simulator to determine which selective pressures produce bipedal hopping, and developing a detailed musculoskeletal model of a kangaroo rat to determine the effects of muscle-tendon architecture on hopping dynamics.

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.

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

The group evolved 1,255 *Escherichia coli* populations over 170 generations by serial transfer into fresh media with an increasing concentration of the antibiotic rifampicin, with three treatments: 'Sudden' 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 the level fatal to the ancestor (MIC) half way through the treatment and the highest level at the final transfer; and 'Moderate' in which the populations reached the MIC a quarter of the way through the treatment and the highest level of rifampicin half way through the treatment. The Gradual and Moderate exposures resulted in much higher survivorship (90% and 44% of populations at final transfer, respectively) than Sudden exposure (2%). Gradual and Moderate populations also had a greater variety of mutations and a greater frequency of multiple mutations in the candidate resistance gene *rpoB*—a subunit of RNA polymerase to which rifampicin binds—than the Sudden populations, in which we found only a single mutation per population.

The conventional wisdom suggests that, having spent more time spent at the sub-inhibitory concentration, the Gradual and Moderate populations simply had more time to acquire resistance mutations. The group suggests an alternative hypothesis – that "potentiating" mutations enable the Gradual and Moderate populations to survive. For example, if mutation arises early on in a Gradual population, conferring resistance to a low level of rifampicin, that mutation would persist and acquire other mutations allowing it to survive in the final environment. However, this mutation would have been immediately selected against in the Sudden treatment and the mutational pathway would have been completely inaccessible. To demonstrate the existence of these "potentiating" mutations, the team identified a few candidate Gradual and Moderate populations with multiple mutations in *rpoB* (and sequenced them at various time points to determine the order in which the mutations arose). They constructed all combinations of these mutations in fragments of wildtype *rpoB* using primer-mediated site-directed mutagenesis then

ligated these mutated fragments into the pKOV vector with counter selectable markers and temperature sensitive replication. Using a two-step allelic exchange method, they have now constructed all mutational combinations for two Gradual isolates, two Moderate isolates, and two Sudden isolates. They have also reengineered the wildtype from each constructed mutant using the same method to control for the effects of the allelic exchange protocol. Finally, they have performed a variety of fitness assays on these engineered mutants and their reengineered wildtypes across a spectrum of rifampicin concentrations. These included a spectrophotometric growth rate assay, pairwise competitions between mutants and their immediate ancestors, and viability assays to determine which types could survive standard dilution at certain rifampicin concentrations and which could come up from rarity. These assays demonstrated that three of the four first mutations found in the selected Gradual and Moderate isolates conferred only partial resistance to rifampicin and would not have been accessible in the Sudden treatment. Thus, these evolutionary paths that rescued the population from extinction under an increasingly stressful environment (increasing rifampicin concentration) depended on a lower rate of environmental change.

Postdoc Idelle Cooper (MSU), along with Molly Cummings (UT), Thomas Getty (MSU), Chris Klausmeier (MSU), and Muraleedharan Nair (MSU), is using computational and empirical approaches to understand **rapid evolution of damselflies in response to anthropogenic change**. They proposed three specific goals that integrate our understanding of evolutionary change at multiple levels (biochemical, population, and species): (1) determine the biochemical basis of *Megalagrion* damselfly pigmentation, (2) quantify *Megalagrion* distribution and selection relative to UV, and build computational models to predict range shifts during anthropogenic change, and (3) measure variation and selection on coloration in two local damselflies species that underwent a recent range overlap, *Calopteryx maculata* and *C. aequabilis*. Preliminary work by Cooper, Nair, and MSU postdoc Yunbao Liu 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 with UT graduate student Eben Gering 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 team also conducted extensive surveys of *Megalagrion* species distributions and body color relative to UV levels and measured natural selection on pigmentation in one species in a caged experiment. Fifteen damselflies species were surveyed on the islands of Kauai, Oahu, Maui, Molokai, and Hawaii. Finally, range shifts plus trait changes allowing species to persist 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. aeuqabilis*, has shifted north by more than 500 kilometers in the last 35 years. Additionally, we measured sexual selection between species on wing pigmentation in enclosed tent experiments at KBS and in Ontario, during the summers of 2011 and 2012. Measurements of sexual selection between species on wing pigmentation indicate that wing pigment is a signal of species identification, particularly for *C. maculata*.

Interactions among genes

Many 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.

Several BEACON studies are looking at a specific, complex trait to understand interactions among genes and gene networks. Billie Swalla (UW) 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. Specific aims are to determine which developmental signaling networks are necessary for *P. flava* regeneration, identify additional candidate genes that may also be crucial for *P. flava* regeneration, and develop additional methods to determine the roles of key genes and signaling pathways activated during hemichordate regeneration.

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. In this project, Swalla and Brown are developing genomic models for investigating chordate evolution that make use of two closely related ascidian species that have dramatically different larval body plans. *Molgula oculata* eggs develop into free-swimming chordate tadpole larvae, whereas a closely related sister species, *Molgula occulta*, develops into an anural, or tailless ascidian. Fertilization and cleavage in *M. occulta* are remarkably similar in timing and pattern to its sister species, *M. oculata*. However, the anural *M. occulta* embryo fails to differentiate several chordate features, including an otolith (gravity sensing vesicle), notochord and tail muscle cells, which are characteristic of ascidian tailed tadpole larvae. Swalla and Brown have been investigating the cellular and molecular basis of these tailless ascidians by comparing the transcriptome of the hybrid and the two species embryos at several different developmental stages. Surprisingly, the notochord specification gene network is expressed, in spite of the embryo lacking a notochord. However, metamorphosis genes are also expressed early, much earlier than has ever been seen in other ascidian species. The team has just sequenced the genomes of *Molgula occulta*, *Molgula oculata* and *Molgula occidentalis*, a tailed molgulid ascidian from Florida that is gravid all year long. They will then be assembled and analyzed.

Phenotypic plasticity refers to the ability of a single genotype to express multiple phenotypes dependent upon environmental differences. Alexander Shingleton (MSU), Herbert Sauro (UW), and Peter Bates (MSU) 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.

Over the past year, MSU graduate student Yu Liang has constructed and evaluated an ODE model of the IIS pathway. Model simulations are consistent with published data and indicate 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 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 targets 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? This may be due to how changes in gene expression influence the robustness of the pathway to accurately and precisely signal variation in an environmental signal. Apart from its implications in evolutionary biology, the model is also **an important resource in understanding how insulin-sensitivity is regulated at a molecular genetic level**.

Few studies have directly examined the evolutionary origin and maintenance of communication systems. Heather Eisthen and Barry Williams (MSU) are **pinpointing the genetic origins and functional co-option of a peptide pheromone**. Pheromonal communication presents an exciting opportunity to address this problem because the signal is discrete and because both the signal and response to it can be measured quantitatively. Amphibian pheromones are unique in that they are peptides, allowing a rare chance to examine the evolution of the genes coding for particular pheromones. The first peptide pheromone to be discovered was sodefrin, a female-attracting pheromone released by male Japanese fire-belly newts (*Cynops pyrrhogaster*). Evolutionarily related peptide pheromones have now been described in other newt genera as well as in another family of salamanders, Plethodontidae. The team's preliminary bioinformatics research has identified the small gene family that encodes sodefrin and sodefrin-like peptides. Surprisingly, this gene family is present in all annotated vertebrate genomes, but has never been ascribed a potential function outside of salamanders.

These results have two important implications. First, the use of sodefrin as a pheromone is either the result of co-option of a pre-existing vertebrate gene or may be an exceptional case of a peptide pheromone in all vertebrates. Second, if the sodefrin homologs in other vertebrates, including humans, are not pheromones, they are likely to be newly discovered signaling molecules. The group is examining the evolution of the gene family coding for sodefrin-like molecules in vertebrates and will also functionally verify the phylogenetic distribution of animals that use sodefrin as a pheromone in order to polarize the evolutionary origin of the gene as well as the pheromonal function of the gene product. These studies will lay the groundwork to investigate population-level differences in sodefrin protein structure, examine protein processing and physiological responsiveness, and identify the function of sodefrin-like peptides among an array of vertebrates.

Julius Jackson and Erik Goodman (MSU) are using digital organisms to **model metabolic gene clustering in bacteria**. There are many differences and similarities in bacterial protein structure that are not easily explained by current models of molecular evolution. A notable example is the evidence for a species-specific vector of relative amino acid frequencies for the heterologous functional set of enzymes within a bacterial species. Any set of enzymes within a bacterial species has an amino acid composition that is distinct according to phylogeny, while conserving enzyme functions. Jackson and Goodman postulate that the framework of large sets of proteins within a species must have a high similarity of amino acid content that varies from species to species, while the reactive sites remain constant. The conservation of the function vector combined with species-specific variation in the amino acid composition vector requires explanation of selective pressures that give rise to such consistent differences. Furthermore, there are strong linkages exhibited among genes coding for enzymes that are involved in the same pathway, raising the question of whether these linkages might possibly result from higher effective enzyme concentrations in the immediate vicinity of the transcription and (spatially close) translation and subsequent catalytic activity of the proteins encoded by these genes. These questions are difficult to answer *in vitro*, and MSU graduate student Gowon Patterson plans to approach these or closely related questions using a novel computational platform that he will develop to test the adequacy of various hypotheses to explain these phenomena.

In addition to these studies focusing on the interactions of specific genes, Robert Heckendorn (UI) and Ian Dworkin (MSU) aim to **cross-fertilize techniques from evolutionary computation and biology to better understand epistasis**. The major goal of this project is to generate statistically sound and biologically relevant algorithms for epistatic analysis combining techniques developed in Evolutionary Computation and multivariate statistics. These algorithms will be tested on real biological data from the labs of Dworkin (MSU), Lenski (MSU), Hohenlohe (UI), and Daniel Weinreich (Brown University).

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, which 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. The group developed an in-house gene fabrication facility, which allows them to design and synthesize genes or gene fragments in a high throughput fashion, including the gene fragments which encode the 'recoded' versions of the PhiX bacteria phage genome. One of these versions was recoded from the wild-type sequence to use only the most highly utilized codons in the *E. coli* bacterial host (PhiX Hi). The second recoded PhiX bacteria phage genome (PhiX lo) was recoded to use only the least commonly used codons based on *E. coli* translational bias. The assembly of the entire 5,386bp of the PhiX genome directly from synthetic oligonucleotides proved to be fraught with many assembly and sequence errors. The team decided to divide the genome up into smaller fragments that would then be integrated into the wild-type host genome one section at a time. This approach had the added benefit of being able to potentially measure the fitness effects of codon bias skewing on a small subset of phiX genes.

Herbert Sauro (UW) and postdoc Sean Sleight (UW) are 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 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 are 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.

The specific project goal is to engineer a multi-gene circuit that expresses three fluorescent proteins independently and in combination, develop a randomization method for genetic circuits and metabolic pathways, and perform directed evolution experiments to select for robust designs. Sauro and Sleight engineered a prototype CMY genetic circuit that visually produces cyan,

magenta, and yellow colors independently and in combination using different inducer molecules. Since the production of each color can be independently controlled, this allows for the production of a spectrum of colors that can be visualized in normal light conditions, and each color can be quantified using fluorescence measurements. They performed an evolution experiment to measure the evolutionary stability dynamics of this prototype CMY genetic circuit in 88 replicate populations of *Escherichia coli*, propagated with all colors turned on. The results using particular inducer concentrations show that all 88 replicate populations change from a dark, green-brown color to a cyanish color after only 40 generations. They sequenced a single clone from four independently evolved populations and all clones have the same loss-of-function deletion mutation between homologous transcriptional terminators that removes the magenta and yellow expression cassettes. This parallel evolution was somewhat expected from results of previous work, but they expect that randomized and reengineered versions of this circuit without repeats will produce more divergent results due to more stochastic loss-of-function mutations.

Thrust Group 2: Evolution of Behavior and Intelligence.

Research in thrust group 2 focuses on the evolution of behavior of individuals, particularly in the context of social behavior, including cooperation, social coordination, and communication. 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 15 projects are funded in this thrust group, and can be grouped into two broad areas: 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.

Christoph Adami (MSU), Fred Dyer (MSU), Robert Heckendorn (UI), Benjamin Kerr (UW), Charles Ofria (MSU), Robert T. Pennock (MSU), and Peter Stone (UT) are studying the **evolution of cognition, communication, and social coordination** in both biological and artificial systems. The goal is to study the evolution of the ability of independently moving agents to coordinate their movement in a swarm and for knowledgeable members of the swarm to convey information through their behavior that will enable other members to orient toward a distant, unseen goal. Progress has been made in three ways. First, in the biological model system (honey bee swarms and waggle dances) they have piloted video and computational methods for the analysis of swarm coordination, and for the analysis of the behavior of dancers and followers in the context of the dance language. Second, they have made progress in extending the Avida

platform to study the collective movement of swarms of avidians toward a common goal. Third, using the Markov Network Brain platform, they have implemented a system for studying the evolution of swarming under selection from predatory agents that are themselves evolving. This project has already yielded the exciting result that the phenomenon of "predator confusion," whereby the efficiency of a predator is impaired when multiple prey are within striking distance, is sufficient to drive the evolution of swarming. This result validates the usefulness of this platform for studying evolution of swarm behavior, and also provides the foundation for further investigations of swarm guidance.

Kay Holekamp (MSU), Benjamin Kerr (UW), and Risto Miikkulainen (UT) are working 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. In prior work they showed that hunting behavior similar to that of hyenas does not require direct communication; interaction based on stigmergic coordination (cooperation without direct communication) is sufficient and often more efficient than those based on direct communication. Indeed, much of hyenas' hunting behaviors tend to be driven by movements of the prey rather than direct communication between the hyenas. On the other hand, they also found that if agents can communicate their locations, their behaviors become more flexible. Building on this foundation, in the past year they focused on understanding how an actual communication system—i.e., a set of signals common to the species—would emerge (instead of simple communication of the location). The results show that the need for flexibility was still the driver, but interestingly, reciprocity was also necessary: the agents needed to experience both sides of the communication, in order to develop a system that was common to all individuals. Social hierarchies are very strong in hyenas: even if lower-ranked individuals may have done most of the work in obtaining the kill, higher-ranked hyenas get to eat first. It is surprising that such a seemingly unfair system would survive in evolution. The team's hypothesis is that it does because the alternative – frequent fights between individuals – would have such a high cost. In preliminary simulations (in an artificial benchmark task) it turned out that indeed effective evolution and cost of fitness evaluations could be traded off.

Philip McKinley and Chris Waters (both MSU) are using **biocomputational techniques to study the evolution of cooperation in bacteria**. Despite the ubiquity of cooperation in the natural world, its evolutionary origins are difficult to understand, since non-cooperators (cheaters) are predicted to benefit from the cooperative behavior without paying the associated costs. Hamilton showed that under inclusive fitness theory, cooperation can be favored when the associated costs are less than the benefits provided to carriers of the cooperative allele, multiplied by the relatedness of the participants, or more succinctly, $C < rB$. However, quantifying these costs and benefits, which manifest themselves as changes in the frequencies of the cooperative allele, often poses a formidable challenge. The primarily goal of this study was to increase our understanding of the evolution of complex collective behaviors, such as biofilm formation and quorum sensing, and in particular, the effect of resource availability. The project coupled *in silico* evolution experiments using self-replicating digital organisms with *in vitro*

studies of specific bacteria (primarily *Vibrio cholerae* and *Vibrio harveyi*). Combining these two distinct but related approaches led to important findings not possible with either method alone.

In bacteria, **biofilms** are multi-cellular communities encased in a protective extracellular matrix. Biofilms are an important element of natural food chains, but their shielding properties make them a serious problem in human health, agriculture, and the operation of mechanical systems. The team examined the evolution of biofilm formation both in Avida digital organisms and *V. cholerae*. Avidian biofilms are formed when organisms produce a shared common good, designated by execution of a particular logic task, that protects them from a random "kill" event. They evolved virtual biofilms in Avida and observed that an increase in resource availability produced a higher level of cooperation. Surprisingly, the experiments revealed that the transition from non-cooperation to biofilm formation was sharp, when the resource level reached a critical threshold. The team next tested this novel finding in the Waters Lab using *V. cholerae*. Replicate populations of *Vibrio cholerae* were grown and evolved in different concentrations of lysogeny broth. Populations were able to persist in these environments by producing EPS and forming biofilms, which allowed cells to adhere to a surface that was passaged daily into fresh media. These experiments revealed that populations evolved in resource-rich environments formed significantly more robust biofilms than those in resource-poor environments. Moreover, as in the Avida population, the increase in cooperation did not occur gradually, but rather as a rapid transition to cooperation above a critical level of resource. 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.

Quorum sensing is a collective signaling behavior whereby actions of individuals depend on the density of the surrounding population. To realize QS, bacteria continually secrete and detect molecules called autoinducers (AIs), eventually reaching a threshold that triggers a change in individual gene expression, producing a distributed, coordinated behavioral change. QS is proposed to be a mechanism for coordination of many cooperative behaviors, including biofilm formation, yet the evolution of this behavior is not well understood. Here again the investigation included both digital and in vitro experiments. The team extended an earlier study of the evolution of QS in Avida, where they evolved QS and then attempted to disrupt QS through the introduction of signal-blind or signal-negative mutant organisms. Surprisingly, they observed the evolution resistance to these "quorum quenching" measures, a result of import to research on anti-infective treatments. The group then examined the evolution and maintenance of quorum sensing (QS) in the bioluminescent bacterium *Vibrio harveyi*. A continuous culture experiment revealed that QS defectors slowly evolved in rich LM media, whereas defectors accumulated at a more rapid rate in nutrient poor media. They hypothesize that this difference is due to the relative cost of cooperation in these two conditions, and we are further testing this hypothesis using different growth environments. They also determined that continuous culture of a *V. harveyi* QS deficient strain evolves to constitutively communicate. This result suggests that communication and cooperation must be favored in these conditions. They have initiated genome sequencing to identify the causative mutations of this phenotype. They have also identified a novel environment that requires communication for growth and determined that QS defectors act as cheaters in a frequency-dependent manner in this condition. They are presently searching for additional environments that show QS-dependence to tease out the relationship of QS to environmental adaption.

E. Peter Greenberg (UW), Benjamin Kerr (UW), Philip McKinley (MSU), John Mittler (UW), and Chris Waters (MSU) are addressing the question, **can communication stabilize cooperation?** This project is centered on uncovering the role of communication in the evolution of cooperation (e.g., public good production). The team is focusing on populations of bacteria that cooperate conditionally based on density, through the process termed quorum sensing. Through a set of genetic manipulations and evolution experiments, they are addressing the connections between quorum sensing and cooperation in a variety of microbial systems (*P. aeruginosa*, *E. coli*, *B. thailandensis*, and *V. harveyi*) as well as a digital system (AVIDA).

Kay Holekamp (MSU) and Risto Miikkulainen (UT) are examining **social evolution and learning in computational and biological agents**. The goal of this project is to understand how learning interacts with evolution. In particular, methods of social learning—i.e., learning from any successful individual in the population—will be developed and tested against other forms of learning, aiming to develop better algorithms for constructing intelligent agents. Observed learning behaviors in hyena societies will be used as motivation for these methods. In the preliminary work for this project, UT graduate students Eliana Feasley and Wesley Tansey developed a simulation of a foraging domain where the agents, evolved through neuroevolution, could also learn from each other. They found that such social learning resulted in more effective behaviors, and they were found faster. Also, it was important that the agents were able to choose their teachers, instead of having one (e.g. a parent or champion) designated as a teacher for all other agents. In this way, it was possible to learn from anyone who had a good idea, instead of copying both the good and the bad behaviors of the designated teachers. Third, dividing the population into subgroups helped maintain diversity, and improved evolution and learning. The focus has now shifted to understanding such social learning in animal societies, as motivation and target for further development of these methods. The focus will be on understanding what roles learning and evolution play in constructing complex behavior, and in particular, whether a fast or slow environmental change emphasizes learning and evolution differently. The emulation results may shed light on observed behaviors in nature, and may lead to improved methods for constructing complex artificial agents.

Evolving smarter electronic and robotic systems

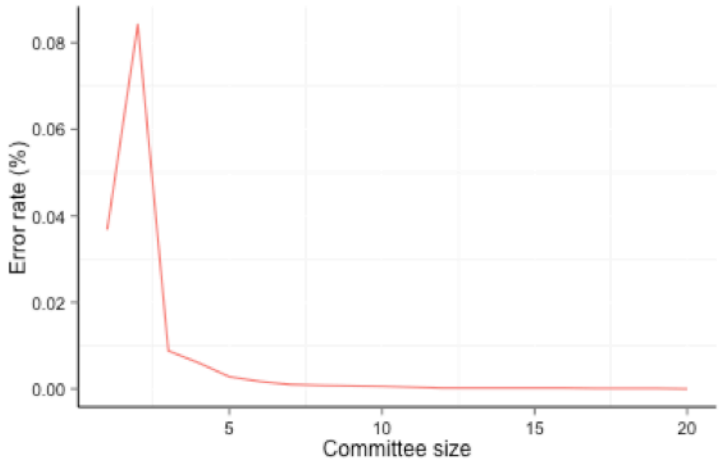
Engineering research in this area is focused on using evolutionary computational techniques to develop better applications, as diverse as handwriting recognition, home assistance robots, cancer detection systems, greenhouse controls, control of energy storage systems, and land use policies.

Chris Adami (MSU) and Risto Miikkulainen (UT), with postdoc David Knoester (MSU), postdoc Arend Hintze (MSU), and graduate student Samuel Chapman (MSU), are evolving a **256-node neural controller** to recognize human handwriting in a project they named **Darwin vs. DARPA**. The goal of this project is to use evolution as a substitute for design in creating a computational structure that is brain-like, and not based on a von Neumann computer architecture. DARPA's SyNAPSE project, now using a silicon chip design, has as one of its stated goals to perform hand-written digit recognition on their neurochip. They have achieved an accuracy of 94% image recognition in the simulation of their design, and of 89% in the hardware

implementation of it. **At this point in the project, the team has not only beaten DARPA's performance, but also the world record of machine performance, as well as outperformed the best human performance on this task.** The first part of this project is focused on evolving a Markov brain that recognizes the numerals 0-9 from the MNIST database. There are 60,000 different images in the training set, and 10,000 images in the test set. The accuracy of the algorithm is given by the percentage of test images that are classified incorrectly. The historically best classifier is a multi-layer neural network that was trained on a massively parallel GPU cluster, but not only with the 60,000 images, but a much larger set obtained by deforming the initial images. The 6-layer network with 2500+2000+1500+1000+500+10 neurons achieved an error rate of 0.38% (misclassifying 38 out of 10,000 test images) after 115 hours of computation time (Ciresan, D. C., et al. 2010. Deep, big, simple neural nets for handwritten digit recognition. Neural computation. 22: 3207-3220). The current world record architecture misclassifies 23 images (Ciresan, D., U. Meier & J. Schmidhuber. 2012. Multi-column Deep Neural Networks for Image Classification. Presented at Computer Vision and Pattern Recognition (CVPR 2012) Providence, Rhode Island). More realistic comparisons are non-parallel approaches that do not use image deformation. The famous deep-learning result (Hinton, G. E. & R. R. Salakhutdinov. 2006. Reducing the dimensionality of data with neural networks. Science 313: 504-507.) achieved an error rate of 1.2% using a 784-500-500-2000-10 network, with pre-training of each layer. This algorithm was implemented by the SyNAPSE team, but with a 6% error rate. Adami and Miikkulainen use a very different approach than what has been seen in the literature - Markov brain networks, that is, networks of hidden Markov gates whose connectivity and function are evolved. For this task, they used deterministic logic gates, which implies that the networks evolved are classical logic circuits. Because these circuits use digital inputs, they convert the grey-scale image (encoded in 8 bits) to digital by turning all pixels with an intermediate level grey-scale or higher (127 up to 256) to on, while turning those with level less that 127 to off. While the entire 782-pixel image is provided to the networks, on average the brains only connect to a subset of them (about 100). In hindsight, these turn out to be the most informative pixels, so evolution provides for an initial data compression via selecting only those pixels that matter for classification. Of course, this implies that each individual network is unlikely to be able to perform perfect classification. The team uses a novel fitness function that maximizes the shared entropy between classes and output patterns on 16 bits. Each of the output classes is the result of aggregating an excitatory and inhibitory signal. By inverting the resulting mapping from classes to outputs (the "firing pattern" of the network), they can analyze the firing pattern of the network on the test data, and infer the image class. If several different patterns map back to the same class, they resolve the ambiguity by choosing the most common of the classes that resulted in the pattern. For the Genetic Algorithm, they use an "island model" where the population of 1,200 is subdivided into twelve populations of 100, each of them seeing (evolved on) only 5,000 of the 60,000 test images. Using a small migration rate between islands, we are able to evolve the population at a much faster rate (as opposed to showing each agent all 60,000 images), and increase the variance in the population. An Elite selection scheme assures that beneficial mutations are not lost to drift. Using these tools, the team can evolve brains that have, on average, an error rate of 5% on the test set—that is, each brain misclassifies about 500 of the 10,000 test images (our best individual brains achieve an error rate of around 3.5%). This rate is very encouraging, as each brain only connects to about 100 of the 782 pixels—that is, they are blind to a large fraction of the image. The prediction accuracy can be increased further by taking "committees" of brains for the decision making process. For example, in each of 100

independent individual runs a different brain evolved, and therefore a different classifier. Interestingly, these classifiers make mistakes about *different* things, simply because evolution creates new classifiers every time. As a consequence, a committee of classifiers is provably better than the best brain in the set, and often the worst committee is better than the best individual classifier. The graph below shows the error rate of a committee of brains, ordered by performance on the training set (ordering by achieved mutual information or fitness gives the same results). A committee of the two best brains actually leads to a worse prediction, but a committee of just the six best gives an error rate of 0.017% (17 out of 10,000 test images misclassified). This performance beats the current world record of 23 misclassified images.

The figure furthermore shows that a committee of just 12 members leads to only 2 misclassified images, and using the 20 best brains as a committee reduces the error rate further to zero. Given that humans misclassify 20 images on average, ***it is clear that evolution has now achieved an improbable world record.*** In fact, it is clear that evolution of digital logic automatically discovers all of the information in the data set, even when humans cannot achieve that feat. This capacity can be attributed to the differences in learned context for human recognition as opposed to automated recognition. The features that our evolved circuits use for classification include features that humans use, but also use additional features that are unintuitive for human image recognition. The team is now working on classifying a more ambitious set of images: the "Special Database 19" data set from NIST, comprising about 810,000 images of numerals and upper-case and lower-case letters, at 128x128 pixel resolution. Of those, 82,587 images are to be used as a test set.



Fraction of images misclassified as a function of committee size. A committee of 14 independently evolved brains reduces the error rate to 2 misclassified images.

In a project focusing on systems to help the elderly or disabled, Abdollah Homaifar and Albert Esterline (NCAT) are working on the design and implementation of an **assistive robotic residence home**. The team 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 an RFID partially augmented home. The robot has full or partial knowledge of targets and partial knowledge of target location. Thus,

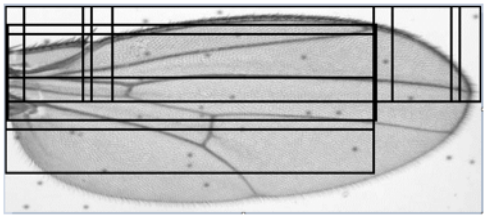
learning and decision-making are integral parts of this project. Progress to date has focused on self-localization algorithms, path-planning using graph search techniques in an environment with obstacles, and developing a hierarchical evolutionary algorithm to encourage cooperation through learning. The next steps are to further increase the quality of the localization estimate and to develop a path-planning technique that uses the improved pose knowledge to enable the robot to accurately navigate in a dynamic indoor environment. The group is also working on Simultaneous Localization and Mapping for this environment, which will enable them to include elevations in the form of handicap access hills that may be present in the home. Finally, the group is also planning to study the evolutionary dynamics of the learning algorithm further and to tackle real-world problems that require a substantial degree of cooperation.

In another robotics project, Erik Goodman (MSU), Philip McKinley (MSU), Xiaobo Tan (MSU), Zhun Fan (Tongji University, Shanghai), and Kisung Seo (Seokyeong University, Korea) are designing **controls for biped robotic systems**. The team has studied applying CPG (Central Pattern Generation) to control biped robotic systems. To achieve this goal, they followed a three-step approach. During the first step, the major goal was to study how the change of parameters can affect the performance of CPG and identify the most important parameters. Because there are a large number of parameters existing in the CPG model, a very systematic empirical study, using a genetic algorithm, was undertaken. The second step was to study how changes of CPG topology can influence the performance of CPG. Genetic programming was taken as a major tool to evolve the topology of CPG connection to the robot's joints. The third step was to study how the evolution of CPG can be used to control biped robots, in combination with other mechanisms specifically designed for the walking control of a biped robot. The team has focused on the workspace control method.

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**. Existing screening methods for breast tumors are inaccurate, uncomfortable, and expose the patient to nontrivial levels of ionizing radiation. Mammograms result in 20% false negative and 10% false positive readings, and repeated exposure to X-radiation can itself be carcinogenic. Current alternatives to mammography all have known deficiencies. This team is investigating low-power ultra-band microwave scanning of the breast. Reflection patterns of microwave signals transmitted into the breast are used to detect the presence and location of abnormal tissue. Patients are exposed to less radiation than typically received from a microwave oven, so that testing is extremely safe and causes little discomfort. Challenges remain, however, in developing reliable signal processing algorithms for effective detection and localization of tumors, and for their classification into benign and malignant types. The team is researching the use of evolutionary computation (EC) to seek out signal features that can be deployed in these detection and classification algorithms. The team is in the exploratory phase of research and has been focusing on the best way to represent the collected data, which include 16 different scan lines of the reflected back wave signal for a given patient that correspond to the 16 different antenna locations. The challenge that is currently being addressed is the best way to set up and integrate the data in such a way that underlying artificial features aren't lost and to allow some features to be detected visually. Taking advantage of all antenna positions is the key in depicting the

features in the data. The two general means of representing and integrating the data for a given patient include focusing on (1) the back wave signals and on (2) images that can be reconstructed using those signals.

Gerry Dozier (NCAT) and his students are developing a number of Genetic & Evolutionary Feature Extractors (GEFEs) and Genetic & Evolutionary Feature Selection (GEFeS) methods in a field called **Genetic & Evolutionary Biometrics**. Currently, we are seeing an increase in the use of biometrics as a form of access control. Although biometric-based access control is a welcome alternative to username/password access control, they are vulnerable to their own unique types of attacks in the form of biometric replay attacks and reconstruction attacks. In biometric-based access control system, users must first enroll themselves. The process of enrollment works as follows. Initially, a sample (in the form of facial, finger print, iris images) of each subject is taken (in this research we will be working with facial images). Next a feature extraction method is applied to each sample to create a template for each user. These templates are then stored in an enrollment database. In the future, when a previously enrolled subject would like to gain access to a particular system, a sample is taken of the user, feature extraction is used to extract template associated with the user and this newly acquired template is checked with the previously enrolled templates in the enrollment database. If the newly acquired template is within a pre-specified distance from any of the templates in the enrollment database then the user is allowed access (typically, the newly acquired template will only match with the previously enrolled template associated with user requesting access). A replay attack occurs when a user's newly acquired template is intercepted (typically while being transmitted over a network) as the user is attempting to gain access to a particular system. The intercepted template can be 'replayed' by the interceptor to gain unauthorized access to the system. A reconstruction attack can be even more devastating and occurs when the enrollment database is hacked. The enrolled templates can be used to reconstruct the facial images of enrolled users thus exposing their identity. In this project, a number of genetic and evolutionary based solutions are being developed to mitigate biometrics replay attacks by evolving disposable feature extractors and templates. The development of artificial immunity based negative biometric recognition systems (AINBR) will be used as a means of mitigating biometric reconstruction attacks. In the case of an AINBR system, if the set of detectors comprising the AIS is compromised, it will be extremely difficult for them to determine the identity of the individuals that are allowed access to a particular system.



Fly wing with feature extractors evolved by GEFE. Each rectangle represents a patch from which salient features are extracted.

In a multidisciplinary spinoff of the facial recognition work, Gerry Dozier (NCAT) has teamed with Ian Dworkin (MSU) to develop **fly wing biometrics**. Variation in size and shape in the *Drosophila* wing is a powerful model system in developmental and quantitative genetic analysis. In addition, they are easy structures to image and the Dworkin lab regularly collects tens of thousands of images for work in dissecting the genetic architecture of wing shape. Yet the process of feature selection and extraction remains extremely laborious, thus ultimately providing a bottleneck on data analysis and acquisition, slowing the scientific process. In

particular, feature selection is limited by the biological knowledge and assumptions of the scientists studying this system, with a relatively limited set of features (currently using ~ 96 features, representing a 58-dimensional space). Thus, there is a critical need to both develop tools to provide a more comprehensive set of features from the images directly, and to extract them in a higher throughput manner. The goal for this proposal is aimed at comparing classification methods based on features determined and extracted by the biologists using standard statistical tools (i.e. linear and quadratic discrimination analysis) with genetic & evolutionary computation approaches such as GEFE (Genetic & Evolutionary Feature Extraction); the ultimate goal is to provide a new framework in feature selection and extraction to aid in a new approach to phenotyping, and understanding the underlying biological structure and variation for the wing. The image above provides an example of a feature extractor evolved by GEFE. Each rectangle represents a patch from which salient features are extracted.

Evolutionary engineering can lead to better control of electronic systems with industrial applications: Erik Goodman (MSU), Kalyanmoy Deb (MSU), and visiting scientists Lihong Xu and Chenwen Zhu (Tongji University, Shanghai, visiting BEACON) are developing **robust multi-objective evolutionary optimization to allow greenhouse production/energy use tradeoffs, enabling more energy-efficient production**. Modern greenhouses, especially those in large-scale agricultural projects, require automated control to perform effectively. Not only they are required to maintain an environment that encourage crops to thrive, but do so in a manner that uses resources, such as energy, efficiently. These two objectives, productivity and resource efficiency, will usually be in conflict. The goal of this project is to find a control strategy (or multiple strategies) to satisfy users' requirements in both objectives. To ensure identification a range of good solutions without favoring one objective over another, the team uses Pareto optimization, producing a set of good solutions without biasing one objective over another. Evolutionary Computing (EC) techniques, such as NSGA 2 and and the team's MOCC (Multi-Objective Compatible Control), in particular, are utilized to generate and improve solutions into acceptable performance.

Similarly, Gary Lebby (NCAT) and his graduate students are working on **biologically inspired control of electric energy storage systems**. Within the energy systems community there is a heightened interest in using alternative energy sources as a secondary and in some cases a primary power generation source for a stand-alone energy system. The power generated from these sources is dynamic in nature and can be highly dependent on the surrounding environment; therefore the energy system requires some type of energy storage element to adjust to the dynamics presented by the generation sources. Proper control of the embedded energy storage elements is a key factor for maintaining system reliability and sustaining optimal performance. This project aims to develop a biologically inspired control mechanism for charging and discharging energy storage units within stand-alone energy systems; maintaining optimal performance by minimizing energy losses and reducing unnecessary switching between working states for the energy storage unit, extending their lifetime.

Evolutionary computation can also be a valuable framework for development of land-use policies. Kalyanmoy Deb (MSU) and Erik Goodman (MSU) are working on **robust**

evolutionary multi-objective optimization of practical rural land-use strategies, taking into account environmental impacts. Dr. Oliver Chikumbo, of Scion, a Crown Research Corporation in Rotorua, NZ, visited BEACON under a grant from his government for the month of August, 2011. Since then, he has collaborated regularly via videoconference and email with Goodman and Deb. The team made a breakthrough during his visit that allows, for the first time, an effective multi-objective optimization of land use solutions over a 50-year planning horizon for an area in Rotorua, NZ that drains into Lake Rotorua, which is rapidly being eutrophied. The problem is represented with fourteen objectives, including environmental effects to be minimized and production and profitability objectives to be maximized. The team has obtained funding from sources in New Zealand to support two graduate research students there, and BEACON funding to support an additional graduate student at MSU, yet to be recruited. In the meantime, Deb and Goodman have visited NSF to explore programs to which this research might look for support of the US activities, resulting in a proposal recently submitted to NSF. Ultimately, the project will use evolutionary computation and multi-criterion decision-making methods (being developed) to allow multiple stakeholders, including the indigenous Maori people of the region, to view tradeoffs in the multi-objective landscape so as to arrive at mutually acceptable trade-off solutions.

Ronald Averill, Kalyanmoy Deb, and Erik Goodman (all MSU) are working on methods of **spatial/structural optimization.** Optimization algorithms typically operate in a design space of a fixed size, implying that each design takes a fixed number of parameters. However, many engineering design problems involve a variable number of parameters, such as a variable number of components. Some examples are composite laminate design, sensor placement design, and some packing problems. Such problems will be referred to as variable-size problems. One approach to solving such problems is to fix the number of components in the solution and using standard optimization algorithms. However, it is likely that the optimal number of components is unknown, requiring the problem to be solved multiple times until the optimal number of components is determined. If the range of possible numbers of components is large, this is impractical. An alternative is to use an algorithm that doesn't fix the number of components in a solution, instead allowing different solutions to use different numbers of components. The application of most optimization methods, including gradient-based approaches, is difficult for such a problem. This project investigates the use of genetic algorithms, and possibly other evolutionary algorithms, in solving variable-size problems. The population will contain solutions using a range of numbers of components, and individual solutions may vary their own numbers of components. The variable-size nature of the solutions is the primary challenge in applying the genetic algorithm. This is particularly true for the recombination operator, which produces child solutions from two parent solutions. The question of the possibility of meaningfully recombining parents of differing sizes was one of the motivating factors for beginning this project. The primary goal of this project is to explore variable-size genetic algorithms in a general sense such that they can be more readily applied to practical engineering design problems, but grounding the work in a few real-world applications, to assure its ultimate applicability.

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. Nine funded projects currently fall into this thrust group.

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 are using 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 do not supply metabolites. CoSMO (Cooperation that is Synthetic and Mutually Obligatory) consisted of two complementary yeast strains: a green-fluorescent G strain requiring adenine and supplying lysine, and a red-fluorescent R strain requiring lysine and supplying adenine. The team is subjecting the coculture under either individual-level selection by propagating all cocultures regardless of how well they grow, or under group-level selection by propagating the fastest-growing cocultures.

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. Phenotypic analysis was performed with head-to-head competitions between evolved and ancestral strains. The resistant strain evolved during the experiment, and, in agreement with cellular automata predictions, the resistant strains from structured worlds were the most restrained in their competitive ability (slowest growth rate). To examine the genetic

basis of the evolved phenotypes, the team has performed whole genome resequencing with Illumina technology on isolates from the replicated populations and has identified a set of mutations that may alleviate the cost of toxin resistance. They are now confirming the discovered *de novo* mutations with Sanger sequencing.

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.

Postdoc Kevin Theis (MSU), along with Kay Holekamp (MSU), Benjamin Kerr (UW), Charles Ofria (MSU), and Thomas Schmidt (MSU), is investigating **scent-marking mammals, their microbial symbionts, and the hologenome theory of evolution**. No animal has evolved independently of symbiotic microbes. Instead, each has coevolved with suites of microbes whose genomes have profoundly affected its biology. As a paradigm-shifting consequence, animals are beginning to be viewed as metaorganisms, or holobionts—consortia of hosts and all their symbiotic microbes and viruses—rather than isolated entities. The hologenome theory of evolution—heralded as the new frontier of animal biology—holds that 1) interactions between hosts and microbionts affect the fitness of the holobiont, 2) genetic variation among holobionts can be enhanced by the incorporation of new microbionts, and 3) microbionts can be transmitted across generations of animal hosts with fidelity. The objective of this project is to begin testing predictions of the Hologenome Concept of Evolution by 1) capitalizing on natural variation in microbiotic community structure in the specialized scent glands of African mammals, and 2) by creating and studying replicate artificial holobiont populations within controlled environments using Avida.

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**. Increasingly, ecologists are finding that "rapid" evolutionary change can have important consequences for population, community, and ecosystem dynamics. Strong evidence for these ecoevolutionary interactions has been generated in model systems involving bacteria and viruses (phage). Microorganisms are ideal for studying evolution in action because they have rapid growth rates, achieve high population densities, and are amenable to genetic manipulation. In addition, the ecology and evolution of microbes are important because these taxa play a critical role in the functioning and stability of natural and managed ecosystems. Microbial interactions, specifically those between hosts and their phage, are strongly influenced by resource availability, especially nitrogen (N) and phosphorus (P). Although the differential effects of N and P limitation (i.e., stoichiometry) have been examined in an ecological context, few studies have explored the potential for resource-driven contemporary evolution to have feedbacks on the dynamics of microbial communities. The team is using a combination of Adaptive Dynamics modeling and genomic sequencing to understand the eco-evolutionary dynamics of a marine cyanobacterium (*Synechococcus*) and its phage under N vs. P limitation. Results from this study will increase understanding of the mechanisms of bacterial and virus evolution and its consequences for marine ecosystem functioning.

In an extremely multidisciplinary collaboration, Gerry Dozier (NCAT), Ian Dworkin (MSU), Benjamin Kerr (UW), Richard Lenski (MSU), and Charles Ofria (MSU) 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." The primary goal of this project is to initiate a multi-disciplinary program on the study of the evolution of interacting systems, with a primary aim of estimating the fitness landscapes of such systems, and how they are influenced by evolution. Lenski and graduate student Justin Meyer have studied the coevolution of *E. coli* and Lambda phage that infect them. Their work explores how parasites can evolve to exploit hosts in new ways. To explore how social networks of hosts and their pathogens influence coevolution, members of the Kerr lab evolved metacommunities involving *E. coli* and T3 phage. The migratory connections between subpopulations in these metacommunites define the structure for the network. Currently, the NCAT team is developing the GENERTIA Red Team in an effort to discover Phishing e-mail messages that are not detected by the artificial immune system (IAS). Graduate student Michael Denieu in the Dworkin lab has demonstrated that Drosophila evolving under risk of a specific mantid predator have evolved the ability to discriminate between the predator risk and other conspecifics. Ofria and graduate student Luis Zaman are investigating 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.

In another interdisciplinary collaboration, Jenny Boughman (MSU), Philip McKinley (MSU), and Xiaobo Tan (MSU) are **understanding and synthesizing collective behavior with mixed robotic and live fish schools**. This project aims to facilitate better design and engineering of robotic fish and their schools and advance the understanding of live fish, by merging robotics, computational evolution, and fish biology. Goals of this effort include (1) providing insight into the morphology and controller design of robotic fish by drawing inspiration from biology, conducting computational evolution based on sound dynamic models, and performing robot prototyping and experimentation; (2) creating mixed robotic and live fish schools to enable novel studies of social behavior of stickleback fish, and feeding back such understanding for the synthesis of autonomous behavior in robotic fish schools. Predator inspection is chosen as a context for the latter investigation.

An important objective in this work is to develop accurate but efficient dynamic models for robotic fish that capture faithfully hydrodynamic interactions between the robot and its environment without the need for time-consuming Computational Fluid Dynamics (CFD) simulation. Such models would be critical for evolutionary design of robotic fish. The team has also derived the dynamic model for a robotic fish with a pair of flexible pectoral fins, and is in the process of implementing the simulation codes for this model. In addition, with the help of the

3D printer, they have created a prototype pectoral fin mechanism and demonstrated its operation in air. The group integrated the dynamic model for robotic fish with a flexible tail into an ODE-based simulation environment, and used it to conduct evolutionary design for both fin stiffness and shape. They further fabricated the evolved caudal fins with the 3D printer and validated the simulation results with a robotic fish prototype (designed for easy switching among different caudal fins) in one of the Evolution Park aquatic test environments. The results showed a correlation between evolved results, model predicted behavior, and physical robot performance, with some disparity due to the difficulty in precisely simulating real-world performance in a simulation environment. A report describing this work won a Best Paper Award at ALIFE 2012. Finally, the team has already fabricated a 10-inch long robotic fish modeled after a trout, which will serve as a "robotic predator" in probing the behavior of stickleback fish during predator inspection. Before full experimentation involving robotic fish and live fish, they first conducted preliminary investigations with live fish (*Gasterosteus aculeatus*) in the experimental tanks using a stationary predatory model. They have established that individual fish will interact with novel "predator-like" stimuli, showing stereotypical inspection behaviors, including approach, binocular fixation, and retreating back to shoal mates.

Metagenomics

Metagenomics, or the study of the collected genomes of all of the microbes in a shared environment, is currently the focus of one large BEACON project. Because the vast majority of these 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 goal of this project was to apply evolutionary principles to the interpretation of metagenomes – DNA sequences retrieved directly from microbial communities in nature. Metagenomes are typically used to assess the taxonomic composition and metabolic potential of microbial communities. The team, with MSU postdoc Bjørn Østman, pushed beyond these types of analysis in an effort to assess the strength of selective pressure that different environments exert on specific genes in metagenomes. Selective pressures are usually inferred from theory or measured in microbes grown in the laboratory, but little is known about microbial populations in the wild. The team took advantage of metagenomes from microbial communities in soils under different land uses at the Kellogg Biological Station Long Term Experimental Research site to test ideas. They focused on a pivotal gene in the denitrification pathway (nitrite reductase; nirK), because denitrification in soils contributes approximately 50% of the nitrous oxide currently found in Earth's atmosphere. An improved understanding of the microbial sources of this potent greenhouse gas is a first step towards predictive modeling and potentially managing the denitrifying bacteria in soil. They used a common measure of selective pressure – the ratio of synonymous to nonsynonymous mutations - and found that nirK was under increased purifying selection in agricultural soils compared to in native deciduous forest soils. Comparison of selection pressure on nirK from soils previously used for agriculture showed that release of land from agriculture resulted in

relaxed purifying selection on nirK. This first look at selection pressure in natural microbial communities demonstrates the feasibility of the approach and confirms that land management actively shapes microbial communities through selection. This application of evolutionary principles to metagenomes can be applied to comparisons among any kind of microbial communities, including human-associated microbiomes where a wealth of metagenomic data is accumulating.

Engineering applications of biological collective dynamics

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

Paul Stanfield (NCAT) and Justin Zhan (NCAT) are conducting **biologically and socially inspired computational evolution for product life cycle management**. Durable products and their components are increasingly being equipped with one of several forms of automatic identification technology (AIT) enabling data collection, storage, and transmission of information throughout their life cycles. Newer forms of AIT devices possess the capability for read/write dynamic data storage and transfer, often through wireless communication. Other emerging features include data processing capacity, integration of sensors, and self-powering using energy harvesting. Adding such technology to a product or part transforms it to have many of the capabilities one might associate with advanced biological organisms (memory, processing, communication, sensor-integration). As AIT technology improves and its application expands, it is critical to develop processes and associated optimization approaches for successful implementation. This project looks at improvements in life cycle management that might be developed based on biologically-inspired analogs of evolutionary improvement and network interaction. In essence, the part becomes a biological organism that must collect and process data throughout its lifespan and then pass that data to the next generation. The data that are stored might be thought of as a type of genome, but it is likely to adapt over the life of the part. In addition, the part's being reused might be associated with a number of different system instances. Its interaction with these systems, as well as data interactions with the enterprise system, may have some biological analogs. The ability to model such a system using evolutionary models could provide hope for developing a simple distributed approach, which could be implemented as a real-life process.

BEACON research can improve safety, emergency response, and security. Erik Goodman (MSU) and Robert Till (John Jay College, CUNY) are using evolutionary optimization to **improve emergence response planning using agent-based models to model human behavior**. Many emergencies require the rapid evacuation of an area. It is important that officials deal with such an incident efficiently to save as many lives as possible. Considerable work has been done to find optimal strategies for such situations. This is typically done using top-down conceptual models. The problem with this approach is that it generalizes human behavior and ignores important interactions that may affect the outcome. A better approach is to model from the bottom-up using an Agent-Based Model (ABM). This approach models several agents, which can interact with each other and their environment according to set rules. Agents may have

different parameters to allow for a diverse population. This captures more realistic behavior and reveals the emergent properties of the system as a whole. This ABM looks at the evacuation of a portion of a city in response to a chemical spill from the south with a wind from the south. The agents in this case are drivers with randomly determined destinations, following normal traffic behavior. Officials can speed the evacuation by changing the light timing shortly after a chemical spill has occurred, to one of several patterns optimized ahead of time for various emergencies in various locations. When the emergency occurs, alarms are sounded (signs, radio broadcast, etc.) and some cars will comply with the evacuation directions while others will not hear or will ignore the warning in order to drive to their existing destinations. The output of the ABM is used as the objective function of a genetic algorithm that optimizes the emergency stoplight timings in order to find an optimal solution, minimizing loss of life and serious injury, long before the emergency occurs. This solution can be invoked to operate in real time as soon as a hazardous condition requiring evacuation is localized.

2b. Progress towards metrics listed above.

Integrative Research Goals

1. New research collaborations and proposals

- Of the 46 projects currently underway, 16 are new projects and include new collaborations.
- 162 publications submitted.
- Many projects include funding for students/postdocs/faculty to travel between partner institutions. Videoconferencing equipment at each institution has been improved.
- The competitive internal funding process resulted in a significant increase in inter-institutional and interdisciplinary collaboration. For more details, see VII. Management.
- We do not yet have a formal method to track service by members on doctoral research committees across disciplines and institutions. However, a recent email survey revealed at least 18 BEACON faculty members serving on at least 65 such committees. This number is almost certainly an underestimate, and in the future we will develop a better way to track this metric.

2. New paradigms for research in organic and digital domains

- Number of new sessions at scientific meetings or scientific meetings hosted at BEACON: In the summer of 2012, BEACON hosted the 13th Conference on Artificial Life (ALife13) at BEACON headquarters. About 300 people attended, including many BEACONites. See V. External Partnerships for more details. Additionally, in the past year BEACONites have had a very visible presence at several international scientific meetings. BEACON had a booth at 4 conferences. Evolution 2012 featured at least 34 BEACON talks, and BEACON was one of the "Daily Conference Hosts" of that meeting. BEACONites gave keynote addresses at 3 engineering/CS conferences, which will increase the community's interest in evolutionary methods: IEEE CEC (Miikkulainen), GECCO (Adami), and ALife13 (Kerr).
- Number of new journals and societies: None to report yet.

- New or increased funding for biocomputational research: so far in this reporting period, BEACON researchers have submitted at least 52 proposals for over $35M of external funding, and ~$10M in external funding has been granted.

3. Increase in publications related to evolution in action

- Number of publications: 162 publications submitted by BEACONites in 2012
- Number of citations of work: It is still too early to track citations of articles that have just appeared in the last year, but we have generated a preliminary citation report on Web of Science using the search terms "Grant number 'DBI 0939454' OR Funding Agency 'BEACON Center for the Study of Evolution in Action'." Unfortunately, Web of Science does not index many of the publications in which BEACONites publish their work, and this search results in a severe undercount of BEACON publications (only 45). A Google Scholar search for "DBI 0939454" OR "BEACON Center for the Study of Evolution in Action" returns 148 publications; unfortunately, Google Scholar does not yet provide an automated citation report service similar to that on Web of Science. We plan to hire an undergraduate or graduate student with programming experience to write a script that will automatically search Google Scholar and compile the number of citations for each publication; with this program we will be able to automatically update the information every year.
- High visibility science journalism about BEACON research: In 2012, we put out 15 press releases. At least 60 features on BEACON research appeared in the mainstream and online media in the last reporting period (nearly triple the number in the previous period), including *The New York Times*, *The Washington Post*, *USA Today*, ABC News, MSNBC, and the Huffington Post.

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

- ~4,700 downloads of Avida-ED
- ~4,400 downloads of Avida
- over 2,500 visits to BEACON website monthly, where all resources are linked
- BEACON applied for and received a $200,000 supplement to support development of training materials and curriculum and running of workshops to train biologists (faculty, postdocs and students) OUTSIDE BEACON in development and use of computational tools in support of their research (C. Titus Brown leads this effort).

Ethical Research Goals

1. Responsible Conduct of Research (RCR) training

- We have exceeded our goals for compliance with RCR training - as of August 2011, over 80% of trainees had completed the required training. We anticipate that our goal of 100% will be reached by December 2012.
- No ethics violations to report.

2. Scientific norms/virtues, respect across disciplines

- Robert Pennock has renewed plans for a Scientific Values workshop in collaboration with Toolbox team leader Michael O'Rourke, who has recently moved to MSU.
- The very multi-disciplinary weekly Friday meetings have been going on continuously since October 29, 2010, and we consider them a success.

3. Respect for views horizontally and vertically

- The Toolbox project was temporarily on hold during the past year due to expiration of its earlier NSF grant. However, its PI, Michael O'Rourke, is now a faculty member at MSU, and new plans are firmly in place for the next reporting period.

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

- The Toolbox project was temporarily on hold during the past year due to expiration of its earlier NSF grant. However, its PI, Michael O'Rourke, is now a faculty member at MSU, and new plans are firmly in place for the next reporting period.

Research Output Goals

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

- Number of publications: 162 reported to BEACON (goal was 150)
- Conference presentations: 106 reported, plus another 37 other types of presentations (goal was 150 – likely underreported)
- Grant proposals submitted: 52 submitted (goal was 40)

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

- Second External Advisory Committee meeting held October 2012
- 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 2013. We will hold our project selection process for Year 4 (see explanation in VII. Management) in January 2013 in order to choose projects that will be conducted August 2013-August 2014. 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.

Recent science education reform recognizes that students learn better when information is organized around major unifying concepts (National Research Council, 2012), and all recent science education reform places evolution as a core idea within the biological sciences (Brewer and Smith, 2011; College Board, 2011). Yet, evolution is summarily rejected by nearly half of the general public living in the United States (Miller et al. 2005). Across all BEACON, our educational projects aim to use BEACON research demonstrating evolution in action to reveal the power of evolution, showing (1) evolution is a historical ***AND*** ongoing dynamic process; (2) evolutionary biology is a good example of how science works; (3) evolutionary processes can help us solve complex biological and engineering problems.

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	Multidisciplinary classes being taught across consortium. Mentoring programs established. BEACON postdoctoral fellowship established and first postdoc appointed.
Increased public literacy in evolution and the nature of science	Development of educational materials	Testing of educational materials across audiences has started. Evaluation instruments have been developed.
	Frequency of public use of	Cross-institutional

	online materials or visits to exhibits	dissemination of materials is underway.
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	Diversity surveys are being administered across education projects where appropriate. Data are presented in diversity section.
	Feedback from the External Advisory Committee	Positive feedback. See Appendix C

1c. Problems encountered in making progress towards goals

Internal education activities: We continue to discuss the effectiveness of our graduate training courses offered across institutions given various challenges such as different academic calendars (for example UW is on a quarter system whereas MSU is on a semester system) and lower enrollment now that existing graduate students have taken courses. We have discussed various solutions—some entail larger portions of courses being available online and the possibility of intensive workshop-type training.

Evaluative research of education projects: Our initial evaluation of undergraduate understanding of evolution in action, as compared to that of our experts, indicates that students' understanding of evolutionary processes and mechanisms is complex and that many people hold correct concepts about evolutionary biology while simultaneously holding misconceptions. These results match similar research (Andrews et al. 2012). Hence students may acquire new misconceptions as they learn and master more advanced concepts. We are also aware that in some cases, learning tools and instruments that target one misconception may create or facilitate new misconceptions. Hence, any survey to ascertain learning gains must be sensitive to these issues and may require very fine-grain evaluation. Currently, evaluation of education projects is being led by Dr. Julie Libarkin at the Center for Integrated Studies in General Science and the Geo-Cognition Lab and Dr. Claudia Vergara at the Center for Engineering Education Research (CEER). We are also working towards collaborations with CREATE for STEM at Michigan State University and established evaluators across our consortium according to education project.

2a. Internal Education Activities

BEACON has instituted a series of courses specifically designed to train graduate students across disciplines. Courses include Computational Science for Evolutionary Biologists (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. Some BEACON students already have an appropriate background in both biology and computation, and some of them choose to enroll only in the spring "combined" course. We initiated an evaluation of the course sequence, relative to our training objectives. Results of the evaluation appear at the end of the course descriptions below.

Activity Name	Interdisciplinary Graduate Education
Led by	Titus Brown, Alexander Shingleton, Charles Ofria, and Ian Dworkin
Intended Audience	Beginning graduate students
Approximate # of attendees	~30 per year

Computational Science for Evolutionary Biologists: In 2012, we have recruited 9 students at MSU, 1 at UT, and 4 at UI. We are developing course materials and exploring distance-learning approaches in order to supplement the background that beginning BEACON graduate students bring to their research. In response to the 2011 observations, we are shifting many of the lectures to online screencasts, in a typical "inverted classroom" approach. The goal is to make use of our necessarily limited in-class teleconference time for discussion and broad lectures, while moving the technical content into a setting where it can be played back at leisure. Initial feedback has been positive. Dr. Brown continues to make modifications to the course based on feedback from the previous year, more specifically continuing to work out how best to facilitate coordinated learning across the BEACON campuses. Next year we propose to run the class on an accelerated schedule that matches the UW schedule, so that we can make it easier for graduate students and undergraduates at UW to take the class. We are also working on making the class available as independent study at UT to facilitate graduate student attendance there.

Evolutionary Biology for Non-Life Scientists: ZOL 890-002 is being taught during the Fall 2012 semester at Michigan State University. Nine students from Michigan State University are currently enrolled, and one person is auditing the course. 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. Students generally report that instructor exceeds all evaluation criteria.

Multidisciplinary Approaches to the Study of Evolution: In Spring 2012, 19 students enrolled in the course. The 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. Final projects during Spring 2012 included "The Evolution of Cooperative Social Networks in Avida"; "Effect of Migration Topology on Pathogen Virulence"; and "Evaluating Connectedness of a Neural Network in a Quadruped."

BEACON External Evaluation

September 28, 2012

Findings from Evaluation Activities: Educational Component
Evaluation Period: September 2011 – April 2012
Evaluator: Dr. Claudia Elena Vergara Academic Research Specialist Center for Engineering Education Research (CEER)
E-mail: vergara@msu.edu Telephone: (517) 355-4916

Executive Summary

This document presents a summary of findings based on evaluation activities and data gathered during the 2011 -2012 academic year for the educational component of the BEACON project. The courses covered by this evaluation include:

- Computation for Evolutionary Biologists
- Evolutionary Biology for Non-life Scientists
- Multidisciplinary Approaches to the Study of Evolution

As part of the external evaluation for BEACON: Educational Component, CEER surveyed all students enrolled in the courses listed in Table 1.

Table 1: BEACON Courses Evaluated (2011-2012) and Data Collection Summary

	Fall 2011		Spring 2012
	Evolutionary Bio for Non-Life Scientists	Computation for Evolutionary Biologists	Multidisciplinary Approaches to the Study of Evolution
Students Enrolled	9	22	19
Data Collected. When. (Response Rate)	*Start survey*. Start Fall 2011 (87%)		*End survey*. End Spring 2012 (63%)
	Mid-survey. End Fall 2011 (68%)		

From the participants who responded to both the start and the mid surveys, 76% are enrolled in Computation for Evolutionary Biologists and 24% are enrolled in Evolutionary Biology for Non-Life Scientists. For the end survey 17% of the respondents indicated that they took Computation for Evolutionary Biologists and 8% Evolutionary Biology for Non-Life Scientists.

Participants' Expectations

- The start-survey data indicates that participants chose programming as the most prevalent category (67%) followed by learning computational methods/techniques and skills (52%).
- Eighty seven percent of participants enrolled in the CS for evolutionary Biologists expect gains in programing, 69% in computational methods/techniques including data analyses and 0% in better communication.
- Eighty percent of participants enrolled in the course for non-life science majors expect gains in their ability to communicate better with biologists.
- Comparisons between the start and the mid survey responses indicate that experiences related to the use of Python, collaboration tools and Avida exceeded participants' expectations (Figure 4 detailed report).

- Only 8 participants responded to both the start survey and the end survey. Participants indicate satisfaction with learning about Avida and how to use it to design experiments. They also mentioned gaining practical skills about interacting with people from other institutions and collaborators from different disciplinary backgrounds. Gains in their abilities with statistical analyses were also mentioned.

Opinions about Course Components. The components of the course that allowed participants to best appreciate the connection and application of computational concepts/skills to evolutionary biology in the mid- survey include (Figure 5 detailed report):

- Discussions and readings (39%)
- Avida (39%)
- Programming (22%)
- Homework (17%)
- Application of CS concepts to evolutionary Biology (17%)

The components of the course that allowed participants to best appreciate the connection and application of computational concepts/skills to evolutionary biology in the end-survey include (Figure 6 detailed report):

- Avida (60%)
- Group Project (40%)
- Information Theory (30%)

The components of the course that allowed participants to best appreciate the connection and application of evolutionary biology concepts to other disciplines in the mid- survey include (Figure 7 detailed report):

- Class exercises, discussions and readings (53%)
- Study of concepts in evolution (24%)
- Avida (6%)
- Not part of the course (12%)

The components of the course that allowed participants to best appreciate the connection and application of evolutionary biology concepts to other disciplines in the end- survey include (Figure 8 detailed report):

- Group projects (30%)
- Discussions and readings (20%)
- Genetic algorithms workshop (20%)
- Avida (10%)
- Not part of the course (10%)
- Information Theory (10%)

Participant responses related to **carrying out a scientific study** were no different at the end (spring 2012) and the occurrence of the different categories defined based on the general steps of the scientific method remained the same (Figure 9 detailed report):

- Testing/experimentation (84%)
- Hypothesis (72%)
- Define problem (48%)
- Revise and retest (40%)
- Publish/disseminate (36%)
- Reject or retain hypothesis (32%)
- Observation (32%)

Comparisons of start, mid and end surveys responses revealed no statistically significant differences between start and end responses related to participants' **confidence and ability to interact and communicate with peers in other disciplines**. Also no differences were observed related to their **interest in learning about and grasping concepts in the alternate discipline**--CS in the case of the Evolutionary Biologists and vice versa. Only participants who completed the three surveys were included in these analyses (N=6) (Figure 10 detailed report). Comparisons of start, mid and end surveys responses revealed no differences between start and end responses related to participants' level of agreement with statements related to:

- Pursuing multidisciplinary approaches that include evolutionary biology, CS and/ or engineering to complete their degrees and/or their research.
- Awareness and appreciation about likely disciplinary advances resulting from the application of multidisciplinary approaches that include evolutionary biology, CS and/ or engineering. Only participants who responded to the three surveys are included in the analyses (N=6) (Figure 11 detailed report), which makes finding of statistically significant differences difficult.

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.

Activity Name	**Undergraduate Education in Computational Evolutionary Biology**
Led by	Claus Wilke and Art Covert (UT)
Intended Audience	Undergraduates
Approximate # of attendees	16

Undergraduate Education in Computational Biology: Drs. Claus Wilke and Art Covert continue to receive 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 spring 2012, Dr. Covert taught the FRI (Freshman Research Initiative) course to 16 UT undergraduates. He used the inverted classroom model, where students view videos and read papers outside of the classroom, and use the classroom time to review materials and do exercises/discussions. The video lectures were on python, all made in house by Dr. Covert. All readings were peer-reviewed publications. Labs were inquiry based; each lab required students to (i) form a hypothesis from courses readings and discussions; (ii) test hypothesis with computational experiments; (iii) analyze results with tools and skills from video lectures; (iv) write results in scientific paper format (intro, methods, results, discussion). In the fall 2012, Covert is teaching the follow-up FRI course to 8 UT undergraduates, with the help of 1 undergraduate mentor (only the more successful students from the spring course tend to continue in the fall). Each student pursues a different research project independently, under guidance of Art and stream mentor Jared, a graduate of the 2011 stream. Emily McTavish of the Hillis lab is supervising one student. There are 5 Avida-based projects and 4 non-Avida projects.

The undergraduate research from the FRI has led to two publications, both presented at the Alife 13 conference:

1. A. W. Covert III, J. Carlson-Stevermer, D. Z. Derryberry, and C. O. Wilke (2012). The role of deleterious mutations in the adaptation to a novel envrionment. In Proceedings of the Thirteenth International Conference on the Simulation and Synthesis of Living Systems, C. Adami, D. M. Bryson, C. Ofria and R. T. Pennock, eds., pp. 27-31. MIT Press. doi:10.7551/978-0-262-31050-5-ch004

2. A. W. Covert III, L. Smith, D. Z. Derryberry, and C. O. Wilke (2012). What does sex have to do with it: tracking the fate of deleterious mutations in sexual populations. In Proceedings of the Thirteenth International Conference on the Simulation and Synthesis of Living Systems, C. Adami, D. M. Bryson, C. Ofria and R. T. Pennock, eds., pp. 32-36. MIT Press. doi:10.7551/978-0-262-31050-5-ch005.

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 2012 BEACON Summer REU program at KBS was to give students an opportunity to conduct research on contemporary topics in evolution, with an emphasis on rapid evolution in natural systems, providing undergraduates with the opportunity to pursue cross-disciplinary research at Kellogg Biological Station (KBS) and Friday Harbor Laboratories (FHL). Both sites have strong summer undergraduate research programs involving BEACON faculty and used this as a basis to recruit students to the BEACON programs. Both sites recruited undergraduates to REUs who were given the opportunity to conduct independent research under the mentorship of BEACON faculty or research associates. At KBS, an Undergraduate Research Apprentice (URA) program was offered to provide early career students who were under-prepared for independent research an appropriate research experience. At both KBS and FHL the BEACON REU programs are imbedded in station-wide undergraduate research programs and both attracted exceptional students who were able to conduct, complete and present results from their independent research. Coinciding with this goal, students learned common approaches and methodology to study questions with modern genetic and genomic tools. A few projects were mature enough to result in potentially publishable papers. One goal of this program is to recruit and provide research experiences for students from under-represented groups. While Kellogg Biological Station did not attract large percentages of applicants from under-represented groups, Friday Harbor was more successful in recruiting students from under-represented groups to their REU program in part because they have a larger and more diverse applicant pool. Continued evaluation of these programs is focusing on two issues: how to recruit a diverse and qualified applicant pool and how to provide truly inter-disciplinary research experiences for undergraduates. BEACON had a strong presence at the annual conference of the Society for the Advancement of Chicano and Native Americans in Science, and identified 15 students interested in our REU programs. These students will be actively encouraged to apply to both the KBS and FHL programs. [Note: in addition to the 25 students in the BEACON REU programs at KBS and FHL, 42 additional undergraduate students were involved in summer research experiences under the guidance of BEACON faculty members, funded from a variety of non-BEACON sources. More details are available in section VI. Diversity.]

Activity Name	Reforming a Large Undergraduate Nonmajors Biology Course (Part 1 of Infusing Evolution Through an Entire College Biology Curriclum)
Led by	Randall Hayes (NC A&T)
Intended Audience	Undergraduates
Approximate # of attendees	100s

Reforming Undergraduate Biology: The primary goal of this project is to train adjuncts and graduate teaching assistants to use the latest active learning techniques as we research more

effective ways to teach evolution, particularly to skeptical audiences. The team is beginning by collecting journal responses through an automated writing tutor, simultaneously collecting data on students' mental models of evolution and improving their writing skills (a vital secondary goal is improving our master's students' chances of entering a Ph.D. program). They have recruited 15 TAs (graduate students) and one adjunct. They have met 5 times so far to be trained in active pedagogy (asking questions rather than lecturing) and the ORID model of leading a discussion, which focuses discussion around 4 stages: Observation, Reaction, Interpretation, and Decision. Both of those trainings were led by MacFrank. They have written essay questions to be used for a practice test and taken the real test themselves to see how well they understand the concepts. Chad Rohrbacher will soon begin training them to use Criterion, an online writing tutor, both to improve their own writing and to help them grade the writing of undergraduate students. They will be observed leading their lab sections and critiqued for teaching styles.

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 reporting period, **33 travel grants** (total amount: $21,525) were awarded to students and postdocs, for scientific meetings including Evolution 2012, GECCO 2012, the International Society of Behavioral Ecology, the International Society of Microbial Ecology, Stickleback 2012, Swarmfest 2012, and Model Driven Engineering Languages and Systems. BEACON faculty members offer a grant-writing workshop, which has as a specific goal students' identifying and preparing a grant for submission. In addition, BEACON has provided funds for graduate students to visit laboratories at other institutions in order to gain interdisciplinary experience. For example, computer science graduate student Elijah Lowe (MSU, advised by Titus Brown) spent 6 months at Friday Harbor Laboratories to do field and laboratory work with hemichordates with UW faculty member Billie Swalla. In another example, UT graduate student Emily Jane McTavish went to UI to learn new methods of analysis in Jack Sullivan's lab. BEACON has also joining with **the Center for Academic and Future Faculty Excellence** at MSU to provide additional BEACON-centered training sessions for graduate students and their mentors.

The **BEACON Student/Postdoc Association** has also taken the initiative in putting together professional development activities. The group at MSU has started having monthly lunch meetings, with an average attendance of 22 participants. These events included a tour of the Long Term *E. coli* Evolution lab, which had activities such as a hands-on transfer of the long term *E. coli* lines. They also toured Jenny Boughman's lab, where they learned about how researchers can use robotic fish to understand ecology and evolution in natural fish populations, as well as how to study evolution using long-lived and slowly reproducing organisms. Brian Connelly and Luis Zaman started a series aimed at teaching basic "data science" to BEACON students, which included several seminars on how to store data, how to manipulate data, how to analyze it, and how to plot it. All of these seminars are focused on using free and open source software as well as best practices when it comes to responsible research. Brian Connelly has now moved from MSU to UW, and they plan to start separate seminars across partner universities using the same core structure as the one developed at MSU. In addition to these lunch seminars, the group also negotiated "mini-sabbaticals" for members. These small awards include a limited

amount of funding for a student/postdoc to travel to a partner institution and visit outside the scope of other funding opportunities provided by BEACON.

As part of the BEACON Congress, the student group also organized a 1-day retreat for all members that included presentations on communicating science to the public and how to get grants. There were hands-on sessions to develop elevator pitches, and for writing blog posts to public audiences at an introductory level. The evening ended with a picnic at a local park that brought together students and other researchers from all partner universities. Overall, more than 100 individuals signed up to attend this retreat.

Robert Pennock's (MSU) project **Developing a Virtue-based Approach to RCR Training** specifically meets BEACON's *Ethics Goal* "to practice and promote ethical and responsible research by implementing cross-disciplinary and multi- institutional ethics programs that will inform and guide all participants of the Center." The strategic plan had also identified a barrier to this goal, noting that "We anticipate difficulties ensuring compliance with RCR (responsible conduct of research) training, as students and researchers may find the training requirements burdensome." We hypothesize that part of this feeling of burden arises from the standard "legalistic" way in which RCR training is traditionally done. This project aims to develop and pilot test a new approach to RCR training that is based on what Pennock has called the "scientific virtues." These include traits such as curiosity, objectivity, skepticism, integrity, community, etc. The team will develop presentations, workshops and Toolbox-style modules (Eigenbrode, et al 2007) that embody this virtue-based approach. These modules will be pilot-tested in BEACON weekly meetings and annual Congress, which will also help grad students and post-docs fulfill their RCR requirements. Pennock leveraged this BEACON grant by applying for a grant from the Templeton Foundation to develop a survey instrument to gather data about scientists' perceptions about scientific values and virtues. The $95,725 planning grant was funded and data from its pilot interviews will be used as one basis for developing the virtue-based RCR approach.

2c. External education activities

In October 2011, The National Academies of Science sponsored a convocation "Thinking Evolutionarily: Evolution Education across the Life Sciences." Three BEACON faculty members participated in the event, and the report from the convocation makes it clear that there is need for more research on evolution education and that all students will benefit from more active engagement in evolutionary biology – whether in the form of labs or participation in research addressing evolutionary questions (National Research Council and National Academy of Sciences 2012). BEACON is uniquely situated to respond to this call as our entire program is built around evolution in action – showing how evolution works and evolutionary processes can be used to solve engineering problems. Extensions of this research to education include projects ranging from new evolutionary games for elementary students to software that engages undergraduate students in testing evolutionary hypotheses. **A general model for BEACON's education activities is to provide seed funding to develop and test educational materials, instruments, and tools with small groups and then disseminate these materials to broader audiences, providing training as necessary.** We are experiencing great success with this approach. Our High School Summer Residential Program funded graduate students to develop high school activities focused on evolution in action. These activities were tested over two

summers. Anne Royer, a graduate student involved with the program, received an award from the Society for the Study of Evolution to present these activities to participants at the Professional Development Conference of the National Association of Biology Teachers, held in Dallas in November. BEACON is also funding a workshop for high school teachers at Kellogg Biological Station in July 2013 where many of these activities will be disseminated to high school teachers.

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 II: In July 2012 thirty-two students participated in the weeklong program, learning about evolution in action. Students were recruited from partner school districts, Utica Community Schools, Lansing School District, Detroit Area Pre-College Engineering Program (DAPCEP), Holt School District, Okemos School District, and East Lansing School District, and out of state students. Nineteen students self-identified as female (59%) and 13 students identified as minorities (41%). Building on the success of the previous summer, we increased our numbers from 28 to 32 and in response to participant feedback, we moved the entire program to Kellogg Biological Station. Participants were introduced to the study of evolution in action, computer programming, and various types of engineering taught by BEACON and Engineering faculty. Graduate students led morning sessions focused on activities highlighting evolution in action, including a study of fitness in milkweeds, selection in damselflies, and exploration of digital evolution through the software program BoxCar2D. During the 2012 program a day-long research project was also instituted, led by BEACON graduate students acting as mentors. Students worked in small groups to pursue a question of interest. Projects included "Convergent evolution with BoxCar2D," "Sexual and non-sexual selection in birds: A meta-analysis," and "The effect of predation on the foraging behavior of *Drosophila melanogaster*." The novelty of this project was that students asked a question, designed an experiment, collected data, and created a poster–all in a single day. As one of our mentors proclaimed, "If they had a few more days, they could have generated a publication!" Students presented their projects as either posters or oral presentations.

This program was evaluated with pre- and post-survey instruments, with both student understanding of evolutionary concepts as well as programmatic evaluation carried out. We have received these reports and again the feedback is extremely encouraging. Students clearly gain an appreciation for science, and in particular for the applications of evolutionary biology to solving engineering problems. A brief summary of the evaluation results follow.

BEACON Summer Program for High School Students

Evaluation Report

July 1 – 5, 2012

Kellogg Biological Station

General Student Satisfaction: Of the 30 students who attended the summer program at Kellogg Biological Station (KBS), 18 (60%) were female and 12 (40%) were male. Nine students (30%) were entering grade 11, 18 (60%) were entering grade 12, and 3 (10%) were entering college. One student was beginning "the early college" at Lansing Community College.

Student ratings of their experience in the program

	Response Percent	Response Count
Poor	3.4%	1
Below Average	0.0%	0
Average	3.4%	1
Good	44.8%	13
Excellent	48.3%	14

Rating of sessions regarding how well they prepared students to answer evolution questions.

	Average	Good	Excellent
Understanding variation in natural populations: measuring natural selection in milkweeds	3	18	7
Experiments in engineering with evolution: BoxCar2D	5	10	13
Damselfly adaptations in nature: selection on color and behavior	1	11	16

Note: Scale included the following choices: Poor, Below Average, Average, Good, and Excellent. Categories garnering zero responses are not displayed in the table.

Aggregate responses regarding inquiry projects

	Disagree	Neutral	Agree	Strongly Agree
The project was interesting.	2	2	12	13
The project allowed me to use knowledge I learned this week.	1	1	12	15
The project allowed all group members to contribute.	1	1	14	13
Inquiry projects should be included in next year's BEACON summer program.	2	1	10	16
The inquiry project topic was relevant to the BEACON summer program.	0	3	11	15
The inquiry project made me feel like I was doing science.	2	3	7	17

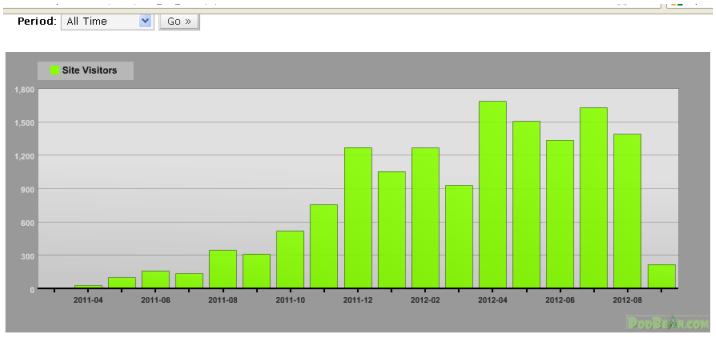
Note: Scale included the following choices: Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree. Categories garnering zero responses are not displayed in the table.

Recommendations for future years include:

1. Have a dedicated tech support person.
2. Bedrooms should have air conditioning.
3. Consider including presentations about specific career types.
4. Continue to include field-work and hands-on activities.
5. Continue to include free time with planned, unstructured activities.
6. Ensure program staff understand their responsibilities.
7. Continue to do careful hiring of undergraduate mentors.
8. Consider how curriculum and pre- and post-program surveys align with program goals.

Activity Name	Continuation for Podcast and Teacher Education Course 2012-2013
Led by	Randall Hayes (NCAT)
Intended Audience	K-12 Teachers
Approximate # of attendees	

PODCAST: As of August 2012, 45 episodes of *VSI* have been produced. Year Two Guests have included scientists at various stages of their careers, including African American ecologist Danielle Lee and BEACON members Kay Holekamp, Melissa Kjelvik, Tasneem Pierce, and Liz Schultheis. Hayes has created a website, **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 1177 times, and the blog site is now averaging *over a thousand hits a month*. It has been visited by people from at least 50 countries, on every continent except Antarctica. The MSU BEACON site is currently reposting links to all blog posts and episodes.



ONLINE COURSE: The online course was taught for the second time in May-June 2012 as BIOL 670: Teaching Evolution. Five students took the course, including one in-service high-school biology teacher. That teacher, Justin Tarpley, has expressed interest in writing a Research Experience for Teachers (RET) supplement to the BEACON grant. This project is now finished, as the course is officially offered at NCAT, through the department and also through the distance learning office. Hayes also plans to extend the opportunity to other BEACON institutions.

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 Educations with Evolution in Action: The goals of this project were threefold: 1) include cutting-edge BEACON research in classroom modules for a Science, Technology & Society class at the undergraduate level; 2) develop online curriculum guides for science fiction short stories dealing with evolution, targeted towards grades 9-16, to encourage the reading skills

necessary for success in graduate or medical school; 3) reach into the elementary schools with simple, fun, scientifically responsible computational models of evolution. Accomplishments to date include the production of lesson plans and, in two cases, video footage of how these should be implemented. Plans to post these materials to the BEACON website for others to use are in progress. Progress on the second goal includes completion of discussion questions focusing on social issues and writing process, as well as skills-based assignments on close reading and summary, for all 7 stories in the *Origins: Tales of Human Evolution* anthology. The curriculum is ready for testing at NCAT, with an eventual goals of outreach to our partner institutions once testing is complete. Outreach into elementary classrooms is also underway and we are recruiting BEACON partners to help us with testing these modules.

Activity Name	**Avida-ED Curriclum Development and Assessment Pilot Study**
Led by	Pennock, Foster, Graves, Hayes, Kerr, Mead, Smith, Ofria, Wilke, Ebert-May, Swalla.
Intended Audience	AP Biology, Undergraduate Biology, Upper level Evolution
Approximate # of attendees	Unknown

Avida-ED is our digital evolution software designed for educational use in undergraduate and graduate courses. The goals of the project are (i) to release a beta version of Avida-ED 2.0 that is ready for classroom testing; (ii) to develop model curriculum materials; (iii) to test the effectiveness of Avida-ED in undergraduate-level courses for teaching and learning about evolution and the nature of science. The team decided that it would be better for long-term consistency, portability and reliability if they did a significant revision of the way that Avida-ED is connected to the Avida engine. Thus, rather than just refactoring the code so that it works with current development tools and operating systems as originally planned, they moved more of the basic graphical functionality into Avida itself into a core viewer framework. By the end of August the team had a nearly-but-not-quite ready beta version of a Mac version of Avida-ED that could run on OS X 10.6 – 10.8.

The team was successful at spreading Avida-ED throughout BEACON. During the year they gave talks and hands-on workshops at all the partners (Pennock: UT, NCA&T, Idaho; Ofria: UW). Responses from co-PIs at partner universities indicate that in 2012-2013 Avida-ED will be used in one or more courses at every BEACON university. For instance, at UW the upper-level undergraduate course Biology 481, Experimental Evolutionary Ecology, is designed to get students thinking about evolutionary processes by combining the lectures on current evolutionary concepts with hands-on experimental evolution labs. Early in the course, the microbial labs, which are highly structured, give the students ideas about the basic elements of experimental research. Midway through the quarter, Avida-ED is introduced. The lab groups then embark on a multi-week project using Avida-ED, which allows far more freedom for discovery and novel experimental design than the prior microbial experiments. Avida-ED allows students to pursue a variety of topics (e.g., ranging from the evolutionary effects of mutation to environmental conditions favoring adaptive radiations) and implement them in a very short amount of time. In particular, the students have time to troubleshoot their experimental protocol and execute additional experiments in the light of their preliminary data. The students write up their findings in a group lab report and some groups present this lab as a final oral presentation. Many of the students report the Avida-ED lab module as their favorite of the entire class because the platform

allows them to take complete control of the experimental process. The aim is to include as many BEACON partners as possible in the assessment study.

Curriculum Development and Assessment Pilot Study: Pennock, Mead and Smith hold a weekly curriculum development meeting with graduate students Amy Lark and Wendy Johnson. Several exercises and instructor support materials have been completed and Lark has developed a survey instrument for the pilot assessment study. All members have completed IRB training and the study has received IRB approval. The assessment study has now begun in several Fall courses.

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 uses a winner-take-all contest structure to encourage exploration of the AVIDA artificial life system and teach essential concepts of evolutionary theory and artificial life to undergraduate and high school students. The contest strategically introduces AVIDA to new institutions, trains future research assistants and addresses the lack of sufficient documentation for the AVIDA platform. This is as a low-risk, low-cost way to quickly develop a broad base of competent AviDeities (Avida programmers) within the BEACON affiliate institutions and provide a model that can be replicated in any educational setting. Field-tested AviDeities will then be ready to assist with AVIDA-based research projects at their home institutions and increase demand for tools produced through BEACON activities.

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

Funding from BEACON was used to create two games, one on *mutation* and the other on *natural selection*. A need for revisions was made clear after showcasing the programs at the **2012 USA Science and Engineering Festival** held in Washington DC, and the pilot data collected using Amazon's Mechanical TURK. After the revisions, the team plans to run additional tests with the programs, in-person as well as online, write up the data, and publish our findings. Once they have reached these benchmarks, they hope to secure funding for two additional EVOAPPS, covering the topics of **time** and **inheritance**. They also hope to publish the games with the Multimedia Educational Resource for Learning and Online Teaching (MERLOT) to help with the dissemination of the EVOAPPS beyond the museum setting.

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

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, several modifications to The Ladybug Game are being made, 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 (providing protective coloration) to study how that influences player behavior and in turn aphid evolution. The team is developing educational materials (Melissa Kjelvik, a graduate student at MSU is developing the curriculum) that will allow the ladybug game to be brought into more formal classroom settings.

Two versions of the Ladybug program have been developed, one using a single screen and displaying significant data; the other using a splitscreen with two aphid populations and two ladybugs so that viewers can clearly see the effects of different forms of selection (in the form of different ladybug behavior). The second version was presented at the ***USA Science and Engineering Festival*** and was very well received. A preliminary version of the program has been ported to Android devices. They are currently developing the splitscreen version into a 5-lesson classroom experience. The overall framework for the code is complete, as are 4 of the 5 lesson plans. The 5-lesson version of the program and a stand-alone version for Android smartphones should be completed by December 2012. The team is discussing with the Palouse Discovery Science Center the possibility of creating an installation based on the stand-alone splitscreen version of the program.

Ladybug Lessons:

Lesson 1: Introduction. This lesson shows the basic mechanics of the game; several aphids move around on a background that is different shades of a particular color (usually green) and a single ladybug is placed with them that the students can move around the screen in an attempt to "eat" the aphids. In this introduction, the "selection" function is the student themselves, who decide where the ladybug moves and in this way, decide which aphids "survive." Heritability and variation of traits for the aphids are both turned on so students can observe how their actions drive the evolution of the aphid population.

Lesson 2: Variation. This lesson allows the student to observe the impact that random variation has on the ability of the population to adapt to a changing environment. In this lesson, the screen is split into two halves: one half has variation turned on, the other has variation turned off. Students can change the color of the background, and are encouraged to do so, and observe the effects on the population (aphid color contrasts with the background influence their visibility to the predator). The population with variation turned off will not be able to adapt to a new color, since each offspring is the exact duplicate of its parent, while the population with variation turned on will be able to adapt to the new color.

Lesson 3: Heritability. This lesson enables the student to observe the effect of inheritance on the ability of a population to adapt to its environment. Similar to variation lesson, the screen is split into two halves, one with inheritance turned off, and the other with it on. With inheritance turned off offspring aphids will have completely random colors (i.e., they don't inherit colors from their parent). This lesson is a bit more subtle, in that both populations will show variation in

the offspring produced. However, only the population with inheritance turned on will show a steady movement of the overall coloration toward the background; the other population will simply produce random-colored offspring each time. It is important that the instructor guide the students to see this particular phenomenon, as it may not be immediately apparent to the untrained eye.

Lesson 4: Selection. This lesson shows how selection works to reinforce particular traits in a population. For this experiment, one ladybug will be able to "see" all of the aphids, regardless of their coloration and background, and the other ladybug will have the normal chance to miss an aphid based on its ability to blend into the background. Aphid speed can be fixed and/or variable based upon a selection box. Since the ladybug effectively acts as the selection function, by eating poorly fit aphids, the population where the ladybug has a hard time "seeing" the aphids that match the background color should quickly evolve to that color. However, the population where the ladybug sees all aphids regardless of color should stay fairly random, or evolve to make the aphids faster since color is no longer the most useful trait to their survival.

Lesson 5: Inquiry. In this lesson students have the ability to define the parameters of the model. They can turn on/off (or scale) all three of the parameters introduced above: variation, heritability, and selective pressure. The instructor should have the students formulate basic hypotheses; will the aphids evolve to match their background? Will the aphids evolve to go faster or slower? This should help to cement the student's understanding of evolution as a by-product of selection, and that small, random changes propagated to our progeny can lead to large sweeping differences over time.

Activity Name	**Unleash Your Inner Scientist**
Led by	Louise Mead and Kristin Jenkins
Intended Audience	K-12 Teachers
Approximate # of attendees	20

The BEACON-BioQUEST Teacher Workshop for high school teachers will run at Kellogg Biological Station June 28-July 3 2013 and will provide examples of the pedagogical shifts necessary for more open inquiry approaches in lecture and lab, and support participants in identifying and modifying current instructional materials, all with an objective of integrating evolution throughout labs and lessons whenever possible. Teachers will be encouraged to consider using a broad collection of labs, such as Avida-ED, and field exercises, as demonstrated by faculty at KBS. A few of the field exercises will be ones that have been tested with the BEACON High School Summer institute participants. The workshop will also provide an opportunity to develop a substantial biological research experience for students through a long-term lab, which will give students time to become familiar with the biological system and an opportunity to refine techniques and questions by repeating experiments. Faculty associated with the Kellogg Biological Station and BEACON will give guest lectures to enhance content knowledge for the teachers' own professional development. Initial contact with Drs. Connor, Getty, Teal, and Whittaker was made but dates have yet to be confirmed. By engaging with this highly motivated community, BEACON and BioQUEST can impact the way in which biology students are introduced to the field. This is an open door to the high school classroom, and a way to introduce a broad range of students to the fascination and applications of science, and in particular, evolution in action.

Activity Name	A Planning Grant for the Relevancy of Evolution to Our Daily Lives: A Museum Exhibit
Led by	Laura Crothers (UT)
Intended Audience	K-12, Undergrad, Grad, General Public
Approximate # of attendees	Unknown

Relevancy of Evolution to Our Daily Lives is working to develop up to 10 narratives that can be used in interactive exhibit modules. Laura Crothers, a PhD student in UT Austin's *Ecology, Evolution & Behavior* program continues to work with a committee of specialists in biology, computer science, and science education to develop materials for the exhibit. The scientists and research focuses are as follows:

- Emily McTavish/David Hillis (*UT Austin* – longhorn cattle evolutionary origins)
- Tom Hladish/Lauren Meyers (*UT Austin* – influenza evolutionary dynamics)
- Jeff Morris (*MSU* – experimental evolution and global warming)
- Robert Heckendorn (*U of Idaho* – game theoretical evolutionary models)
- Molly Cummings (*UT Austin* – biomimetics, camouflage evolution)
- Bree Rosenblum (*U of Idaho/UC Berkeley* – rapid evolution in lizards)

Working with Texas Memorial Museum staff, Ms. Crothers has researched and developed narratives for each research project, organized the narratives into an overarching story, created mock-ups of narrative panels and interactive elements of the exhibit, and identified specimens to feature in each section. She has also created a detailed budget that we are using to approach local organizations and individuals to fund exhibit construction. The team is currently conducting extensive review of content before construction. Review audiences include middle school students in the Austin area, informal science education staff at the MSU Museum, science educators specializing in evolution education, and crowds at local outreach events. All of this feedback will be integrated into the content before final exhibit construction. Ongoing activities also include finalizing design elements, purchasing/renting specimens, and developing videos and online supplemental materials to accompany the exhibit. Future goals include writing supplementary teacher training modules and developing a science education research project based on the exhibit content. Please go to the following links for examples of project outputs:

https://www.dropbox.com/sh/f6qwj5ukavnilku/-POBG6UPPn

Sample outputs include graphical mockups, a 3D virtual tour of the exhibit space and several videos of interactives.

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

Evolution in Action MSU Museum Exhibit: As described in the 2011 report, the MSU Museum is working to deliver educational products that engage the broadest of audiences with the relevance and research of BEACON. Work continues on these projects as follows: The initial BEACON installation for the MSU Museum is completed and on display. The "Hyenas Rule" virtual outreach program (VOP) about hyena evolution research was started in early 2011 but not

completed. This VOP was temporarily put on hold, awaiting BEACON graduate student input and Museum staff availability. The intent is to identify an appropriate graduate student during fall semester, 2012 and complete the VOP for spring pilot, 2013. An external evaluator was contracted to work with Museum educators to create, administer, and interpret evaluation instruments for the Evolution in Action gallery exhibits. An evaluation plan was created, including listing project goals and intended outcomes as well as the associated evaluation methodologies. An exit survey has been created and administered to small groups as a pilot. The instrument was revised and will be administered to larger public groups in later fall, 2012. Results of that survey and the other evaluation components will be provided by or before submission of the 2013 progress report.

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 project will be comprised of approximately 150 three-dimensional glowing, sensing and audio-producing sculptural robots. Robotic units will be mounted on the walls and be capable of communicating with each other (via wireless protocol) and with viewers that enter the intended installation space. The finished installation will have the feeling of a cave filled with synthetic bioluminescent life forms all competing for human interaction, thus the installation will act as a "living laboratory" as well as a focal point for BEACON visitors and researchers. The interaction inherent in the Biolume installation will be governed by evolutionary methods and principles to evolve behaviors to better interact socially with humans. The installation will therefore act as a "laboratory" to explore applied evolution as it relates to human interaction.

Over the summer the team decided to completely change the hardware, switching from multiple Atmel processors and opting for a new product called Raspberry PI. (http://www.raspberrypi.org) This change has drastically reduced the price and massively increased the processing power of each unit. Unfortunately, this slowed down the project, but the team made the decision that migrating to new hardware will end up making the Biolume installation more robust, flexible and much easier to use as it runs on Linux. Over the summer Malcolm worked with implementing code into the new hardware. The team is now prototyping the new hardware "shield" that fits onto the Raspberry PI hardware, adapting the "off-the-shelf" hardware to work as an evolving synthetic digital organism: Biolume.

2d. Integrating research and education

The Michigan State Museum has completed, and Texas Natural Science Center is 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.

Several BEACONites have developed their own outreach activities based on their BEACON-funded research.

- Charlotte Konikoff and Billie Swalla (UW) curate the Hemichordata World Database, as 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.
- In 2010 and 2011, Bree Rosenblum (UI) ran a White Sands Lizard Camp where middle-school children participated in an evolutionary biology short course. More than half of the students were Latino and more than half were from low income backgrounds and Children in Need of Services (CHINS). In 2010, Rosenblum assisted with developing a bilingual exhibit about Evolution at White Sands National Monument (that will reach ~500,000 visitors per year), including a award-winning park service movie, "A Land in Motion", that introduces a lay audience to concepts of environmental change. In 2011 Rosenblum ran a White Sands Science Symposium and brought together researcher from across the country to present their scientific results to the public. During the reporting period Rosenblum also organized a White Sands Science Symposium, presented at several Women in Science events, and developed materials on Evolution in Action for inclusion in magazines and textbooks.
- Jenny Boughman (MSU) and members of her lab have developed a number of public outreach events targeted at Michigan schoolchildren, the general public (a Darwin Day event at the MSU museum and both radio and video presentations), and teachers. Boughman also organized and ran a Women in Science event at Evolution 2012.
- Xiaobo Tan, Phil McKinley, and Jenny Boughman (MSU) have conducted interactive robotic fish/Evolution Park demos and lab tours to participants of numerous outreach programs and student groups, such as the Residential BEACON High School Program, the Grandparents University Program, and high school classes from Portland, Leslie, and Dewitt, Michigan. Other examples of their outreach activities include:
    - Selected by NSF to represent the Foundation, Tan's group presented an exhibit "Robotic fish patrolling waters" (http://www.youtube.com/watch?v=jWli8IuG7NE&feature=plcp) at the 2012 US Science and Engineering Festival in April 2012;
    - McKinley presented the results of the robotic fish project as part of MSU's Frontiers in Science Weekend Workshop Series in April 2012. The workshops provide opportunities for teachers learn about new research developments while earning university credits for continuing certification.
    - Boughman's group offered a capstone inquiry-based project at the Kellogg Biological Station during the BEACON High School Week in summer 2012. The students designed experiment, collected and analyzed data, and presented their findings, based on predator inspection hypotheses all in one day-long event.
- In summer 2012, Philip McKinley and Brian Connelly mentored Wendy Johnson, a biology teacher at Lansing Catholic High School, as part of the NSF Research Experience for Teachers program. Ms. Johnson conducted research on the evolution of group behavior, including quorum sensing, and is currently developing corresponding lesson plans for use in her classroom and distribution to other high schools. In April 2012, McKinley and Connelly presented results of this project as part of MSU's Frontiers in Science Weekend Workshop

Series. The workshops provide opportunities for teachers learn about new research developments while earning university credits for continuing certification. The topic of this workshop was the evolution of cooperation. In May 2012, Chris Waters also led a Frontiers in Science workshop to teach local high school science teachers about biofilm formation and quorum sensing. The teachers toured the lab and grew their own bioluminescent *V. harveyi*. In summer 2012, the Waters Lab hosted SROP student Alani Adkins. Finally, McKinley and Waters have hosted numerous visitors and student groups (including the DePauw NSF REU team; North Carolina A&T student visitors; graduate recruits; and high school classes from Portland, Leslie, and Dewitt, Michigan).

2e. Progress towards metrics described above

Indicators and metrics for optimal outcome one (placing graduates in multidisciplinary positions) are long-range and we are only beginning to collect data on this metric. However, current research programs of many of our graduate students show multidisciplinary approaches: for example, Luis Zaman is testing hypotheses both within a computational system as well as in the wet lab. We have also sent graduate students to numerous meetings over the past year to present their research – for example, at least 34 talks at Evolution 2012 were from BEACON representatives.

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 2012-2013, with improvements in technology to improve inter-institutional educational experience.
- BEACON hosted International ALife 13 conference in summer 2012.
- Professional development through MSU's CAFFE (future faculty enrichment) and informal/formal active mentoring was carried out in Spring 2012.
- We have created a tiered mentoring system for training undergraduates through apprenticeships and research experiences.

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

- We continue to invest about 10% of our NSF BEACON funding in education and outreach projects.
- "Evolution in Action" gallery completed at MSU Museum and UT Austin continues with development of exhibit focused on The Relevancy of Evolution.
- We have created a BEACON Education Listserv
- We have collected baseline data on undergraduate understanding of evolutionary biology as relates specifically to BEACON goals.
- We developed and are testing Evolution in Action lessons for all grade levels (K-4; 5-8; 9-12; Undergraduate) and started dissemination through teacher workshops and presentations at national meetings, both teacher professional development and scientific.

Progress: Increased interest in STEM careers

- We continued to offer the BEACON High School Residential Program in summer 2012.

Thirty-two students from across Michigan attended the program. We are working to recruit exceptional students from other regions as well.

- **Sixty-six undergraduate students, including 41 students from underrepresented groups** from across the country worked with BEACON faculty on evolutionary research in summer, 2012. Students were funded through a variety of programs and initiatives.
- A total of five Education RAs were hired in BEACON to work on projects across campuses.
- Across all our campuses, graduate students and faculty participating in programs aimed at presenting BEACON research and STEM education and careers information to 3rd-12th graders (~250 participants).
- Student participation in the Freshman Research Initiative at UT Austin provided hands-on research opportunities in computational biology.
- 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.
- Received funding from NESCent for a Catalysis Meeting on K-12 Evolution Education to Underserved Minorities.

2f. Educational plans for next reporting period

We will continue to test and review all our educational projects, working to bring curriculum developed at one institution to other institutions across the consortium. As an example, graduate students and faculty at the University of Washington are proposing to infuse the Citizen Science project run by the Seattle Aquarium with "Evolution in Action." Because this program brings teachers and their students to the Pacific coast to collect data, we envision portions of the KBS High School Residential Program will be directly applicable and plans would include graduate students from KBS traveling to University of Washington to work with graduate student mentors from the University of Washington. While we have held off establishing a BEACON Education Advisory Board, we did hold a number of education sessions at the BEACON Congress and are still discussing the possibility of an education advisory board. Three BEACON faculty members have funds from the National Evolutionary Synthesis Center to hold a catalysis meeting on evolution education to underrepresented minorities. A focus of this meeting will be to discuss plans to carry out a broad survey across institutions to help us better understand challenges to reaching underserved groups. Related to this endeavor, Dr. Mead joined Dr. Joe Kracjik of CREATE for STEM at Michigan State University and Dr. Michelle Williams in the College of Education at MSU, along with Toby Citron at the University of Michigan, to submit a SEPA grant proposal to the National Institutes of Health. Should this project become funded, it will provide BEACON an opportunity to contribute to a framework for genomics education at the middle school level.

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 are establishing an Industrial Affiliates Program 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	All 5 BEACON institutions have signed boilerplate agreement for industrial collaborations through BEACON and are actively recruiting industrial affiliates
Receiving industry-provided challenge problems and data with feedback	Number of instances that challenge problems, data, and feedback are received	At least six companies are providing challenge problems and feedback.
New collaborative research with Industry partners	Number of publications	At least 7
	Number and amount of joint grant proposals submitted	1 submitted
Dissemination and use of BEACON tools and data	Number of downloads of BEACON tools/data relative to baseline	~4700 downloads of Avida-ED; ~4400 downloads of Avida platform
Spinoffs formed	Number of spinoffs formed	1 in the previous reporting period, no new spinoffs this period, but foundation laid for 1 that may form this period or next
Adoption of new BEACON-developed technology by industry	Number of instances of BEACON projects, processes, and techniques adopted by industry	1

1c. Problems encountered

We are a little behind schedule on our plans to have industrial affiliates sign the IP agreement. It took longer than anticipated to negotiate a "boilerplate" IP agreement acceptable to all parties for signature by Industrial Affiliates, but all 5 universities are now on board. 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, and to a lesser extent, the Director, Dr. Erik Goodman, have been engaging several industrial organizations to publicize BEACON's mission and provide an overview of evolution in action areas of expertise. Dr. Cheng is also working with the PIs at the BEACON partner institutions to coordinate industrial contacts to avoid redundant efforts. Several BEACONites are engaged in knowledge transfer activities (see below) and are also actively recruiting industrial partners.

The lack of companies signing Industrial Affiliates agreements does not reflect a lack of companies interacting with BEACON on solution of their problems, but just that the IA mechanism has proven not necessarily to be a prerequisite for such interactions. BEACON's posture toward industry has been and continues to be to cooperate first and not stress IA paperwork, so long as the company is willing to bring appropriate information to BEACON and provide active participation by their own personnel. At such time as companies become eager to intensify the relationship, then either the IA or a traditional contract will be appropriate. Therefore, it may be time to reformulate some of BEACON's goals regarding knowledge transfer to industry to encompass this much more frequent relationship that is less encumbered with legal obstacles than to count companies signing Industrial Affiliates paperwork.

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

- **Ford:** Led by Betty Cheng (MSU). 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. Cheng continues to receive challenge problems from Ford.
- **Northrop Grumman:** Philip McKinley and Charles Ofria (MSU) received seed funding ($30,000) to use evolutionary computation and digital evolution techniques to design underwater autonomous vehicles.
- **Scion, Inc.:** Led by Erik Goodman and Kalyanmoy Deb (MSU). Dr. Oliver Chikumbo, of Scion, a Crown Research Corporation in Rotorua, NZ, visited BEACON under a grant from his government for the month of August 2011. Since then, he has collaborated regularly via videoconference and email with Goodman and Deb. The team made a breakthrough during his visit that allows, for the first time, an effective multi-objective optimization of land use solutions over a 50-year planning horizon for an area in Rotorua, NZ that drains into Lake Rotorua, which is rapidly being eutrophied [Chikumbo, Deb and Goodman 2012]. The problem is represented with fourteen objectives, including

environmental effects to be minimized and production and profitability objectives to be maximized. The team has obtained funding from sources in New Zealand to support two graduate research students there, and BEACON funding to support an additional graduate student at MSU, yet to be recruited. In the meantime, Deb and Goodman have visited NSF to explore programs to which this research might look for support of the US activities, and they submitted a proposal in October, 2012. Ultimately, the project will use evolutionary computation and multi-criterion decision-making methods (being developed) to allow multiple stakeholders, including the indigenous Maori people of the region, to view tradeoffs in the multi-objective landscape so as to arrive at mutually acceptable trade-off solutions.

- **NASA.** Led by Gerry Dozier (NCAT). Dozier is working with NASA to develop X-TOOLSS (eXploration Toolset for the Optimization of Launch and Space Systems). The software is being developed and maintained by BEACON@A&T. One may download a copy of X-TOOLSS at: http://nxt.ncat.edu.
- **Secure Designs, Inc.** Led by Gerry Dozier (NCAT). 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.
- **Continental Automotive:** Led by Betty Cheng (MSU). Continental has provided class projects for Cheng's undergraduate software engineering class. Cheng and graduate student Erik Fredericks began initial research in harnessing evolutionary computation to augment a whole-vehicle safety system developed by Continental. This would have seen EC take a major role in determining sensor placement on a vehicle, sensor parameters, and testing of the system through the generation of evolved test cases. They are currently negotiating a research grant.
- **BAE Systems:** Led by Betty Cheng. Cheng has received funding from BAE Systems to support the project: "Harnessing Evolutionary Computation to Support Software Composition with Code-Level Adaptors." The research project will explore how evolutionary computing can be harnessed to automatically generate code-level adaptors and evolve software to satisfy changes in either the system's requirements or its execution environment.
- **General Motors:** Led by Betty Cheng. Cheng recently obtained informal approval for a grant to be used to support EC-based model-driven engineering for adaptive systems to enable detection and mitigation of uncertainty for onboard automotive systems. General Motors is also participating as customers for course projects.
- **EpiFire**: Led by Lauren Meyers, UT Austin, Biology. Meyers is developing software to study epidemiology using contact networks. This work is used for research and teaching at UT Austin, Univ of Washington.

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

Software Packages Developed

OpenNERO: simulation environment for research in multiagent systems
Igor Valerievich Karpov; Risto Miikkulainen
http://opennero.googlecode.com

NEAT software for evolving neural networks V1.2.1
Kenneth O Stanley; Igor Valerievich Karpov; Erkin Bahceci; Risto Miikkulainen
http://nn.cs.utexas.edu/?neat

PyEC software for Evolutionary Annealing and a number of other evolutionary and stochastic optimization algorithms
Alan Lockett; Risto Miikkulainen
http://nn.cs.utexas.edu/?pyec

UT^2 software for the winning entry in the BotPrize 2012 competition
Igor Valerievich Karpov; Jacob Schrum; Risto Miikkulainen
http://nn.cs.utexas.edu/?ut2

ESL software for Egalitarian Social Learning in the robot foraging domain
Eliana Feasley; Wesley Tansey
http://nn.cs.utexas.edu/?esl

2c. Progress towards indicators/metrics listed above

1. Signed Intellectual Property agreements with Industrial Affiliates. No affiliates have signed agreements yet, but several BEACONites are actively working with industry partners without signature of such agreements.

2. Industry-provided challenge problems (i.e. "Real World" problems) and data with feedback. Betty Cheng has received such challenge problems from Ford, Continental, General Motors, and BAE Systems. Erik Goodman is working on one problem with Scion, Inc., and Charles Ofria & Philip McKinley are working with Northrop Grumman.

3. New collaborative research with industry partners. At least 7 publications submitted in this reporting period have resulted from collaborations with industry partners. McKinley and Ofria submitted a proposal to the Office of Naval Research jointly with industry partner Northrop Grumman. Additionally, in the international project between Scion (NZ) and BEACON, each side has submitted proposals to their own governments to support work in their country on this collaborative project.

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.

The following table presents number of downloads for the Avida-ED system and for the Avida digital evolution platform. Note that these do not count direct clones of the Avida repository, which remains essentially impossible to track.

Platform	No. of Downloads (Aug 2010 - Nov 2011) (*Previous reporting period*)	No. of Downloads (Aug 2011 - present)
Avida-ED		
Experimental Multi-Dish version for Mac	174	286
For Windows	3477	2903
For Mac	1105	1174
Manual	488	344
Total	*5244*	*4707*
Avida		
SourceForge.net	8230	4405

5. Spinoffs formed. While no spinoffs were originally anticipated in the first five years of the Center, one spinoff was successfully established in the previous reporting period: Digital Certainty, Inc., was founded by Risto Miikkulainen (UT), focusing on applications of neuroevolution.

6. Adoption of new BEACON-developed technology by industry. No progress to report this early. It is noted that in many cases of industrial collaboration, the results are intended to be used as "enabling technology," rather than as a stand-alone product. As such, for competitive reasons, many companies will not (are not allowed) to inform us if they are directly or indirectly making use of a given enabling technology. With continuing industrial collaborations, one may infer that the research results continue to be of interest to the respective industrial organizations.

2d. Knowledge Transfer plans for the next reporting period

- Continue to collect additional challenge problems from current and new industrial collaborators.
- Obtain funding to 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.
- While the repository is under development, have all BEACON partners add mechanisms to track access to their respective tools and techniques
- Form a small core of BEACON faculty working in the intersection of computation and evolutionary computing to identify strategies, activities, and BEACON events for providing BEACON students with industrial experience, such as internships and full-time employment.

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 and educators who are working in the area of evolution in action, with other centers that can broaden our impact, and with minority faculty members at non-BEACON institutions and/or faculty members at minority-serving universities to provide research opportunities for those faculty and their students.

1b. Performance metrics

We are tracking the activities resulting from external partnerships.

1c. Problems encountered

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

2a. Partnership activities

Activity: Materials and Workshops for Cyberinfrastructure Education in Biology

Organizations/people involved: SESYNC (Socio-Environmental Synthesis Center), NESCent (National Evolutionary Synthesis Center), iPlant Collaborative

Narrative: BEACON has recently been awarded a $200K supplemental grant from NSF to address the cyberinfrastructure needs of BIO centers and center-like institutions. This project, led by C. Titus Brown, will (1) extend existing online computational science training material to facilitate self-learning by biologists across a wide range of expertise; (2) run a number of focused workshops to teach the materials and train others in delivery; (3) develop reusable assessment strategies to study the effect of these materials on learning and help identify unmet learning needs; and (4) host several meetings across a number of centers to develop a list of shared educational needs.

Activity: 13th International Conference on the Simulation & Synthesis of Living Systems (ALife 13)

Organizations/people involved: International Society of Artificial Life

Narrative: In July 2012, BEACON hosted the ALife 13 conference, overlapping the BEACON Congress on one day. By hosting the two events concurrently, we increased participation by BEACONites in the ALife conference, especially by biologists who might not normally attend

this conference. About 300 people attended the conference. Keynote speakers included Steven Benner, Oron Catts, Benjamin Kerr, Radhika Nagpal, and 2009 Nobel Laureate Jack Szostak, who gave a public lecture titled "The origin of life and the emergence of Darwinian evolution" that was attended by over 500 people. More information about the conference can be found online at http://alife13.org.

Activity: BEACON External Faculty Affiliate Program

Organizations/people involved: University of California Irvine/Adriana Briscoe

Narrative: In 2012, BEACON launched its External Faculty Affiliate Program to partner with minority faculty at non-BEACON institutions. Dr. Adriana Briscoe at UC Irvine is our first Affiliate. This program is described in greater detail in the Diversity section.

Activity: BEACON Luminary Scholars Program

Organizations/people involved: Spelman College, University of Texas Pan American

Narrative: BEACON has submitted an REU Site proposal to begin a new undergraduate research program with Spelman College (a historically black college) and UT Pan Am (a Hispanic-serving institution). This program would bring undergraduate students from these two colleges to BEACON institutions for summer research, and would provide resources for faculty to conduct research during the academic year with these students. This program is described in more detail in the Diversity section.

Activity: Increasing BEACON content in high school and college curricula

Organizations/people involved: National Association of Biology Teachers

Narrative: Education Director Louise Mead is working directly with NABT to find ways to develop and introduce BEACON materials for high school and college biology classes. This activity includes teacher training sessions, and is described in more detail in the Education section.

Activity: Catalysis Meeting: K-12 Evolution Education and the Underserved

Organizations/people involved: NESCent

Narrative: Education Director Louise Mead and Diversity Director Judi Brown Clarke have been awarded a Catalysis meeting grant by NESCent. This meeting will take place in 2013.

Visiting researchers during this reporting period: 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: 7 so far

Number of submitted external grant proposals: 3 so far

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

BEACON will issue a second 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 two overarching goals are to: 1) ensure diversity is represented as an inclusive and connecting thread through all aspects of BEACON, and 2) exceed national norms for diversity at all levels in the Center. We will achieve and sustain diversity at BEACON through inclusive recruitment strategies and will provide professional development opportunities at all levels, including culturally competent formal mentoring.

Overall, BEACON has been successful with our diversity efforts this reporting period. To highlight our positive outcomes, below are 2011 *Plans for the Next Reporting Period* goals listed in last year's annual report with results:

We found that many underrepresented students were underprepared for the summer REU experience, and therefore will create a two-tiered program for next summer. We will combine REUs (for students with strong lab/research backgrounds) with Undergraduate Research Apprenticeships (for students with little to no lab/research background). We are writing a collaborative research proposal, blending multiple funding sources, to create summer research opportunities at MSU, Friday Harbor, KBS, and UT Austin's Freshman Research Initiative (FRI) program.

- Results: Accomplished. Using the application process, we were able to identify students with either no or limited lab/research experience and place them into labs with nurturing faculty/graduate student mentors. This required considerable effort to identify faculty willing to mentor at this high interactive level. Additionally, we provided ongoing formal mentoring training for all graduate students and post-docs in direct contact with the REU students.

We are hiring an evaluator to formally assess the summer research programs. Our evaluator is Ayesha Boyce, a Ph.D. student at University of Illinois, who 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.

- Results: Accomplished. The evaluation was designed to assess the quality of experience of BEACON Research Experience for Undergraduates (REU). The evaluation design serves both formative and summative purposes, intended to provide useful feedback information to Center staff. To achieve these purposes, the evaluation design included both quantitative and qualitative methods combined to produce a fair representation of the complexity of the Center's activities and their impacts. To address the evaluation questions, data were collected using the following mix of collection methods: 1) Pre-program, mid-program, and post-program surveys of REU student and (faculty, post-docs, graduate) mentors; 2) observations of REU activities; 3) Interviews with a mix of Center staff and students; and 4) analysis of existing Center documents (i.e., website, annual reports, training materials etc.).

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.

- Results: Accomplished. These bi-monthly calls with education and diversity directors continue. Diversity Director Brown Clarke took the lead on establishing the agenda and secured funding for a full day, pre-meeting prior to the annual NSF Directors Meeting in August. At this meeting, we collaborated and shared ideas around strategies on the renewal process, summer research programs, publishing, engaging the public in STC research, establishing your legacy, and formal faculty mentoring.

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.

- Results: In progress. We are working with the MSU Resource Center for Persons with Disabilities to ensure our website is compliant. BEACON has hired a videographer to create our branding introduction video and to capture Friday seminars and other special events; we will have closed captioning to ensure it meet standards.

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.

- Results: Accomplished. Chair of BEACON's Diversity Steering Committee is Dr. Percy Pierre, the founder of MSU's Sloan Program. This joint appointment has proven very positive in the collaborative recruitment of graduate students.

The BEACON High School Summer Program 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.

- Results: Accomplished. The BEACON High School Summer Program is a residential summer education/hands-on research program that runs at the MSU Kellogg Biological Station. In 2011, we served 28 students, with 12 or 43% underrepresented minorities and 17 or 61% females. In 2012, there were 32 students, with 13 or 40% underrepresented minorities and 19 or 59% females. Collectively we have provided a rich in-depth experience in evolutionary science to 60 rising 11th and 12th grade high school students, with 42% underrepresented minorities and 60% females. As this program gains experience, its materials and lessons can be made more broadly available.

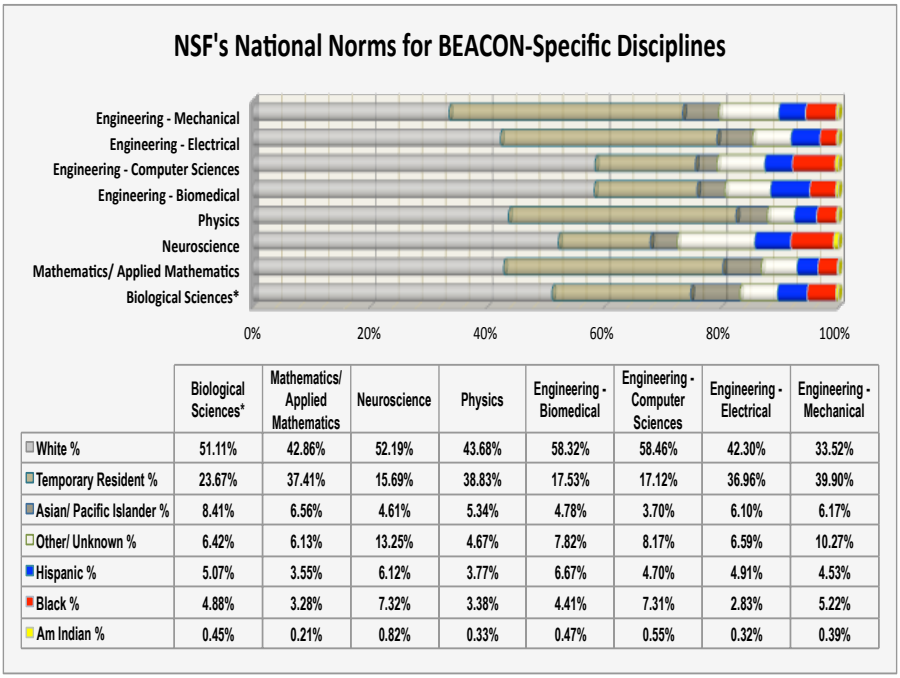
Brown Clarke has drafted the Faculty Affiliate FRP to recruit diverse faculty from non-BEACON universities (Oct 2011). BEACONites will submit recommendations to the executive committee for selection (Dec 2011).

- Results: Accomplished. BEACON awarded its first Faculty Affiliate fellowship to Dr. Adriana Briscoe from University of California Irvine. She was awarded a mini-grant of up to $100,000 over a two-year period to conduct research and explore the possibility of becoming permanent member of BEACON. The grant has a two-year overlapping funding cycle, therefore after this initial year we will have two active Faculty Affiliates each subsequent year.

1b. Performance and management indicators

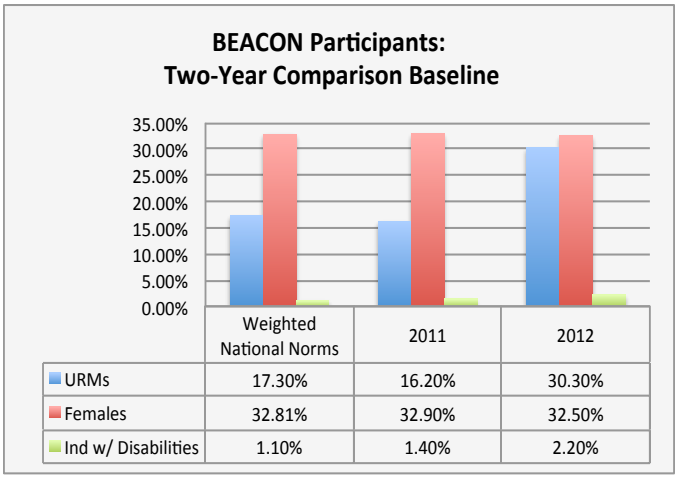
BEACON has established baseline data for diversity measures and created mechanisms to ensure its accuracy. We have collected comparative data on the numbers (and percentages) of undergraduate and graduate students, post-docs, and faculty participants from diverse demographic groups, including women, underrepresented minorities, and individuals with disabilities.

In an effort to make accurate comparisons, the detailed chart to the right illustrates how we captured national norms for BEACON-specific disciplines using data from NSF's 2012 data tables (see http://www.nsf.gov/statistics/wmpd/start.cfm). Based on available data, we had to collapse some tables into smaller categories.



	Biological Sciences*	Mathematics/ Applied Mathematics	Neuroscience	Physics	Engineering - Biomedical	Engineering - Computer Sciences	Engineering - Electrical	Engineering - Mechanical
White %	51.11%	42.86%	52.19%	43.68%	58.32%	58.46%	42.30%	33.52%
Temporary Resident %	23.67%	37.41%	15.69%	38.83%	17.53%	17.12%	36.96%	39.90%
Asian/ Pacific Islander %	8.41%	6.56%	4.61%	5.34%	4.78%	3.70%	6.10%	6.17%
Other/ Unknown %	6.42%	6.13%	13.25%	4.67%	7.82%	8.17%	6.59%	10.27%
Hispanic %	5.07%	3.55%	6.12%	3.77%	6.67%	4.70%	4.91%	4.53%
Black %	4.88%	3.28%	7.32%	3.38%	4.41%	7.31%	2.83%	5.22%
Am Indian %	0.45%	0.21%	0.82%	0.33%	0.47%	0.55%	0.32%	0.39%

Underrepresented Minorities (URMs): Our stated target is to achieve a 5% increase by October 2013, and 10% increase by October 2015, over the above-stated baseline of national norms for BEACON-specific disciplines. In 2012, BEACON participants are 53% White, 25% Black, 10% Asian, 4% Hispanic/Latino, 1% American Indian, and 7% *two or more races/ethnicities*. Currently 37% of BEACON participants are self-reporting as URMs, an impressive 48% increase over 2011, which was only 16%. This is a result of increases in numbers and better reporting.



	Weighted National Norms	2011	2012
URMs	17.30%	16.20%	30.30%
Females	32.81%	32.90%	32.50%
Ind w/ Disabilities	1.10%	1.40%	2.20%

Women: In an effort to ensure BEACON accurately reflects and compares data on females against the national norms, we weighted the percentages by BEACON-specific disciplines (e.g.; biological sciences, computer sciences, and engineering.

The detailed table below illustrates how we calculated the weighing percentages using the respective formulas.

Categories Tabulating Females	BEACON			National Norms	National Norms
	Total	Females	Average	Unweighted	Weighted
Females Aggregate	**274**	**89**	**32.5%**	**37.5%**	**32.62%**
Biological Sciences	138	65	47.1%	0	
Computer Science	87	19	21.8%	0	
Engineering	49	5	10.2%	0	
Female Undergraduates	**85**	**35**	**41.2%**	**36.6%**	**36.48%**
Biological Sciences	38	23	60.5%	59.0%	
Computer Science	31	11	35.5%	18.2%	
Engineering	16	2	12.5%	18.4%	
Female Graduates	**98**	**30**	**30.6%**	**31.3%**	**32.93%**
Biological Sciences	41	20	48.8%	52.9%	
Computer Science	34	5	14.7%	20.9%	
Engineering	20	3	15.0%	17.4%	
Female Post-Doc	**26**	**7**	**26.9%**	**44.0%**	**43.72%**
Biological Sciences	19	8	42.1%	52.4%	
Computer Science	6	1	16.7%	20.7%	
Engineering (Electrical & Mechanical)	1	0	0.0%	16.9%	
Female Faculty	**68**	**15**	**22.1%**	**35.5%**	**21.68%**
Biological Sciences	40	14	35.0%	35.9%	
Computer Science	16	2	12.5%	1.5%	
Engineering	12	0	0.0%	1.2%	

Weighting of Percentages		
Categories Tabulating Females	**Aggregate National Norms By BEACON-Specific Disciplines**	**Weighted %**
Females Aggregate	**36.47 x (85/274) + 33.95 x (98/274) + 45.69 x (26/274) + 21.68 x (68/274)=**	**32.62%**
Female Undergraduates	**59.0 x (38/85) + 18.2 x (31/85) + 18.4 x (16/85) =**	**36.48%**
Female Graduate Masters	**52.9 x (41/98) + 20.9 x (34/98) + 17.4 x (20/98) =**	**32.93%**
Female Post-Doc	**52.4 x (19/26) + 28.2 x (06/26) + 23.2 x (01/26) =**	**43.72%**
Female Faculty	**35.9 x (40/68) + 01.5 x (16/68) + 01.2 x (12/68) =**	**21.68%**

Overall, BEACON (32.5%) is slightly below the national norms (32.6%) for female participants; below are the details (note: N=total, F=females):

- **Undergraduates** (N=85/F=35) BEACON (41.2%) exceeded the National Norm (36.5%). This was accomplished by the expansion of the summer research programs, and increased opportunities for undergraduates to work in labs and take BEACON-specific courses.

- **Graduates** (N=98/F=30) BEACON (30.6%) was below the National Norm (32.93%). This is an area where BEACON has a great opportunity to make progressive strides in increasing diversity, and will use the following strategies:
  - 1) Internal - recruit current graduate students attending BEACON partner schools; and
  - 2) External - utilize the summer REU programs and graduate recruitment conferences to inclusively recruit female students.

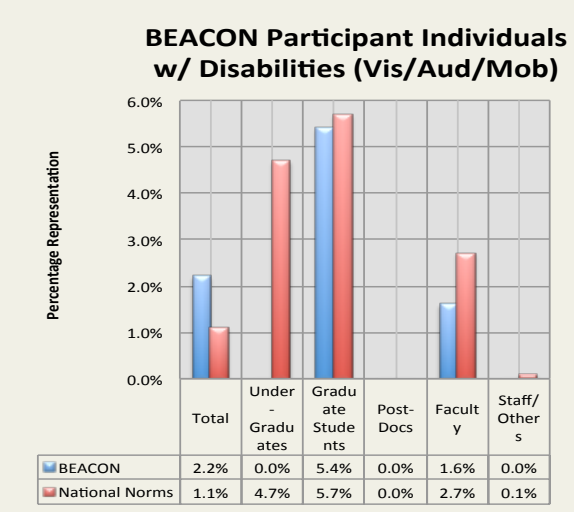
- **Post-Docs** (N=26/F=7) BEACON (26.9%) was well below the National Norm (43.7%). Biological sciences (42.1%) vs. National Norms (52.4%), computer science (16.7%) vs. National Norms (20.7%), and engineering (0%) vs. National Norms (16.9%) are each at lower percentages.
  - Strategy: We will take the following approach: 1) Internal - recruit current Ph.D students from BEACON partner schools, and 2) use the BEACON post-doc

fellowship; and 3) External – create a recruiting pipeline from universities BEACON have established relationship with, and utilize graduate recruitment conferences.

- **Faculty** (N=68/F=15) BEACON (22.1%) exceeded the National Norm (21.7%). While BEACON did well in this category, there are opportunities to increase female faculty in electrical and mechanical engineering.
  - Strategy: We will take the following internal approach: recruit current faculty at BEACON partner schools to collaborate on research, teach classes, submit grants, and/or write publications. Continue to use the BEACON Faculty Affiliate Program to recruit female faculty members.

Individuals with Disabilities: BEACON continues to work hard to provide safe and adaptive environments for individuals with disabilities. Currently 2.2% of our participants self-reported as having a disability, this exceeds the National Norms at 1.1%. This is approximately a 10% increase from 2011.

While we are pleased to report that more individuals are self-reporting, we acknowledge that our participant numbers are still underreported for various reasons. This includes individuals that have verbally disclosed they have a disability, but do not choose to reflect that in their personal profile.



	Total	Under-Graduates	Graduate Students	Post-Docs	Faculty	Staff/Others
BEACON	2.2%	0.0%	5.4%	0.0%	1.6%	0.0%
National Norms	1.1%	4.7%	5.7%	0.0%	2.7%	0.1%

1c. Problems encountered

One continuing challenge is that diversity and inclusion efforts are typically thought to be limited to programming and recruiting. At BEACON we are working hard at changing the culture to promote open communication, knowledge sharing, and innovation by creating a collegial, mutually respectful environment. It allows everyone to bring his or her full faculties to bear in the workplace by fostering a unified culture of acceptance.

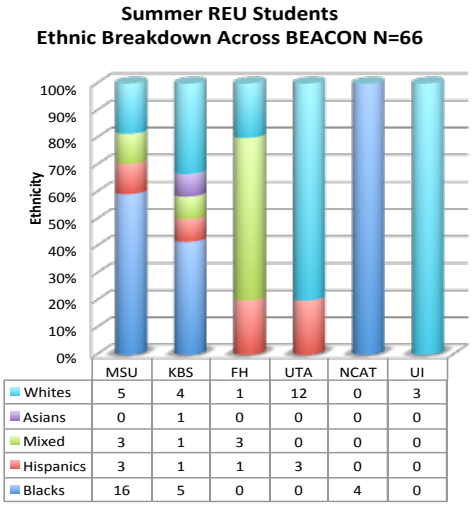
We are addressing this challenge with the following actions:

- Budget requests must address diversity, stating how they enhance it (if applicable).
- Ensure that diversity is represented as a connecting thread through all aspects of BEACON; e.g., representation on website, cultural competency training, accommodating environments, etc.
- Creating welcoming 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

We have many ongoing activities contributing to this goal. BEACON's Research Experience for Undergraduates (REU) Program is a 10-week intensive residential program targeting the recruitment of underrepresented students to conduct research with a faculty mentors.

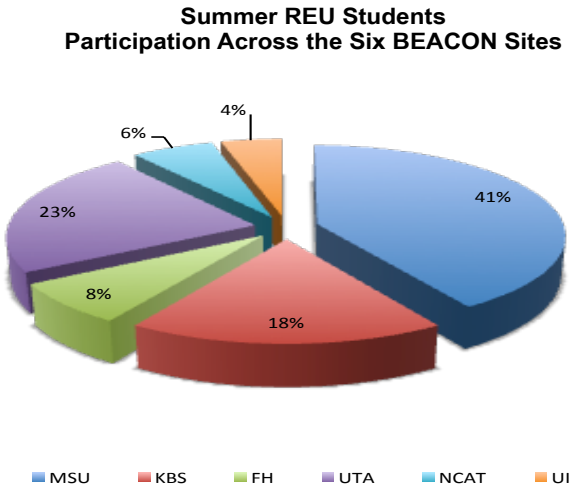
This past summer, we funded 67 students across the BEACON partner schools, at six different sites. This included wet labs, dry labs, computer/simulations, field experiences, and/or a combination. 40 of these students (~60%) were underrepresented minorities.



	MSU	KBS	FH	UTA	NCAT	UI
Whites	5	4	1	12	0	3
Asians	0	1	0	0	0	0
Mixed	3	1	3	0	0	0
Hispanics	3	1	1	3	0	0
Blacks	16	5	0	0	4	0

Additionally BEACON provided culturally competent, formal **mentor training** to graduate students and post-docs mentoring URAs in labs; with on-going weekly training and technical assist to address any challenges.

Evaluation: BEACON partnered with NSF colleagues at I-STEM (University of Illinois) and administered pre-, mid-, and post- surveys to students and mentors, as well as conducted group observations and focus group interviews



- **Respondents**: 55 participants; 31 males, 23 females, 1 androgynous
- **Ethnicity**: 38 Black/African American, 3 White/Caucasian, 6 Hispanic, 1 African-American/Korean, 2 Asian, 1 Black/Native Am., 1 Puerto Rican, 1 Haitian Creole, 1 Mixed, 1 Mexican-American
- **Preliminary Results:** on a 5-point Likert Scale, mean response rates show and overall 3.96 satisfaction rate

Here are some key survey results:

- 78% of students reported very strong to strong results on *I can communicate across disciplines and within my discipline*; this is extremely important for intradisciplinary and multidisciplinary research.
- 76% of students reported very strong to strong results on *I will be more motivated in my courses*; this shows a broader understanding of applied learning
- 92% of students reported very strong to strong results on a positive *overall experience.*

Question	Very Strong	Strong	Neutral/Ave.	Weak	Very weak	Mean	SD
9. Communicate across disciplines	14 25.50%	29 52.70%	11 20.00%	1 1.80%	0 0.00%	4.02	0.733
10. Communicate with my discipline	21 38.20%	22 40.00%	11 20.00%	1 1.80%	0 0.00%	4.15	0.803
23. I plan to pursue a graduate degree	33 60.00%	9 16.40%	9 16.40%	4 7.30%	0 0.00%	4.29	0.994
25. I will be more motivated in my courses	27 50%	14 25.90%	13 24.10%	0 0.00%	0 0.00%	4.26	0.828
26. I am more confident in my discipline-specific knowledge	21 38.20%	24 43.60%	9 16.40%	1 1.80%	0 0.00%	4.18	0.772
30. I have better appreciation of multi-disciplinary research approaches*	23 42.60%	24 44.40%	6 11.10%	1 1.90%	0 0.00%	4.28	0.738
45. I would select my mentor as my mentor for graduate study	18 32.70%	16 29.10%	10 18.20%	6 10.90%	5 9.10%	3.65	1.294
46. I would recommend my mentor for future SROP students	22	20	10	2	1	4.09	0.948
75. Overall Experience	21 38.20%	30 54.50%	4 7.30%	0 0.00%	0 0.00%	4.31	0.605

In an effort to establish **sustainability**, six grants have been submitted to external funders. Success to date: Drs. Eisthen & Lonstein were awarded a NSF REU site for the Integrative Biology of Social Behavior (IBSB); this funding is for three years, supporting 10 neuroscience undergraduates in summer 2013.

BEACON submitted a proposal to NSF for supplemental REU funding called **Luminary Scholars: A BEACON Intensive Undergraduate Research Program**. This is an intensive undergraduate research program that will support approximately ten underrepresented racial/ethnic minority students each year come to BEACON for summer research opportunities then return to their home institutions and continue their undergraduate research for 10 hours per week during the academic year, under the guidance of identified faculty members at the home institutions in collaboration with BEACON faculty in evolutionary science research.

Students can participate in this opportunity for up to two years and then become outstanding candidates for direct admission to a BEACON graduate program, and for BEACON support. A coordinated **Research Opportunity Award** (ROA) proposal is also being prepared to offset the

annual costs of having the faculty members come to MSU to work with BEACON researchers on coordinating the summer and academic year research of the students.

BEACON's Diversity Director Brown Clarke and Education Director Mead are collaborating with Nevada's proposed project entitled *The Solar Energy-Water-Environment Nexus* for NSF's EPSCoR Track 1 Research Infrastructure Improvement (RII) program solicitation, where they will be members of the External Advisory Committee.

BEACON was awarded **NESCent support for a catalysis meeting** entitled ***K-12 Evolution Education to Underserved Minorities***. The meeting will occur this spring 2013 and include experts from across the nation in evolutionary science across different disciplines and levels

BEACON supported numerous **outreach events** that exposed K-12 underrepresented students to evolutionary science/STEM education.

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.

As part of BEACON's annual budget allocation process the following funded projects were specifically aimed to increase diversity in BEACON sciences and in STEM. Also listed are research and education projects that have significant diversity components.

The **BEACON Field Research Experiences for Undergraduates** was designed to provide undergraduates with the opportunity to pursue cross-disciplinary research at the Kellogg Biological Station (KBS) and Friday Harbor Laboratories (FHL). Both sites have strong summer undergraduate research programs involving BEACON faculty and used this as a basis to recruit students to the BEACON programs. Both sites recruited undergraduates to REUs who were given the opportunity to conduct independent research under the mentorship of BEACON faculty or research associates. A goal of this program is to recruit and provide research experiences for students from underrepresented groups; however, at KBS there was only limited success in meeting this goal. Only 14% of the applicant pool was from an underrepresented group, from which 2 of 9 (or 22%) were selected. Only 10% of the applicants to the KBS URA program were minorities, from which 5 of 16 (or 31%) were selected, none for the URA program. The Friday Harbor program is more successful in recruiting students from under-represented groups to their REU program in part because they have a larger and more diverse applicant pool. The evaluation of these programs (still in progress) will focus on two issues: how to recruit a diverse and qualified applicant pool and how to provide truly interdisciplinary research experiences for undergraduates.

To recruit applicants, announcements about this program were posted to on-line job boards and environmental/ecological list-serves. Many of the applicants to this program noted that they had learned of the program from advisors, but online recruitment also played an important role in recruitment: 56% of applicants to the KBS program indicated they learned of the program through online or electronic sources. Forty-one students from 15 institutions applied to the KBS URA program from which a total of 16 students were selected, 3 for BEACON (2 men, 1 woman; 1 African American, 1 Asian, 1 Caucasian). The KBS REU program had 127 applicants from 58 colleges and universities with a range of demographic characteristics (15% minority); nine students were selected for the KBS REU program (22% minority). All of the KBS BEACON REU students were women. The applicant pool to both programs was biased toward

women (60%) and the highest quality/best prepared students to both programs were women and so both the KBS URA and REU programs had over 70% women.

BEACON High School Summer Residential Program advances three of the four BEACON goals for public and K-12 education by building on current successful partnerships between BEACON institutions and K-12 schools. For instance, The KBS K-12/GK-12 program with assistance from a BEACON-funded half-time RA will work closely with curriculum development specialists, BEACON faculty, and K-12 Outreach specialist to develop innovative and creative hands-on BEACON curriculum appropriate for high school summer program participants. BEACON HS Summer Program students will have opportunities to learn about evolution in action. We will use cutting-edge educational research to reveal and remedy fundamental problems with teachers' and students' understanding of evolutionary processes (Anderson et al. 2002). Curriculum development work to make strong connections with the MSP biodiversity strand and formative assessment work will be led by Anderson. Impact on diversity continues to be strong for the BEACON HS Summer Institute drawing 59% women and 41% historically underrepresented participants who are academically strong to the fields of science and computer science.

Enhancing Diversity through Evolution in Action at the Molecular Level: Barry Williams led an MSU summer program for diverse students, recruited from NC A&T, Spelman College, and Notre Dame, which included a 10-week course designed to teach students the basics of evolution, genetics, molecular biology and microbiology. Students develop cutting edge research skills, learn the process of science and concepts in evolution, and will be exposed to scientific undergraduate and graduate student culture. The course incorporates research from the Williams' lab that includes molecular evolution, genetics, molecular biology, and microbiology. The multi-disciplinary approaches are used to address questions in each of three research projects that are central to the mission of BEACON. The first is experimental evolution to examine the adaptive processes that influence evolution of pathogenicity in yeast. The second is determination of the mutational fitness landscapes for yeast proteins. The third is to identify segregating mutations that contribute to population specific yeast adaptations to pathogenicity in human hosts. Because the nature of this work is both bio-medical and evolution in action, Dr. Williams has been quite fortunate in recruiting students that might not otherwise be interested in evolutionary biology. It should be noted that 60% of Dr. Williams' students returned from last years REU experience.

BEACON Day @ NCA&T: Dr. Gerry Dozier (NCAT) will host a BEACON-wide day highlighting 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, originally scheduled for November 5, 2012, has been postponed to Spring 2013 (date to be determined) because of unavailability of some key participants.

Enrich Research Experience for Undergraduate Students from Underrepresented Ethnic Background and/or Living with Disability (Dr. Wenying Shou – UW) 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 select several dozen underrepresented students with strong science and math skills, 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 the fellowship. These students are usually incoming freshmen to UW, which means that they can continue training in interdisciplinary evolution research.

Several BEACON funded research and education projects also reported diversity impacts, summarized in the table below.

Name	Project	Diversity Impact
Laura Crothers (UT)	A Planning Grant for The Relevancy of Evolution to Our Daily Lives: A Museum Exhibit	Three of the six scientists on this project are female.
Erik Goodman (MSU)	Aggregation and Co-evolution of Instructional Units in Digital Organisms to Model Metabolic Gene Clustering in Bacteria	Supports a new PhD student from underrepresented minority. One of the faculty members on this project is also African American, and this project provides him a strong research involvement with BEACON in addition to his leadership regarding graduate students and postdocs as future faculty members.
Rob Pennock	Avida-ED Curriculum Development and Assessment Pilot Study	This project funded two female graduate students.
Gary Lebby	Biologically Inspired Control of Electric Energy Storage Systems	The funding supported underrepresented (ethnic and female) graduate and undergraduate students.
Benjamin Kerr	Can Communication Stabilize Cooperation?	The funding supported underrepresented (ethnic and female) graduate and undergraduate students
Scott Harrison	Coevolution of Genome Sections in Gram-negative Bacteria	Four of the five students who are involved with this project are minorities, and the three investigators for this project are each from different ethnic groups. Three of the five students are female, and two of the five students are male.
Randall Hayes	BEACON Podcast and Teacher Education Course	Podcast guests have included scientists at various stages of their careers, including African American ecologist Danielle Lee and female BEACON members Kay Holekamp, Melissa Kjelvik, Tasneem Pierce, and Liz Schultheis.
Abdollah Homaifar	Design and Implementation of	Two underrepresented Ph.D. students are working on different aspects of this research.

	Assistive Robotic Residence Home	
Randall Hayes	Engaging Educators with Evolution in Action	This curriculum will be pilot tested at NC A&T with undergraduates and possibly with high school students at the newly opened STEM academy, most of which are from underrepresented minorities.
Thomas Getty	Evolution Curriculum for Elementary Classrooms	A female Ph.D student is supported with these funds.
Fred Dyer	Evolution of cognition, communication, and social coordination	Directly support the training of a graduate student from an underrepresented group, and includes participation of MSU Alumna Laura Grabowski, a faculty member in Computer Science at UT Pan American, which will enable us to build a recruiting pipeline for students from that minority-serving institution.
Risto Miikkulainen	Evolution of Cooperation Among Competing Predators	The project includes two female participants, including a co-PI and a PhD student in Computer Science.
Erik Goodman	Evolutionary Algorithms for Enhanced Ultra-Wideband Microwave Imaging of Breast Cancer Tumors	A female African American PhD student in Electrical and Computer Engineering is conducting her research as a part of this team and is now supported by an NSF Graduate Fellowship.
Terence Soule	Evolutionary Games for K-6th	One of the graduate students working on this project is classified as partially disabled by the US Navy.
Luke Harmon	Long-term consequences of evolution in action examined over a phylogeny	As a part of this project, Harmon taught an R course in Santa Barbara, CA. Course participants were diverse, and included nearly 50% of students from minority backgrounds (mainly Hispanic).
Richard Lenski	Mystery of Mysteries	Training of an underrepresented ethnic minority graduate student
Kevin R Theis	Scent marking mammals, their microbial symbionts, and the hologenome theory of evolution	A minority graduate student has a prominent advisory role in developing the Avida model to evaluate the Hologenome concept of evolution.
Jeffrey Conner	The genetic basis of weediness: rapid evolution of flowering time in wild radish	Three minority students, including two women, from HBCUs (NC A&T and Jackson State) spent the summer in Conner's lab doing research projects. All three presented posters on their work at the KBS Summer Research Symposium.
Claus Wilke	Undergraduate Research Education in Computational Biology	The fall class (fall 2012) has three female and one Hispanic male student out of 8 students total; i.e., 50% of the current students are underrepresented

		minorities in computational science. Covert is supervising a new graduate student in the Wilke lab who is an African American female.
Craig McGowan	Why hop? Understanding morphology, mechanics, and natural selection in the evolution of bipedal hopping	The McGowan Lab collaborated with the University of Idaho Native American Student Center HOIST program to provide a research opportunity on this project for a Native American high school student interested in going to collage to study math and science. The student worked in the lab for 6 weeks this summer, helping to process the images from CT scanner.

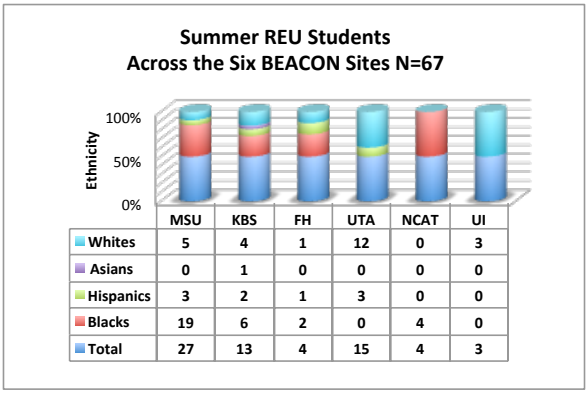
2b. Impact of these activities on enhancing diversity at the center

Overall BEACON has achieved positive results in its two overarching goals to: 1) ensure diversity is represented as an inclusive and connecting thread throughout all aspects of BEACON, and 2) exceed national norms for diversity at all levels in the Center. We are cultivating a climate that values the richness of diversity, and demonstrating our commitment by ensuring inclusive opportunities are not limited to any one person and are sustainable within the infrastructure. We are also beginning to enjoy the fact that (undergraduate and graduate) students and faculty are self-identifying their interest in evolutionary science and are coming to us as a destination Center; this is extremely critical to have a sustainable pipeline of talent for recruitment and inclusion.

2c. Progress towards goals

In an effort not to be redundant on the above-stated information, below are some additional outcomes:

- BEACON's Research Experience for Undergraduates (REU) Program, a 10-week intensive residential program targeting the recruitment of underrepresented students to conduct research with a faculty mentors. This past summer, we funded 67 students (40 were underrepresented minorities) across the BEACON consortium at six different sites.
  - The total cost of programming was $428,860; which reflects the following blended funding model:
    - BEACON funds @ 31.2%; and leveraged funds @ 68.8%. Or, for every $1 of BEACON funding spent we leveraged $3.20 from other sources.



	MSU	KBS	FH	UTA	NCAT	UI
Whites	5	4	1	12	0	3
Asians	0	1	0	0	0	0
Hispanics	3	2	1	3	0	0
Blacks	19	6	2	0	4	0
Total	27	13	4	15	4	3

K-12: The BEACON K-12 Program is a residential summer research program that runs at the MSU Kellogg Biological Station. In 2011, we served 28 students, with 12 or 43% underrepresented minorities and 17 or 61% females. In 2012, there were 32 students, with 13 or 40% underrepresented minorities and 19 or 59% females. Collectively we have provided a rich in-depth experience in evolutionary science to 60 rising 11th and 12th grade high school students, with 42% underrepresented minorities and 60% females.

Undergraduates: BEACON (41.2%) exceeded the National Norm (36.5%) for females. We found that many underrepresented students were underprepared for the summer REU experience and created a two-tiered program by combining REUs for students with strong lab/research backgrounds with URA (Undergraduate Research Apprenticeships) for student with little to no lab/research background. Using the application process, we were able to categorize students and place them into labs with appropriate nurturing faculty/graduate student mentors. This required considerable effort to identify faculty willing to mentor at this high interactive level.

Graduates: BEACON provided ongoing formal mentoring training for all graduate students and post-docs in direct contact with the REU students.

Post-Docs: BEACON provided ongoing formal mentoring training for all graduate students and post-docs in direct contact with the REU students.

Faculty: BEACON awarded its first Faculty Affiliate fellowship to Dr. Adriana Briscoe from University of California Irvine. She was awarded a mini-grant of up to $100,000 over a two-year period to conduct research and explore the possibility of becoming permanent member of BEACON. The grant has a two-year overlapping funding cycles, therefore after this initial year we will have two active Faculty Affiliates each subsequent year.

Faculty: In an effort to secure external funding for REUs, Drs. Eisthen & Lonstein were awarded a NSF REU site for the Integrative Biology of Social Behavior (IBSB); this funding is for three years, supporting ten (10) underrepresented neuroscience undergraduates in summer 2013-2016.

Collaborative Partners:

- We are hiring an evaluator to formally assess the summer research programs. Our evaluator is Ayesha Boyce, a Ph.D. student at University of Illinois, who 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. Our overall results captured that 78% of students reported “very strong” to “strong” results on I can communicate across disciplines and within my discipline; this is extremely important for intradisciplinary and multidisciplinary research; 76% of students reported “very strong” to “strong” results on I will be more motivated in my courses; this shows a broader understanding of applied learning; and 92% of students reported “very strong” to “strong” results on a positive overall experience.
- BEACON initiated a conference call for the diversity and education directors in all the NSF STCs. This has become a bi-monthly event and opportunity for problem solving and sharing of best/promising practices among colleagues. Diversity Director Brown Clarke shared the lead on established the agenda and secured funding for a full day, pre-meeting prior to the annual NSF Directors Meeting in August. At this meeting, we collaborate and shared ideas around strategies on the renewal process, summer research programs,

publishing, engaging the public in STC research, establishing your legacy, and formal faculty mentoring.

- BEACON's Diversity Director Brown Clarke and Education Director Mead are collaborating with Nevada's proposed project entitled The Solar Energy-Water-Environment Nexus for NSF's EPSCoR Track 1 Research Infrastructure Improvement (RII) program solicitation, where they will be members of the External Advisory Committee.
- BEACON was awarded NESCent support for a catalysis meeting entitled K-12 Evolution Education to Underserved Minorities. The meeting will occur this spring 2013 and include experts from across the nation in evolutionary science across different disciplines and levels.

2d. Plans for the next reporting period

- BEACON will target is efforts to increase female participation; specifically, we will focus on graduate students, post-docs, and faculty in computer science, electrical engineering, and mechanical engineering. Strategies have been outlined in *Section:1b. Performance and Management Indicators.*
- BEACON will partner with I-STEM to administer a diversity climate survey to all participants across the partner schools to capture opinions on how we are doing.
- BEACON will sustain its baseline diversity efforts, with the intention of exceeding National Norms in all participant categories and disciplines.
- BEACON will continue to leverage funding and secure grants to support diversity efforts and research opportunities for URMs.

VII. MANAGEMENT

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

There are no changes to the Center's overall organizational strategy and rationale since the last reporting period. There have been a few minor changes to personnel, and our project selection process has been refined.

Personnel changes. One of our two thrust group leaders for the Genomes, Networks & Evolvability group, Thomas Schmidt, is moving to a new position at University of Michigan in January 2013, and Kalyanmoy Deb will replace him as thrust group co-leader. The Diversity Coordinator for UI, Mark Edwards, has left for another university; we will soon identify an appropriate faculty member to replace him in his BEACON role. Dr. Julie Libarkin, head of MSU's Geocognition Research Laboratory, is now the lead for evaluating BEACON's education and outreach projects. Our updated Organizational Chart (Appendix B) reflects these minor changes.

Project Selection 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). Each research project is 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 9 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

This process was successfully implemented across all 5 BEACON member institutions in BEACON’s “Project Year 2” (projects beginning summer/fall 2011 and ending spring/summer 2012). For the selection process for Project Year 3, we implemented a ninth criterion, Budget Appropriateness:

Projects will be evaluated for whether the requested budget is appropriate for the scope of the work planned and appropriate for BEACON’s seed funding model. Large costs will need to have a strong justification, as will faculty salaries. In general, higher priority is placed on funding for students and postdocs than on faculty salaries. However, including faculty salary in the budget is not prohibited. When it can be justified (e.g., an education project that requires significant

summer effort from a faculty member, or a research project at an institution with heavy teaching loads), this cost is not prohibited from being included in the budget.

Additionally, for the Year 3 selection process, all education and outreach projects were required to include an evaluation plan, and assistance in preparing such a plan was provided.

The Executive Committee identified some further necessary refinements that will be implemented in the Year 4 project selection process, the most important of which relates to length of funding period. Previously, all BEACON projects were funded for one year, and could apply for renewal for a second year. However, this limitation created uncertainty with regard to graduate student funding, especially at institutions/departments that do not typically provide teaching assistantships to grad students. In Year 4, applicants will now be able to apply for one year or two years of funding. Two-year projects will require additional justification for the extended length of the project.

Year 3 projects, as well as the completed projects from "Project Years 1 and 2," are described in Section II. Application instructions for the fourth round of requests have been distributed to all BEACON members and the requests will be evaluated beginning January 10, 2013.

The only other major change is that the BEACON Student/Postdoc Association is now fully functional. The group uses the main BEACON student and postdoc email lists for their communication needs, so that they are able to reach all of the students and postdocs that participate in or are affiliated with BEACON. They also maintain a Facebook group that currently has 83 members. At MSU, the group is led by Luis Zaman, Caroline Turner, and Emily Weigel. The partner universities have the following liaisons: Daniel Opoku (NC A&T), Matt Pennell (UI), Art Covert (UT), and Carrie Glenney (UW). The group holds monthly meetings at MSU and organizes activities such as lab visits, data science seminars, and other professional development activities, which are be described in greater detail in the Education section of the annual report. In addition to these lunch seminars, the group also negotiated "mini-sabbaticals" for members. These include a limited amount of funding for a student/postdoc to travel to a partner institution and visit outside the scope of other funding opportunities provided by BEACON. While no one has opted to use one yet, several individuals have shown interest but couldn't find the time during the summer to go. We anticipate that at least one or two individuals will take advantage of this opportunity in the next year. The group also organized a student/postdoc retreat day as part of the BEACON Congress that included presentations on communicating science to the public and how to get grants. The evening ended with a picnic at a local park that brought together students and other researchers from all partner universities. Overall, more than 100 individuals signed up to attend this retreat.

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.

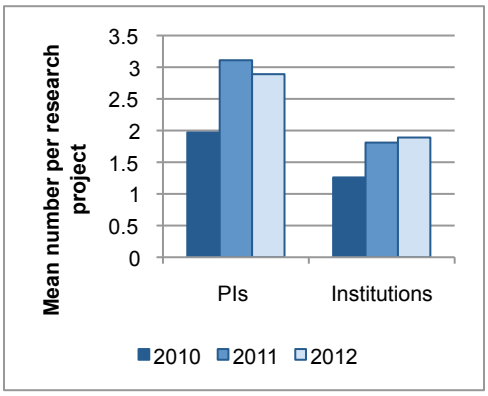
Management Goals		
GOAL	**METRICS**	**PROGRESS**
Increase in cross-disciplinary research and education	Number of paper/conference submissions by BEACON authors	The number of cross-disciplinary submissions (using a strict definition) increased 125% from last reporting period
	Number of new courses	One new course offered at MSU in Fall 2011
	Number of students enrolled in cross-disciplinary courses	Fall 2011: 32; Spring 2012: 19
	Number of funding proposals submitted	Number of cross-disciplinary grants submitted since last reporting period is the same as the previous period.
Increase in cross-institutional research and education	Number of paper/conference submissions	Increase of 150% since last reporting period.
	Number of new courses	One new course offered at MSU in Fall 2011
	Number of students in cross-institutional courses	Fall 2011: 23; Spring 2012: 19
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	52 external grant proposals submitted in this funding period; 5 can be considered cross-disciplinary and/or cross-institutional by a strict definition
	Award dollars	BEACONites have been awarded over $10.6M in this funding period, exceeding goal of $5M/year
Increase in new participants	Number of faculty, post-docs, and students	Since baseline (Nov 2010): No change in faculty; postdocs increased from 21 to 28 (33% increase); grad students increased from 86 to 98 (14% increase). At Affiliate level, much larger increases.
Effective support of Center operations by Management team	Survey for participants about management team	Year 2 evaluation was positive but revealed areas for improvement, which we are addressing
	Feedback from External Advisory Committee	Feedback is very positive (Appendix C)

Center is perceived by NSF as exemplary	Renewal of NSF funding	Renewal was approved for our third funding increment, and we have received positive feedback from NSF
	Number of public mentions made by NSF about BEACON	7 mentions of BEACON on nsf.gov during this reporting period; BEACON also selected as one of the NSF projects represented in US Science and Engineering Festival

Using a very strict definition of cross-disciplinary and cross-institutional paper, conference, and proposal submissions – that is, including authors with academic affiliations in different broad fields [defined as biology, computer science, and engineering] and at least two of the five participating BEACON institutions – results in rather low raw numbers.

Cross-disciplinary paper/conference submissions: 18
Cross-institutional paper/conference submissions: 5
Cross-disciplinary grant proposals: 5
Cross-institutional grant proposals: 2

However, this metric is misleading because 1) many BEACON faculty members are themselves truly multidisciplinary, and though the publication may be on the surface a collaboration between two members of the same department, the work itself may be multidisciplinary (for example, BEACON's Prof. Adami is a physicist appointed in Microbiology and Molecular Genetics); and 2) many researchers collaborate with faculty from non-BEACON institutions, and are publishing inter-institutional work that does not fit our definition.



The competitive internal funding process at BEACON rewards interdisciplinary and inter-institutional collaboration, and has resulted in a significant increase in such collaboration (between 2010 and 2011, one-way ANOVA, $p<0.001$). Of the 41 research, education, and diversity projects funded in Project Year 3, 51% are cross-disciplinary, 63% are cross-institutional, and 41% are both cross-disciplinary and cross-institutional. We anticipate that these newer collaborations will lead to a spike in number of cross-disciplinary and cross-institutional paper, conference, and proposal submissions.

BEACON Organizational Formative Evaluation Report. Drs. Patricia Farrell and Marilyn Amey are conducting an on-going process of data collection focused on factors affecting the organizational development of five institutions into an inter-institutional, interdisciplinary collaboration.

In year one, they began by evaluating the effect that organizational efforts (e.g., leadership, communication processes, educational efforts) have on the BEACON Center, and the factors involved. They developed a 56-item survey with both closed and open-ended questions based on the Center's strategic plan, literature on organizational change and interdisciplinary research, and research on cross-institutional STEM projects. The target population for the baseline survey included all active participants—principal investigators, faculty, post docs, students, and staff. Response rates for this and all other data collection efforts are represented in Table 1. In spring, 2011 they held focus groups with BEACON graduate students and interviews with post-doctoral fellows to capture participants' perceptions about the Center as a whole, as well as understand their experiences with communication, collaboration, support, and professional training within BEACON. These two groups of participants were selected based on the desire to understand the wide variation in responses on the first-year organizational survey.

In year two, Farrell and Amey surveyed three key groups who represent the future of BEACON – assistant professors, post docs, and doctoral students - to determine topics of most interest/concern to them. The five most commonly cited issues became the focus of five mini-surveys sent once per month beginning in January, 2012. The five mini-surveys focused on (1) BEACON & Department/College Support & Funding, (2) BEACON Inter-disciplinary & Cross-institutional Work, (3) BEACON Outreach & Education, (4) BEACON Career & Professional Development/Mentoring, and (5) BEACON Research Thrusts. Findings from the year-one survey highlighted the department chair as a key individual or gatekeeper who influences whether or not faculty and students are committed to and actively involved in BEACON. Because of this, they also conducted interviews with chairs of departments/colleges involved with BEACON across the five participating institutions. The chairs chosen to participate represented faculty from the science and engineering disciplines, and at least two chairs were chosen from each institution, based on number of individuals involved in BEACON.

For each of the data collection methods, descriptive statistics (where applicable), including crosstabs, were used to understand the data and identify patterns both by institution and by group (e.g., faculty, post docs, etc.). To identify emergent themes, open-ended survey responses were analyzed using open coding by each researcher independently. The research team then engaged in discussion to determine key topical areas. Individual and focus group interviews were audio-recorded, and parts were transcribed verbatim. The same approach to data reduction and coding verification among research team members was followed.

The 2012 Organizational Formative Evaluation Report (October, 2012) made several recommendations for improvement:

- Increase departments' and institutions' perceived value of faculty participation in BEACON
- Create a strategic communications plan and education materials to promote BEACON to upper administration, and fellow faculty members, post docs, and students within and outside the institution
- Create a learning organization within BEACON to teach participants about the five institutions, departments and disciplines involved.
- Help researchers figure out how their work can have an impact on society—e.g., magazine articles, education materials, patents, editorials.
- Maximize opportunities for people to meet and interact in meaningful ways.

- Focus on creating and sustaining a culture of interaction that ensures that faculty members understand their role as advisors/mentors in introducing post docs and graduate students to colleagues.
- Assistant professors suggested providing information about the budget request process earlier and providing more feedback on the requests.
- Create a knowledge management system/share tools that can aid participants and individuals inside and outside academia, which can also be used to market participants and their work.
- Help advisors and mentors understand their role in facilitating connections between students/post-docs and other faculty members and encourage them to be active in this.
- Create webinars, brochures, workshops, etc., to educate laypeople on evolution in action.

Nearly all of these recommendations are items that BEACON management was either already planning to implement, or was aware that a need likely existed—these results are strong evidence that the planned directions align well with the perceived needs of BEACON's members and the leadership at the partner universities. Over the next year, we will be working to address these recommendations in many ways:

- creating a BEACON video and other promotional materials to explain our research and activities to the public, as well as to departmental and institutional leadership
- renewing our relationship with the Toolbox team to create new interdisciplinary communication and learning workshops
- adding more structured opportunities for networking and collaboration at the BEACON Congress
- creating more professional development training opportunities
- improving the budget request process
- upgrading our intranet system to allow it to function as a "knowledge management system"

1d. Problems encountered

Our primary challenges 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.

Communicating online and via video. Our external and internal website is used extensively by BEACON's participants and affiliates and is a great source of information about people and ongoing activities. Our email lists are also heavily used to distribute information. We have upgraded our videoconferencing technology so that we now have very few technical difficulties during our weekly BEACON seminar, our BEACON classes, and other long-distance collaborative activities.

Need for increased face-to-face interaction. Despite progress in long-distance communication technology, our participants continue to express the feeling that the best way to communicate and create a sense of community is with face-to-face interaction. We provide travel funding for members to visit participating institutions for collaborative work. Our primary face-to-face event is the BEACON Congress, where members from all five institutions come together

to present results from research and education activities and to brainstorm around research problems. By popular demand, at the 2012 Congress we held a Student/Postdoc Retreat day at the beginning of Congress. This day included a session on communicating science to the public (led by Danielle Whittaker), a session on grant writing (led by George Gilchrist, NSF), an interactive "elevator speech" session, a collaborative blog-writing session, and a student/postdoc picnic. This event went a long way towards helping make students and postdocs feel more integrated with the Center, but we are planning additional changes for the 2013 Congress. In 2012, the Congress was two full days (in addition to the student/postdoc retreat day); in 2013, we will add a third full day. We will also create more structured opportunities for students and postdocs to network with faculty members.

Time limit on budget requests. As noted above, the one-year limit on BEACON project funding was creating problems for graduate students, so we have changed the limit on requests to a maximum of two years.

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. Since the last reporting period, we have begun updating the site to improve functionality and user experience. These changes are still in progress, but we anticipate completing the upgrade by summer 2013. The infrastructure for the site is being replaced to enable new functionality, but the user interface is being maintained as stable as possible.

Central website. Our website is located at www.beacon-center.org. The front page of this website is in a blog format. We have featured weekly blog posts by BEACON students, postdocs, and faculty describing their research at a level accessible to the scientific public every Monday morning since April 4, 2011. The original blog theme was "BEACON Researchers at Work," in which students and postdocs describe their research questions and approach, and include a photo to introduce" themselves to the public. This theme is still ongoing, but the Student/Postdoc association suggested a second theme, "Evolution 101," which is now underway. In this theme, students and postdocs write posts explaining basic concepts in evolution, including Epistasis, Fitness Landscapes, Maternal Effects, Kin Selection, Synthetic Biology, and many more. The managing director solicits, schedules, and edits these posts. In addition, we also post news stories about BEACON research and education activities 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 (188 "likes" as of 10/11/12) and Twitter (192 followers as of 10/11/12). 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 2-3 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). Presenters are 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), and some MSU members attend from Kellogg Biological Station. 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. For smaller and informal meetings across campuses we are using either Skype or a combination of Adobe 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 second meeting of BEACON's External Advisory Board was held October 8, 2012, at Michigan State University. The summary report from that meeting is in Appendix C.

4. Changes to the Center's strategic plan

The goals and optimal outcomes remain the same, but in some cases the action items taken in the past year have been somewhat different than what was originally outlined in the strategic plan. In particular, there are changes to the Knowledge Transfer section of the plan (see IV. Knowledge Transfer for a discussion). We have updated the strategic plan to reflect progress already made, and to realign targets and action items with the directions we have been taking.

VIII. Center-Wide Outputs and Issues

1a. Center publications

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116. Ravel JM, Gajer PM, Abdo Z, Schneider GM, Koenig SM, McCulle SM, Karlebach SM, Gorle RM, Russell JM, Tacket CM, Brotman RM, Davis CM, Ault KM, Peralta L, Forney L (2012). Vaginal microbiome of reproductive-age women. *Proc. Natl. Acad. Sci. (USA)* 108: 4680 - 4687.
117. Rawal A, Holekamp KE, Miikkulainen R, Rajagopalan P (2012). Evolution of a Communication Code in Cooperative Tasks. *Artificial Life (13th International Conference on the Synthesis and Simulation of Living Systems)*.
118. Rawal A, Rajagopalan P, Holekamp KE, Kerr B, Miikkulainen R (2012). The Role of Reward Structure, Coordination Mechanism, and Net Return in the Evolution of Cooperation. *Proceedings of the 2011 IEEE Conference on Computational Intelligence and Games.*
119. Reba A, Meyer AG, Barrick JE (2012). Computational tests of a thermal cycling strategy to isolate more complex functional nucleic acid motifs from random sequence pools by in vitro selection. *ALife 13*.
120. Ribeck N, Lenski R (2012). Quantifying frequency-dependent fitness effects in evolving microbial populations. *ALife13*.
121. Rohrbacher C (Submitted). Evolving: Using science fiction to engage students in evolutionary theory. *Evos: The Journal of the Evolutionary Studies Consortium*.
122. Rose MR, Flatt T, Graves JL, Greer LF, Martinez D, Matos M, Mueller LD, Shmookler-Reis RJ, Shahrestani P (2012). What is aging? *Frontiers in Genetics* 3: 134.
123. Rosenblum B, Harmon L, Sarver BA, Brown JW, DesRoches S, Hardwick K, Hether T, Eastman J, Pennell M (In press). Goldilocks meets Santa Rosalia: an ephemeral speciation model explains patterns of diversification across time scales. *Evolutionary Biology.*
124. Rosvall KA, Reichard DG, Ferguson SM, Whittaker DJ, Ketterson ED (2012). Robust behavioral effects of song playback in the absence of testosterone or corticosterone release. *Hormones and Behavior* 62: 418 - 415.
125. Ryerkerk M, Averill R, Deb K, Goodman ED (2012). Optimization for Variable-Size Problems Using Genetic Algorithms. *14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*.
126. Ryerkerk M, Averill RC, Deb K, Goodman ED (2012). Meaningful Representation and Recombination of Variable Length Genomes. *2012 Genetic & Evolutionary Computation Conference (GECCO 2012)*.
127. Safadi RA, Eaton KA, Waters CM, Rudrik JT, Sloup RE, Abu-Ali GS, Manning SD (2012). Correlation between in vivo biofilm formation and virulence gene expression in *Escherichia coli* O104:H4. *PLOS One* 7: 7 e41628.
128. Sambanthamoorthy K, Sloup RE, Parashar V, Smith JM, Kim EE, Semmelhack MF, Neiditch MB, Waters CM (In Press). Identification of Small Molecules that Antagonize Diguanylate Enzymes to Inhibit Biofilm Formation. *Antimicrobial Agents and Chemotherapy.*
129. Schrum J, Karpov IV, Miikkulainen R (2012). Humanlike Combat Behavior via Multiobjective Neuroevolution. In: *Believable Bots*.
130. Schrum J, Miikkulainen R (2012). Evolving Multimodal Networks for Multitask Games. *Transactions on Computational Intelligence and AI in Games* 4: 94 - 111.

131. Sen D, Abdo Z, Brown CJ, Sullivan J (In Press). Inferring the evolutionary history of IncP-1 plasmids despite incongruence among backbone gene trees. *Mol. Biol. Evol.*
132. Smith JE, Swanson E, Reed D, Holekamp KE (in press). Evolution of cooperation among mammalian carnivores and its relevance to hominins. *Current Anthropology.*
133. Solomon M, Heckendorn R, Soule T (2012). A Comparison of Communication Strategies in Cooperative Learning. *Genetic and Evolutionary Computation Conference 2012*.
134. Songwei Z, Haigen H, Xu L, Guanghui L (2012). Nonlinear Adaptive PID Control for Greenhouse Environment Based on RBF Network. *Sensors* 12: 5328 - 5348.
135. Soule T, Heckendorn R (2012). A Practical Platform for On-line Genetic Programming for Robotics. In: *Workshop on Genetic Programming Theory and Practice*.
136. Srivastava D, Waters CM (In Press). A Tangled Web: Regulatory Connections Between Quorum Sensing and Cyclic di-GMP. *Journal of Bacteriology.*
137. Swanson E, Holekamp KE, Lundrigan B, Arsznov B, Sakai ST (in press). Multiple determinants of brain size and brain architecture in mammalian carnivores. *PLoS One.*
138. Tansey W, Feasley E, Miikkulainen R (2012). Accelerating Evolution via Egalitarian Social Learning. *The 14th Annual Genetic and Evolutionary Computation Conference (GECCO 2012).*
139. Valsalam VK, Hiller J, MacCurdy R, Lipson H, Miikkulainen R (In Press). Constructing Controllers for Physical Multilegged Robots using the ENSO Neuroevolution Approach. *Evolutionary Intelligence*.
140. Van Meter PhD PE, Holekamp KE, Swanson E (Submitted). Developmental constraints on behavioral flexibility. *Philosophical Transactions of the Royal Society*.
141. Villalobos C (2012). Impacts of ocean acidification on the sand dollar, Dendraster excentircus fertilization success and early development. *SACNAS*.
142. Waite A, Shou W (In Press). Adaptation to a new environment allows cooperators to stochastically purge cheaters. *Proceedings of the National Academy of Sciences USA*.
143. Walker A (Submitted). STEAM and literary Darwinism in a first year undergraduate seminar classroom. *Evos: The Journal of the Evolutionary Studies Consortium*.
144. Walker B, Ofria C (2012). Evolutionary Potential is Maximized at Intermediate Diversity Levels. *13th International Conference for Artificial Life*.
145. Wang J, Chen S, Tan X (2012). Control-oriented averaging of tail-actuated robotic fish dynamics. *2013 American Control Conference*.
146. Wang J, McKinley P, Tan X (2012). Dynamic modeling of robotic fish with a flexible caudal fin. *The 2012 ASME Dynamic Systems and Control Conference.*
147. Wanko P, Stanfield PM (2012). Adaptive Metaheuristics with Schooling Genetic Algorithms. *Industrial and Systems Engineering Research Conference*.
148. Waters C (In Press). Hfq-dependent co-ordinate control of cyclic diguanylate synthesis and catabolism in the palque pathogen Yersinia pestis. *Molecular Microbiology*.
149. Whittaker DJ, Gerlach NM, Soini HA, Novotny MV, Ketterson ED (Submitted). Bird odour predicts reproductive success. *Proceedings of the Royal Society B.*
150. Whittaker DJ, Ketterson ED, Atwell JW, Cardoso GC, Price TD (submitted). Testosterone mediates successful establishment of a songbird population in a novel environment. *Proceedings of the Royal Society B.*
151. Whittaker DJ, Ketterson ED, Atwell JW, Cardoso GC, Robertson KW, Campbell-Nelson SJ (2012). Boldness and stress physiology in a novel urban environment suggest rapid evolutionary adaptation. *Behavioral Ecology* 23: 960 - 969.

152. Whittaker DJ, Ketterson ED, Atwell JW, Peterson MP, Dapper AL (2012). Maintenance of MHC Class IIB diversity in a recently established songbird population. *Journal of Avian Biology* 43: 109 - 118.
153. Workineh A, Dugda MT, Homaifar Dr. A, Lebby G (2012). GMDH and RBFGRNN Networks for Multi-Class Data Classification. *The 14th International Conference on Artificial Intelligence*.
154. Workineh A, Homaifar A (Submitted). Evolving Hierarchical Cooperation in Classifiers via Fitness Proportionate Niching. *IEEE Transactions on Evolutionary Computation.*
155. Workineh A, Homaifar Dr. A (2012). A New Bidding Strategy in LCS using a Decentralized Loaning and Bid History. *IEEE Aerospace Conference*.
156. Workineh A, Homaifar Dr. A (2012). Fitness Proportionate Niching: A Different Perspective on Co-evolution of Diverse Population. *ALife13*.
157. Workineh A, Homaifar Dr. A (2012). Fitness Proportionate Reward Sharing: a Viable Default Hierarchy Formation Strategy in LCS. *International Conference on Genetic and Evolutionary Methods (GEM'12)*.
158. Xu Y, Xu L, Li D, Wu Y (2012). Pedestrian Detection Using Background Subtraction Assisted Support Vector Machine. *11th International Conference on Intelligent Systems Design and Applications (ISDA)*.
159. Yano H, Deckert GE, Rogers LM, Top E (2012). Roles of long and short replication initiation proteins in the fate of IncP-1 plasmids. J. Bacteriol. 194 1533 - 1543
160. Yedid G, Stredwick J, Ofria C, Agapow P (2012). Selective Mass Extinctions on Erosion of Evolutionary History in Communities of Digital Organisms. *PLoS ONE* 7: e37233.
161. Zaman L, Ofria C, Lenski R (2012). Finger-painting Fitness Landscapes: An Interactive Tool for Exploring Complex Evolutionary Dynamics. *13th International Conference for Artificial Life*.
162. Zaman L, Wagner A. Evolving digital ecological networks. *PLOS Computational Biology.*

1b. Conference presentations

1. Adami C (2012). Biosignatures for Alien Life Detection. Gordon Conference on Origin of Life, Galveston, TX, 1/12/2012. (Invited talk)
2. Adami C (2012). Evolutionary Game Theory: A Tutorial. Artificial Life 13, Michigan State University, 7/19/2012. (Invited talk)
3. Adami C (2012). Evolutionary robotics for space missions. International Forum on the Game of Nature, Zhenzhou, China, 11/28/2011. (Invited talk)
4. Adami C (2012). Information is fitness: A guiding principle for evolution. Tufts University Workshop on Complex System Evolution, Tufts University, Boston, MA, 6/11/2012. (Invited talk)
5. Adami C; Marstaller L; Hintze A (2012). Discovering Concepts and Representation in Evolved Brains. Allen Foundation Principal Investigators Meeting, Madison, WI, 6/27/2012. (Invited talk)
6. Anderson C (2012). Ecological and mutation-order speciation in digital organisms. BEACON Congress, East Lansing, MI, 7/16/12 - 7/19/12

7. Anderson C (2012). Ecological and mutation-order speciation in digital organisms. Evolution, Ottawa, Canada, 7/6/12 - 7/10/12
8. Anderson C (2012). The role of standing genetic variation in adaptation of digital organisms to a new environment. Artificial Life 13, East Lansing, MI, 7/19/12 - 7/22/12
9. Blount Z (2012). Making the New from the Old: The Evolution of a Novel Trait in a Experimental Population of E. coli. Think Evolution IV: A Summer Institute for Science Educators, Berkeley, California, July 30, 2012 - August 3, 2012. (Invited talk)
10. Blount Z; Lenski R (2012). Evidence of Niche-Specific Adaptive Mutation Accumulation in a Novel Ecotype in an Experimental Population of *E. coli* Following the Evolution of a Key Adaptation. 112th General Meeting of the American Society for Microbiology, San Francisco, CA, USA, June 16, 2012 - June 19, 2012.
11. Blount Z; Lenski R (2012). Evidence of Speciation in an Experimental Population of E. coli Following the Evolution of a Key Adaptation. ALife 13, East Lansing, MI, USA, July 19, 2012 - July 22, 2012.
12. Blount Z; Lenski R (2012). Evidence of Speciation in an Experimental Population of E. coli Following the Evolution of a Key Adaptation. First Joint Congress on Evolutionary Biology, Ottawa, Ontario, Canada, July 6, 2012 - July 10, 2012
13. Briscoe A (2012). The role of natural selection in shaping the color vision systems of mimetic butterflies. BVI Young Vision Researchers' Colloquium, Bristol, U.K. 07/29/12 - 07/29/12. (Invited talk)
14. Bryson DM (2012). Digital Evolution Surprisingly Robust to Poor Design Decisions. Artificial Life 13, East Lansing, MI, 7/19/2012 - 7/22/2012. (Invited talk)
15. Chandler CH; Ofria C; Dworkin I (2012). Runaway sexual selection leads to good genes. 1st Joint Congress on Evolutionary Biology, Ottawa, Ontario, Canada, July 6th - July 10th
16. Chandler J (2012). Acyl-homoserine lactone quorum sensing and interspecies competition. American Society for Microbiology General Meeting, San Francisco, CA. (Invited talk)
17. Chandler J (2012). The role of cell-density-dependent exopolysaccharide production in rugose colonies of Burkholderia thailandensis. ASM Biofilm Meeting, Miami, FL.
18. Chari SR; Dworkin I (2012). Distinct evolutionary trajectories via compensatory evolution in developmentally perturbed populations: A tale of 4 mutations & 44 populations. 1st Joint Congress on Evolutionary Biology, Ottawa, Ontario, Canada, July 6th - July 10th
19. Chari SR; Dworkin I (2012). Probing Developmental Networks via Compensatory Evolution. 53rd Annual Drosophila Research Conference, Chicago, March 7th - March 11th
20. Conner J; Charbonneau A; Dworkin I (2012). Evolution of an agricultural weed from native Mediterranean ancestors: adaptive loss of vernalization and rosette leaves in wild radish. 1st Joint Congress on Evolutionary Biology, Ottawa, Ontario, Canada, July 6th - July 10th
21. Cooper IA; Getty T (2012). Rapid color evolution in Hawaiian Megalagrion damselflies. Evolution, Ottawa, Canada, July 6, 2012 - July 10, 2012
22. Cooper IA; Getty T (2012). Recent range shifts and the role of sexual signals in premating isolation of sympatric Calopteryx damselflies. Long Term Ecological Research All-Scientist Meeting, Estes Park, CO, September 10, 2012 - September 13, 2012

23. Covert AW; Carlson-Stevermer J; Wilke C (2012). The Effects of Deleterious Mutations on Local Adaptation. Evolution 2012, Ottawa.
24. David B Knoester (2012). Constructing Communication Networks with Evolved Digital Organisms. IEEE Conference on Self-Adaptive and Self-Organizing Systems, Lyon, France, 9/10/2012 - 9/14/2012
25. DeNieu M; Dworkin I (2012). Evolution of antipredator traits in response to a novel predator. 1st Joint Congress on Evolutionary Biology, Ottawa, Ontario, Canada, July 6th - July 10th
26. DeNieu M; Dworkin I (2012). Evolution of morphology and behavior in Drosophila melanogaster in response to predation. 53rd Annual Drosophila Research Conference, Chicago, March 7th - March 11th
27. Glenney C (2012). Evolving Novelty Through Promiscuity. How Bugs Kill Bugs, Nottingham, UK, July 2012.
28. Goodman ED (2012). Tutorial Introduction to Genetic Algorithms. 13th Conference on Artificial Life (ALife13), Kellogg Center, MSU, 7/13/2012 - 7/13/2012. (Invited talk)
29. Greenberg EP (2012). Quorum sensing and cooperation in bacteria. APCChE 2012, Singapore, 02/24/2012 - 02/25/2012. (Invited talk, Plenary)
30. Greenberg EP (2012). Quorum sensing and cooperation in bacteria. ASM Natl Mtg, San Francisco, 06/18/2012. (Invited talk)
31. Greenberg EP (2012). Quorum sensing and social activity in bacteria. Institute of Medicine Workshop, Washington DC, 03/06/2012 - 03/08/2012. (Invited talk, Plenary)
32. Greenberg EP (2012). Quorum sensing and social activity in Pseudomonas. A-Star Singapore, 09/18/2012. (Invited talk)
33. Gupta A; Adami C (2012). Understanding HIV quasispecies evolution using next-generation sequencing. BEACON Congress 2012, MSU.
34. Gutmann AK; McGowan C (2012). Collision dynamics of bipedal hopping. Society for Integrative & Comparative Biology, San Francisco, CA, USA, Jan. 3, 2013 - Jan. 7, 2013
35. Gutmann AK; McKinley P; McGowan C (2012). A detailed musculoskeletal model for studying the evolution of bipedal hopping. BEACON Congress, East Lansing, MI, USA, July 17, 2012 - July 19, 2012
36. Hayes R (2012). Preview of ALife 13. Contact: Cultures of the Imagination, Mountain View, CA, 3/30/2012 - 4/1/2012
37. Hohenlohe P (2012). Population genomics and the rapid evolution of complex phenotypes. The Future of Evo-Devo, Portland, OR, 2/11/2012 - 2/11/2012. (Invited talk)
38. Hohenlohe P (2012). RAD sequencing for SNP discovery and genotyping in natural populations. The Wildlife Society annual meeting, Portland, OR, 10/14/2012 - 10/14/2012. (Invited talk)
39. Holekamp KE; Swanson E (2012). Hyena sociality and behavior: flexibility & constraints. 8th Gottinger Freilandtage, University of Gottingen, Gottingen, Germany, 6 Dec, 2011 - 9 Dec 2011. (Invited talk)
40. Johnson W (2012). Observing Natural Selection in the Classroom. Maine Center for Research in STEM Education (RiSE) National Education Research Conference, University of Maine, June 20, 2012 - June 22, 2012. (Invited talk)
41. Johnson W (2012). Observing Natural Selection in the Classroom. Michigan Science Teachers Association 2012 Annual Conference, Lansing, MI, March 9, 2012.

42. Johnson W (2012). Using Avida-ED in Teaching About Computation. Tapestry Workshop, Michigan State University, August 1, 2012. (Invited talk)
43. Johnson W; Lark A (2012). The impact of Avida-ED digital evolution software on student understanding of natural selection. Research in Science Education (RiSE) 2012 Annual Conference, Orono, Maine, June 19, 2012 - June 22, 2012. (Invited talk)
44. Johnson W; Lark A; Mead LS; Jim Smith; Pennock RT (2012). Evolution in Action in the Classroom: The Effects of Digital Evolution and Bacterial Selection Experiments on Student Learning. Evolution Ottawa: The First Joint Congress on Evolutionary Biology, Ottawa Convention Centre Ottawa, Ontrario, Canada, July 6, 2012 - July 10, 2012
45. Keagy J; Lettieri L; Boughman J. (2012) Exploring the multidimensional male competition fitness landscape of a QTL mapping population. Evolution 2012, Ottawa, ON Canada, 7/6/12 - 7/10/12
46. Keagy J; Lettieri L; Boughman J. (2012) Exploring the multidimensional male competition fitness landscape of a QTL mapping population. ISBE 2012 - 14th International Behavioral Ecology Congress, Lund, Sweden, 8/12/12 - 8/17/12
47. Kjelvik M; Mead LS; Getty T (2012). Aphid Buffet. KBS GK-12 April Teacher Workshop, Kellogg Biological Station, April 11, 2012 - April 11, 2012. (Invited talk)
48. Kjelvik M; Mead LS; Getty T (2012). Basic data literacy for K-12 students: Data Nuggets. Joint Congress of Evolutionary Biology, Ottawa, Ontario, Canada, July 6 - July 11. (Invited talk)
49. Lark A; Johnson W; Mead LS; Jim Smith; Pennock RT (2012). Evolution in Action in the Classroom: Teaching and Learning about Evolution and the Nature of Science with Avida-ED. First Joint Congress on Evolutionary Biology - Evolution Ottawa, Ottawa, Ontario, Canada, July 6, 2012 - July 11, 2012
50. Lark A; Johnson W; Mead LS; Jim Smith; Pennock RT (2012). Experimenting with Natural Selection in the Classroom using Avida-ED. CREATing the Future of STEM Education, East Lansing, MI, May 8, 2012 - May 9, 2012
51. Larsen M; Barrick JE; Lennon J (2012). Nutrient composition drives eco-evolutionary feedbacks between microbes and their phage. BEACON Congress, East Lansing, MI, July 17, 2012 - July 19, 2012
52. Larsen M; Lennon J (2012). Nutrient stoichiometry influences rapid eco-evolutionary feedbacks in marine cyanobacteria and phage. International Society of Microbial Ecology, Copenhagen, Denmark, August 19, 2012 - August 24, 2012
53. Ledbetter M (2012). Continuous in vitro Evolution of a Ribozyme Ligase: A Model Kit for The Evolution of a Biomolecule. Artificial Life 13, East Lansing, MI, 08/19/2012 - 08/22/2012.
54. Lenski R (2012). Exploring Adaptive Landscapes in a Long-term Experiment with Bacteria. American Association for the Advancement of Science, Vancouver, Canada, Feb. 16, 2012 - Feb. 18, 2012. (Invited talk)
55. Lenski R (2012). Repeatability, Contingency, and Novelty: Findings from Two Evolution Experiments. Symposium on Evolution: Transcending the Past, Stanford University (Palo Alto, California), March 12, 2012 - March 13, 2012. (Invited talk)
56. Lenski R (2012). Time Travel - Forward and Reverse - in Experimental Evolution. Symposium on Artificial and Experimental Evolution of Microbes, University of Leuven (Belgium), June 1, 2012 - June 1, 2012. (Invited talk)

57. Lenski R (2012). Time travel in experimental evolution. Bacteria, Archaea & Phages, Cold Spring Harbor Laboratory, NY, 08/23/12 - 08/25/12. (Invited talk)
58. Lettieri L; Keagy J; Boughman J (2012) Moving targets and double agents: sexual selection in sticklebacks. Stickleback 2012, Seattle, WA, USA, July 29, 2012 - August 3, 2012
59. Lettieri L; Keagy J; Boughman J (2012). Moving targets and double agents: sexual selection in sticklebacks. Evolution 2012, Ottawa, Ontario, Canada, July 6, 2012 - July 10, 2012
60. Lettieri L; Keagy J; Boughman J (2012). Moving targets and double agents: sexual selection in sticklebacks. International Behavioral Ecology Congress, Lund, Sweden, August 12, 2012 - August 17, 2012
61. Maliska M; Pennell M; Swalla BJ (2012). Speciation and the evolution of taillessness in molgulid ascidians. Joint Congress on Evolutionary Biology, Ottawa, CN, July 6, 2012 - July 10, 2012
62. Meyer J; Devin Dobias; Ryan Quick; Flores C; Weitz J; Lenski R (2012). Key innovation in a virus triggers a coevolutionary arms race, rapid molecular evolution, and speciation. Evolution, Ottawa, ON Canada, July 5,2012 - July 10, 2012
63. Meyer J; Flores C; Weitz J; Lenski R (2012). Key innovation in a virus catalyzes a coevolutionary arms race. ALife13, East Lansing, MI, USA, July19, 2012 - July 22, 2012
64. Miikkulainen R (2012). Multiagent Learning Through Neuroevolution (Plenary). World Congress on Computational Intelligence, Brisbane, Australia, 6/14/2012. (Invited talk)
65. Miikkulainen R (2012). Multiagent Learning through Neuroevolution. Advanced Analytics Institute, University of Technology Sydney, Australia, June 14th, 2012. (Invited talk)
66. Miikkulainen R (2012). Tutorial on Evolving Neural Networks. Artificial Life Conference, East Lansing, MI, July 19th, 2012. (Invited talk)
67. Miikkulainen R (2012). Tutorial on Evolving Neural Networks. World Congress on Computational Intelligence, Brisbane, Australia, June 10th, 2012. (Invited talk)
68. Morris JJ; Lenski R; Zinser ER (2012). The Black Queen Hypothesis: Evolution of Dependencies Through Adaptive Gene Loss. American Society for Microbiology Annual Meeting, San Francisco, CA, 6/17/12 - 6/20/12
69. Morris JJ; Zinser ER; Lenski R (2012). Evolution of Dependency in Prochlorococcus: an Empirical Test Using an E. Coli Model. Phycological Society of America Annual Meeting, Charleston, SC, 6/20/12 - 6/23/12
70. Olson RS (2012). aBeeDa: A bottom-up approach to the evolution of swarming. BEACON Congress 2012, East Lansing, MI, July 17, 2012 - July 17, 2012
71. Olson RS (2012). Predator confusion is sufficient to evolve swarming. SwarmFest 2012, Charlotte, NC, July 29, 2012 - July 29, 2012
72. Olson RS; Adami C; Dyer F; Hintze A (2012). A bottom-up approach to the evolution of swarming. ALife XIII, East Lansing, MI, July 21, 2012 - July 21, 2012
73. Østman B; Hintze A; Adami C (2012). Impact of Epistasis and Pleiotropy on Adaptation. 16th Evolutionary Biology Meeting, Marseille, France, 9/18/12 - 9/21/12. (Invited talk)
74. Østman B; Teal T; Gomes V; Smith B; Williams BL; Schmidt T (2012). Evolutionary Metagenomics Reveal Selection in Complex Microbial Communities. First Joint Congress on Evolutionary Biology, Ottawa, Ontario, Canada, 7/6/2012 - 7/10/2012

75. Pennock RT (2012). Avida-ED Software Demonstration. Society for the Study of Evolution Conference, Ottawa, Canada, 7/7/2012. (Invited talk)
76. Pennock RT (2012). Digital Darwin: Observing Evolutionary Design in Computer Environments. Grand Rapids Center for Inquiry, 9/12/2012 - 9/12/2012. (Invited talk)
77. Pennock RT (2012). Learning Evolution and the Nature of Science using Avida-ED Digital Evolution Software. International Artificial Life XIII Conference, East Lansing, MI, 7/19/2012.
78. Pennock RT (2012). Learning Evolution and the Nature of Science using Avida-ED Digital Evolution Software. Tapestry Computer Science Workshop, East Lansing MI, 8/1/2012. (Invited talk)
79. Pitchers W; Pool J; Dworkin I (2012). Why are wings wing- shaped? Agents of selection on the wings of D. melanogaster. 1st Joint Congress on Evolutionary Biology, Ottawa, Ontario, Canada, July 6th - July 10th
80. Ribeck N; Lenski R (2012). Quantifying Frequency-Dependent Fitness Effects in Evolving Microbial Populations. ALife 13, East Lansing, MI, July 19, 2012 - July 22, 2012. (Invited talk)
81. Ribeck N; Lenski R (2012). Quantifying Frequency-Dependent Fitness Effects in Evolving Microbial Populations. First Joint Congress on Evolutionary Biology, Ottawa, Ontario, Canada, July 6, 2012 - July 10, 2012
82. Rohrbacher C (2012). Science Fiction and Contextualizing Evolution for Biology Students. Contact Conference, Mountain View, CA, 3/30/2012 - 4/1/2012
83. Rosenblum B (2012). An evolutionary perspective on the conservation of populations on the verge of extinction. University of California, Davis, Symposium on the Conservation of Extremely Small Populations. (Invited talk)
84. Rosenblum B (2012). Natural selection, sexual selection and the genomics of convergent evolution in White Sands lizards. Evolution Meeting. (Invited talk)
85. Roychoudhury P; Krone S (2012). Adaptive evolution in a spatially structured population of bacteriophages. 2012 BEACON Congress, East Lansing, MI, 16-Jul-12 - 19-Jul-12
86. Roychoudhury P; Krone S (2012). Adaptive evolution in a spatially structured population of bacteriophages. Evolution 2012, Ottawa, ON, 6-Jul-12 - 11-Jul-12
87. Soule T (2012). Invited Seminar. Syracuse University, October 3, 2012. (Invited talk)
88. Soule T; Heckendorn R; Rubini JD; DeVault T (2012). Powerful, Affordable Autonomous Robots for On-line Evolution. First annual IBEST Research Expo, University of Idaho, Oct 18, 2012.
89. Soule T; Heckendorn R; Rubini JD; DeVault T; Kjelvik M; Getty T (2012). The Ladybug Game: Observing Evolution in Action for K-6. First annual IBEST Research Expo, University of Idaho, Oct 18, 2012.
90. Soule T; Heckendorn R; Solomon M (2012). A Comparison of Communication Strategies in Evolved Cooperative Learning. First annual IBEST Research Expo, University of Idaho, Oct 18, 2012.
91. Soule T; Heckendorn R. CotsBots. Women in Engineering Day, University of Idaho, Oct 19th, 2012. (Invited talk)
92. Stillwell RC; Shingleton A; Dworkin I; Frankino A (2012). Changing the Slope of a Static Allometry Using Artificial Selection: How we did it. Evolution, Ottawa, CA.

93. Swalla BJ (2012). Origin, Evolution & Development of the Chordates. VI International Meeting of the Latin American Society for Developmental Biology, Montevideo, Uruguay, 4-25-12 - 4-29-12. (Invited talk)
94. Theis KR; Schmidt T; Holekamp KE (2012). A symbiotic approach to the study of animal communication. Behavioral and Cognitive Neuroscience Symposium 2012, Groningen, the Netherlands, 05/23/12 - 05/24/12. (Invited talk)
95. Theis KR; Schmidt T; Holekamp KE (2012). Odor-producing microbes: the unheralded machinery behind animal chemical communication. 112th General Meeting of the American Society for Microbiology, San Francisco, CA, 06/16/12 - 06/19/12. (Invited talk)
96. Top E (2012) Symposium to celebrate the 60th anniversary of Selman Waksman's Nobel award, Rutgers University, New Jersey, December 13, 2012. (Invited talk)
97. Top E (2012). Antibiotic resistance is all (resistance genes that are never lost). European Conference of Clinical Microbiology and Infectious Diseases (ECCMID-22), London, UK, March 31, 2012 - April 3, 2012. (Invited talk)
98. Top E (2012). Coevolution between plasmids and their hosts: consequences for the persistence of drug resistance. 14th International Symposium on Microbial Ecology (ISME-14), Copenhagen, Denmark, August 19, 2012 - August 24, 2012. (Invited talk)
99. Top E (2012). Talk: Real-time evolution of plasmid persistence by acquisition of toxin-antitoxin systems. International Symposium for Plasmid Biology (ISPB), Santander, Spain, September 12, 2012 - September 16, 2012.
100. Waters C (2012). Identification and Characterization of Anti-Biofilm Compounds. GLRCE Annual Meeting, Chicago, IL, 08/2012 - 08/2012. (Invited talk)
101. Weigel EG; Tinghitella R (2012). Mate availability and hybridization in the threespine stickleback. Council of Graduate Students' Graduate Academic Conference, East Lansing, 3/31/12.
102. Weigel EG; Tinghitella R (2012). Mate availability and hybridization in the threespine stickleback. Midwest Ecology and Evolution Conference, Cincinnati, Ohio, 3/22/12 - 3/24/12.
103. Whittaker DJ; Gerlach NM; Ketterson ED (2012). Songbird odor predicts reproductive success. Animal Behavior Society, Albuquerque, NM, June 11, 2012 - June 14, 2012.
104. Wiser M; Lenski R (2012). The view from 50,000 generations: analysis of fitness trajectories in a long-term evolution experiment in Escherichia coli. 2012 Joint Congress on Evolution, Ottawa, Canada, 07/06/2012 - 07/10/2012.
105. Yang Wu; Lihong Xu; Dawei Li; Yuan Xu (2012). Improved CAM Shift Object Tracking Based on Non-linear Kernel Density Estimation and Kalman Filter. 19th International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS), Chiang Mai, Thailand, 2011
106. Zhou Z; Xu L; Dawei Li (2012). A Modified Particle Swarm Neural Network Based on Local Chaotic Optimization Strategy. 5th International Symposium on Computational Intelligence and Design (ISCID), 2012

1c. Other dissemination activities

Talks

1. Adami C; Hintze A; Schossau J (2012). Evolution and Stability of Microbial Games. Theoretical Biology Seminar, University of Zurich, Zurich, 6/5/2012. (Invited talk)
2. Adami C; Olson RS (2012). Phenotypic plasticity speeds up evolution in rugged fitness landscapes. BEACON Seminar, Michigan State U. 2/24/2012
3. Adami C (2012). Microbiology 300: Evolution of Games Microbes Play. Science University, Michigan State U. 4/12/2012. (Invited talk)
4. Conner J (2012). Patterns of correlations in animals and plants. Royal Society Symposium on Adaptive Integration, Kavli International Center, UK, 10/10/12 - 10/12/12. (Invited talk)
5. Goodman ED (2011). BEACON--One Year of Evolution in Action. NSF-wide Invited Lecture, NSF HQ, Arlington, VA, Nov. 10, 2011 - Nov. 10, 2011. (Invited talk)
6. Goodman ED (2012). BEACON Status Report. BEACON Congress 2012, MSU, 07/17/2012 - 07/17/2012
7. Goodman ED (2012). Evolution and Packaging. Departmental Seminar, School of Packaging, MSU, 11/5/2011 - 11/5/2011. (Invited talk)
8. Goodman ED (2012). Evolution in Action in Biological and Digital Domains. Seminar, Center for Study of Complex Systems, University of Michigan, Ann Arbor, February 21, 2012 - February 21, 2012. (Invited talk)
9. Goodman ED (2012). Opportunity in BEACON Center. Michigan AGEP Alliance Fall Conference, MSU, 09/07/2012 - 09/07/2012. (Invited talk)
10. Goodman ED (2012). Study Evolution in Action in Biological and Computational Domains, and Sometimes, Apply the Lessons in Engineering and CS. NSF Division of Environmental Biology Staff Meeting, NSF HQ, Arlington, VA, 08/29/2012 - 08/29/2012. (Invited talk)
11. Greenberg EP (2012) Quorum sensing and bacterial sociality. Seminar, UTSW, 02/07/2012. (Invited talk)
12. Greenberg EP (2012). Qourm sensing and bacterial sociality. Nanyang University, Singapore, 02/24/2012. (Invited talk)
13. Greenberg EP (2012). Quorum sensing and cooperation in bacteria. South China Agricultural University, 09/19/2012. (Invited talk)
14. Greenberg EP (2012). Quorum sensing and social activity in Pseudomonas. Yale University, 03/02/2012.
15. Greenberg EP (2012). Quorum sensing in Pseudomonas aeruginosa. Univ Ciolorado Sch of Medicine, 03/22/2012. (Invited talk)
16. Harrison SH (2012). By the Light of Evolution, Teaching Students about Nature's Inventories and Informational Structures. BEACON Seminar, North Carolina A&T State University, 9/14/2012 - 9/14/2012
17. Hayes R; Rohrbacher C (2012). BEACON -- what is it? NCATSU College of Arts & Sciences Faculty Meeting, Greensboro, NC, 8/10/2012. (Invited talk)
18. Hohenlohe P (2012). Conservation genomics: lessons from RAD sequencing in stickleback and salmonids. Cornell Center for Comparative and Population Genomics seminar series, Cornell University, 5/14/2012 - 5/14/2012. (Invited talk)

19. Hohenlohe P (2012). Dimensionality of evolution: inferences from interaction matrices. BEACON weekly seminar series, University of Idaho, 6/1/2012 - 6/1/2012. (Invited talk)
20. Hohenlohe P (2012). Population genomics for evolutionary and conservation biology in non-model organisms. Bioinformatics and Computational Biology seminar series, Iowa State University, 3/22/2012 - 3/22/2012. (Invited talk)
21. Hohenlohe P (2012). RAD sequencing for conservation genomics: lessons from threespine stickleback and other taxa. Conservation Genetics seminar series, University of Montana, 3/9/2012 - 3/9/2012. (Invited talk)
22. Hohenlohe P (2012). The dimensionality of evolution. Mathematics Department seminar series, University of Idaho, 4/5/2012 - 4/5/2012. (Invited talk)
23. Hohenlohe P (2012). The genomic architecture of rapid adaptation in threespine stickleback. Washington State University, 2/6/2012 - 2/6/2012. (Invited talk)
24. Kjelvik M; Soule T; Mead LS; Getty T (2012). Teaching evolutionary concepts to elementary students using LadyBug. KBS GK-12 December Teacher Workshop, Kellogg Biological Station, December 7, 2011 - December 7, 2011. (Invited talk)
25. Konikoff C (2012). Dynamics of signal transduction during hemichordate regeneration: An evo-devo approach. MF4, University of Washington, February 2, 2012.
26. Lenski R (2012). Time Travel in Experimental Evolution. Cornell University, 09/14/2012. (Invited talk)
27. Lenski R (2012). Time Travel in Experimental Evolution. University of Texas, Austin, 11/29/2012. (Invited talk) The Paul D. Gottlieb Distinguished Lecture.
28. Meyer J (2012). Coevolution of Bacterial/Phage Interactions: From Angstrom Shifts in Proteins to Ecological Community Assembly. Harvard Medical School's 2012 Systems Biology Department Retreat, Sebasco Harbar Resort, Maine, May 11, 2012 - May 13, 2012. (Invited talk)
29. Miikkulainen R (2012). Technological Innovation as Competitive Search. IBM Silicon Valley, April 12th, 2012. (Invited talk)
30. Rosenblum B (2012). Evolution and pathogenicity in the deadly chytrid pathogen of amphibians. National Academies Institute of Medicine. (Invited talk)
31. Tan X (2012). Robotic fish for environmental monitoring: Challenges and potential solutions. Grandparents University Program, East Lansing, MI, 6/26/2012 - 6/26/2012. (Invited talk)
32. Tan X (2012). Robotic fish: From bio-inspired design to environmental monitoring. 2012 US Science and Engineering Festival, Washington, DC, 04/27/2012 - 04/29/2012. (Invited talk)
33. Top E (2012). Mechanism and dynamics of plasmid-host coevolution. Invited seminar, School of Biosciences, University of Birmingham, UK, April 3, 2012 - April 4, 2012. (Invited talk)
34. Whittaker DJ (2012). Communicating your science to the public. College of Wooster, March 7, 2012. (Invited talk)
35. Whittaker DJ (2012). Making scents of it all: How songbirds use odor to communicate. Tri Beta Sponsored Speaker, College of Wooster, March 8, 2012. (Invited talk)
36. Williams BL (2012). Graduate Research at the Intersection of Molecular Biology and Evolution. Spellman College Department of Biology, Spellman College, Atlanta, GA
37. Zaman L (2012). Complexity Driven by Host-Parasite Coevolution. EEBB Colloquium, MSU, 3/14 - 3/14. (Invited talk)

Publications

1. Graves Jr. JL (2012). Rules of breeding Harper's Magazine 4 - 4
2. Johnson W (2012). Free Software and Lesson Plans to Bring Evolution in Action into the Classroom. Michigan Science Teachers Association Newsletter vol 64.3 19.
3. Waters CM (2012). The Meteoric Rise of the Signaling Molecule Cyclic di-GMP. Microbe 353 - 359

2. Awards and Honors

	Recipient	Reason for Award	Award Name and Sponsor	Date	Award Type
1	Briscoe, Adriana	Research	Overseas Visiting Scholarship, St. John's College, Cambridge University	10/01/12-12/19/12	Fellowship
2	Chesney, Mairin	Research	First Place Undergraduate ACM Student Research Competition, Grace Hopper Celebration of Women in Computing	October 2012	Scientific
3	Clark, Tony Joseph	Research	NSF Graduate Research Fellowship	March 2012	Fellowship
4	Clark, Tony; Moore, Jared, Wang, Jianxun; Tan, Xiaobo; McKinley, Philip	Best Paper Award	Thirteenth International Conference on the Synthesis and Simulation of Living Systems	2012	Scientific
5	Connelly, Brian	Outstanding graduate Research	Outstanding Graduate Student award, MSU Department of Computer Science and Engineering, College of Engineering	April 2012	Scientific
6	Connelly, Brian	Service	Outstanding Graduate Service award, MSU Department of Computer Science and Engineering	April 2012	Other
7	Fleet, Blair	Research	NSF Graduate Research Fellowship Program	April 2012	Fellowship

8	Fleet, Blair	Research	GEM (National Consortium for Graduate Degrees for Minorities in Engineering and Science) Fellowship	April 2012	Fellowship
9	Glenney, Carrie	Research	NSF Graduate Research Fellowship	2012	Fellowship
10	Graves, Joseph L., Jr	60th Anniversary of NSF Graduate Research Fellowship	Sensational Sixty, National Science Foundation	2012	Scientific
11	Greenberg, E. Pete	Research and Mentoring	DC White Award for Research and Mentoring, American Society for Microbiology	June 2012	Scientific, Education
12	Greenberg, E. Pete	Honorary Degree	Doctor of Laws, honoris causa, University of Guelph	June 2012	Education
13	Holekamp, Kay E.	Outstanding alumna	Smith Medal, Smith College	September 2012	Other
14	Lackey, Alycia	Research	Dissertation Continuation Fellowship, MSU College of Natural Science	April 2012	Fellowship
15	Lenski, Richard	Fundamental contributions to conceptual unification of biological sciences	Sewall Wright Award, American Society of Naturalists	2012	Scientific
16	Lenski, Richard	President Elect (2012), President (2013), Past President (2014)	Elected President of the Society of the Study of Evolution	2012-2014	Other
17	Lenski, Richard	Research	Fellow of the Ecological Society of America	2012	Scientific
18	Lynch, Danny	Best presentation (work from Titus Brown's lab)	University of the Virgin Islands Fall Symposium	2012	Scientific
19	Miikkulainen, Risto, with Igor Karpov and Jacob	Winner	Humanlike Bot Competition, World Congress on	June 2012	Scientific

	Schrum		Computational Intelligence		
20	Pennock, Robert T.	Interdisciplinary team excellence for Avida-ED project	Excellence Award in Interdisciplinary Scholarship, MSU Chapter of The Honor Society of Phi Kappa Phi	April 2012	Education
21	Royer, Anne	Evolution-in-Action lessons	NABT Travel Award, Society for the Study of Evolution	March 2012	Education
22	Soule, Terence	Overall performance	Presidential Mid-Career Award, University of Idaho	2012	Education
23	Soule, Terence	Best Paper	Best paper ALIFE track, GECCO 2012	July 2012	Scientific
24	Swalla, Billie J	Mentoring	Undergraduate Research Mentor Award, University of Washington	May 2012	Education
25	Weigel, Emily Grace	Research	NSF Graduate Research Fellowship Honorable Mention	March 2012	Other
26	Weigel, Emily Grace		Future Academic Scholars in Teaching (FAST) Fellowship, NSF/CIRTL at MSU	April 2012	Fellowship
27	Weigel, Emily Grace	Teaching Award	Finalist for Bailey Scholars Teaching/Learning Program, Bailey Fellows at MSU	April 2012	Education
28	Whittaker, Danielle J.	Research	Mountain Lake Biological Station Early Career Fellowship	March 2012	Fellowship

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

	Student Name	Degree	Years to Degree	Placement
1	Sarah Benson-Amram (MSU)	PhD	6	Faculty at University of Wyoming
2	David Michael Bryson (MSU)	PhD	7	Academic Specialist at

				BEACON
3	Brian Connelly (MSU)	PhD	4	Postdoc at UW (BEACON)
4	Nerva Espinosa (MSU)	MS		PhD program at MSU
5	Blair Fleet (MSU)	MS	2	PhD program at MSU
6	John Paul Jerome (MSU)	PhD	5	Plant Research Laboratory, MSU
7	Alan Lockett (UT)	PhD	7	IDSIA, Switzerland
8	Justin Meyer (MSU)	PhD	5	Harvard Medical School Fellow, Systems Biology
9	Gowon Patterson (MSU)	MS	2	PhD program at MSU
10	Neem Serra (UW)	MS	1	PhD program at MSU
11	Anand Subramoney (UT)	MS		Industry

4a. General outputs of knowledge transfer activities

	Patent Name and Inventors/Authors	Number	Application Date	Receipt Date
1	Inhibitors of Bacterial Diguanylate Cyclase: Chris Waters, M. B. Neiditch, M. F. Semmelhack, K. Sambanthamoorthy	TEC2012-0094PROV	7/10/12	

4b. Other outputs of knowledge transfer activities

Invention Disclosure: Jeffrey E. Barrick (UT), breseq. http://barricklab.org/breseq ; http://code.google.com/p/breseq

Software Packages Developed

OpenNERO: simulation environment for research in multiagent systems
Igor Valerievich Karpov; Risto Miikkulainen
http://opennero.googlecode.com

NEAT software for evolving neural networks V1.2.1
Kenneth O Stanley; Igor Valerievich Karpov; Erkin Bahceci; Risto Miikkulainen
http://nn.cs.utexas.edu/?neat

PyEC software for Evolutionary Annealing and a number of other evolutionary and stochastic optimization algorithms
Alan Lockett; Risto Miikkulainen
http://nn.cs.utexas.edu/?pyec

UT^2 software for the winning entry in the BotPrize 2012 competition
Igor Valerievich Karpov; Jacob Schrum; Risto Miikkulainen
http://nn.cs.utexas.edu/?ut2

ESL software for Egalitarian Social Learning in the robot foraging domain
Eliana Feasley; Wesley Tansey
http://nn.cs.utexas.edu/?esl

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?
1	Ford Motor Company	Company			KT	N
2	Northrop Grumman	Company	2980 Fairview Park Drive Falls Church, VA 22042	Will Chambers	KT	N
3	Scion, Inc	Company	Te Papa Tipu Innovation Park 49 Sala Street, Rotorua 3010 Private Bag 3020 Rotorua 3046 New Zealand	Oliver Chikumbo	KT	Y
4	Secure Designs, Inc.	Company	301 North Elm Street Suite 201 Greensboro, NC 27401		KT	N
5	Continental Automotive GmbH	Company	Vahrenwalder Straße 9 30165 Hanover Germany		KT	N
6	BAE Systems	Company			KT	N
7	General Motors	Company	PO Box 33170 Detroit, MI 48232-5170		KT	N
8	NASA	Federal Agency	Public Communications Office NASA Headquarters Suite 5K39 Washington, DC 20546-000		KT	N
9	Spelman College	Other (Academic)	350 Spelman Lane Atlanta, GA 30314	Aditi Pai	Research, Education, Diversity	Y
10	University of Texas Pan American	Other (Academic)	1201 West University Dr. Edinburg, TX 78539	Laura Grabowski	Research, Education, Diversity	Y
11	NESCent	Other	2024 W. Main Street Suite A200 Durham, NC 27705-4667	Karen Cranston	Research, Education	Y
12	SESYNC	Other	1 Park Place Suite 300 Annapolis, MD 21401	Mary Shelley	Research, Education	Y
13	iPlant	Other	Thomas W. Keating Building 1657 East Helen Street Tucson, Az 85721	Stephen Goff	Research, Education	N
14	International Society of	Other		Mark Bedau	Research	N

	Artificial Life					
15	National Association of Biology Teachers	Other	1313 Dolley Madison Blvd, Suite 402, McLean, VA 22101		Education	N

7. Summary table

1	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.	7
2	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)	13
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	$827,896
4	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)	295

8. Media publicity

Press Releases

9/19/12: NSF Press Release: Bacteria's key innovation helps understand evolution [VIDEO]
http://www.nsf.gov/news/news_summ.jsp?org=NSF&cntn_id=125492
9/19/12: Evolution is as complicated as 1-2-3
http://news.msu.edu/story/evolution-is-as-complicated-as-1-2-3/
8/29/12: Computer viruses could take a lesson from showy peacocks
http://news.msu.edu/story/computer-viruses-could-take-a-lesson-from-showy-peacocks/
8/10/12: Why do organisms build tissues they seemingly never use?
http://news.msu.edu/story/why-do-organisms-build-tissues-they-seemingly-never-use/
8/8/12: Hyenas that think outside the box solve problems faster
http://news.msu.edu/story/hyenas-that-think-outside-the-box-solve-problems-faster/
8/7/12: Division of labor offers insight into the evolution of multicellular
http://news.msu.edu/story/division-of-labor-offers-insight-into-the-evolution-cells/
7/26/12: Big horns trump smooth pickup lines every time
http://news.msu.edu/story/big-horns-trump-smooth-pickup-lines-every-time/
7/5: Nobel Laureate to speak at Artificial Life 13 conference
http://news.msu.edu/story/nobel-laureate-to-speak-at-artificial-life-13-conference
4/26/12: BEACON Center to present at national science and engineering festival
http://news.msu.edu/story/beacon-center-to-present-at-national-festival/
4/4/12: Two sophomores named 2012-13 Goldwater Scholars
http://news.msu.edu/story/two-sophomores-named-2012-13-goldwater-scholars/
3/27/12: American Society for Microbiology press release: The Black Queen Hypothesis: A New Evolutionary Theory
http://www.asm.org/index.php/news-room/release032712a.html
2/6/12: MSU Nominees for 2012 Goldwater Scholarship announced
http://news.msu.edu/staff-faculty/story/10305/
1/26/12: MSU researchers show how new viruses evolve, and in some cases, become deadly
http://news.msu.edu/story/10262/
1/26/12: NSF Press release: Researchers show how new viruses evolve, and in some cases, become deadly
http://www.nsf.gov/news/news_summ.jsp?cntn_id=122949&WT
11/21/12: Research sheds new light on body parts' sensitivity to environmental changes
http://news.msu.edu/story/10046/

Media Coverage

10/5/12 Utica Community Schools Newsletter: Hands on Science: Two UCS students take part in prestigious summer study program
http://www.uticak12.org/districtinfo/news/beacon.asp
9/26/12: ABC News: Evolution: Scientists grow 56,000 generations in lab to watch
http://abcnews.go.com/Technology/evolution-action-michigan-state-scientists-grow-coli-56000/story?id=17329160#.UGnuGb93RIt

9/20/12: Salon: In experiment scientists watched evolution happen
http://www.salon.com/2012/09/20/scientists_can_now_watch_evolution_happen/
9/20/12: RedOrbit: Evolution of Escherichia coli helps researchers understand how organisms evolve new functions
http://www.redorbit.com/news/science/1112697558/evolution-e-coli-genome-analysis-092012/
9/19/12: Nature News & Views: Evolution: How the unicorn got its horn
http://www.nature.com/nature/journal/vaop/ncurrent/full/nature11487.html
9/19/12: Ars Technica: Researchers track evolution through snapshots of 40,000 generations
http://arstechnica.com/science/2012/09/researchers-track-evolution-through-snapshots-of-40000-generations/
9/19/12: Washington Post: Evolutionary innovation caught in the act
http://www.washingtonpost.com/national/health-science/evolutionary-innovation-caught-in-the-act/2012/09/19/d9698b6e-0296-11e2-9b24-ff730c7f6312_story.html
9/19/12: The Loom: The birth of the new, the rewiring of the old
http://blogs.discovermagazine.com/loom/2012/09/19/the-birth-of-the-new-the-rewiring-of-the-old/
9/19/12: Science Daily: How organisms evolve new functions: Evolution is as complicated as 1-2-3
http://www.sciencedaily.com/releases/2012/09/120919135411.htm
9/9/12: Telegraph: Hyenas are as bright as primates, research shows
http://www.telegraph.co.uk/earth/wildlife/9530134/Hyenas-are-as-bright-as-primates-research-shows.html
9/4/12: PBS: Faced with a steel box, hyenas try to think outside it
http://www.pbs.org/wnet/nature/inside-nature/the-dirt-this-week-in-nature-august-4-august-10/7785/
9/1/12: Museum magazine, Sept-Oct issue (American Alliance of Museums): Work in Progress: Exhibiting Present-Day Evolution
8/30/12: RedOrbit: What would happen if computer viruses were like digital peacocks?
http://www.redorbit.com/news/technology/1112684472/peacocks-virtual-world-083012-001/
8/29/12: NSF News from the Field: Computer viruses could take a lesson from showy peacocks
http://www.nsf.gov/news/news_summ.jsp?cntn_id=125356
8/29/12: Science Daily: Computer viruses could take a lesson from showy peacocks
http://www.sciencedaily.com/releases/2012/08/120829151237.htm
8/23/12: Nature News: Physicists suggest selfishness can pay
http://www.nature.com/news/physicists-suggest-selfishness-can-pay-1.11254
8/15/12: Nature Research Highlights: Curious hyenas crack puzzles
http://www.nature.com/nature/journal/v488/n7411/full/488256a.html
8/10/12: Futurity: 'Unnecessary' steps help smooth evolution
http://www.futurity.org/science-technology/unnecessary-steps-help-smooth-evolution/
8/10/12: ScienceDaily: Why do organisms build tissues they seemingly never use?
http://www.sciencedaily.com/releases/2012/08/120810133155.htm
8/9/12: Astrobiology Magazine: Division of labor and multicellular life
http://www.astrobio.net/pressrelease/4944/division-of-labor-and-multicellular-life
8/9/12: RedOrbit: Hyenas solve problems faster when they think outside the box
http://www.redorbit.com/news/science/1112672883/hyenas-think-outside-box-080912/
8/9/12: Sigma Xi SmartBrief: Hyenas can solve problems, study says

http://www.smartbrief.com/servlet/ArchiveServlet?issueid=F99B6D3A-5EC5-4716-9B1F-0D74C448CA75&lmid=archives
8/9/12: Futurity: Innovation gives some hyenas an edge
http://www.futurity.org/science-technology/innovation-gives-some-hyenas-an-edge/
8/8/12: ScienceDaily: Hyenas that think outside the box solve problems faster
http://www.sciencedaily.com/releases/2012/08/120808163201.htm
8/8/12: LiveScience: Creative hyenas make better problem solvers
http://www.livescience.com/22207-creative-hyenas-make-better-problem-solvers.html
8/7/12: Ecology Global Network: Division of labor offers insight into the evolution of multicellular life
http://www.ecology.com/2012/08/07/division-labor-evolution-multicellular-life/
8/7/12: ScienceDaily: Division of labor offers insight into the evolution of multicellular life
http://www.sciencedaily.com/releases/2012/08/120807132211.htm
8/2/12: New York Times: Olympic athletes and their parents: Your competitive drive vs. your child's (column by Judi Brown Clarke)
http://www.nytimes.com/roomfordebate/2012/08/02/are-olympic-parents-supportive-or-overbearing/olympic-athletes-and-their-parents-your-competitive-drive-vs-your-childs
7/27/12: Futurity: Studmuffin beetles boast bigger horns
http://www.futurity.org/top-stories/studmuffin-beetles-boast-bigger-horns/
7/27/12: International Business Times: Beetle horns get size enhancement from insulin: study
http://www.ibtimes.com/articles/367742/20120727/beetle-horn-insulin-sexual-selection-signal.htm
7/26/12: USA Today: Antlers make the beetle
http://content.usatoday.com/communities/sciencefair/post/2012/07/antlers-make-the-beetle-/1#.UCp4PWNYsrg
7/26/12: Discover Magazine Blogs - Not Exactly Rocket Science: How the rhino beetle got its horn (and why it cannot lie)
http://blogs.discovermagazine.com/notrocketscience/2012/07/26/how-the-rhino-beetle-got-its-horn-and-why-it-cannot-lie/
7/26/12: ScienceDaily: Big horns trump smooth pickup lines every time
http://www.sciencedaily.com/releases/2012/07/120726154001.htm
7/23/12: The State News: Nobel winner speaks at Wharton
http://www.statenews.com/index.php/article/2012/07/nobel_winner_speaks_at_wharton
6/20/12: LiveScience: Robotic fish patrol waters for pollutants
http://www.livescience.com/21081-robot-fish-patrol-nsf-ria.html
6/18/12: The State News: Conference exposes young women to STEM fields
http://statenews.com/index.php/article/2012/06/conference_exposes_young_women_to_stem_fields
6/4/12: Bloomberg TV: Robotic Fish Search Water for Pollutants (VIDEO)
http://www.bloomberg.com/video/94078211-robotic-fish-search-water-for-pollutants.html
6/1/12: Microbe Magazine: Card trick: the Black Queen from Hearts helps explain reductive evolution in life
http://www.microbemagazine.org/index.php/06-2012-current-topics/5228-card-trick-the-black-queen-from-hearts-helps-explain-reductive-evolution-in-life
5/29/12: Great Lakes Echo: Water-monitoring robofish almost ready to patrol Great Lakes

http://greatlakesecho.org/2012/05/29/water-monitoring-robofish-almost-ready-to-patrol-great-lakes/
5/14/12: LiveScience: Microbes use "Hearts" card game trick to freeload
http://www.livescience.com/20305-black-queen-microbes-evolution.html
5/11/12: RedOrbit: Queen of spades key to new evolutionary hypothesis
http://www.redorbit.com/news/science/1112533447/queen-of-spades-key-to-new-evolutionary-hypothesis/
5/10/12: NSF Discoveries: Queen of spades key to new evolutionary hypothesis
http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=124158&org=NSF
5/2/12: Huffington Post: A black queen in a blue ocean: How microbes evolve to depend on each other
http://www.huffingtonpost.com/jeff-morris/black-queen-hypothesis_b_1471250.html
4/27/12: RedOrbit: Robots That Swim, Drive And Play Soccer; Virtual Humans And Real Storm Chasers Are Part Of The Action At Science And Engineering Festival
http://www.redorbit.com/news/science/1112523537/robots-that-swim-drive-and-play-soccer-virtual-humans-and-real-storm-chasers-are-part-of-the-action-at-science-and-engineering-festival/
4/3/12: Environmental Monitor: Back to school: Robotic fish make a splash
http://www.fondriest.com/news/back-to-school-robotic-fish-make-a-splash.htm
4/2/12: Science 2.0: Evolved Dependency: The Black Queen Hypothesis in Evolution
http://www.science20.com/news_articles/evolved_dependency_black_queen_hypothesis_evolution-88616
3/28/12: io9: Researchers describe a new evolutionary theory: The Black Queen Hypothesis
http://io9.com/5897134/researchers-describe-a-new-evolutionary-theory-the-black-queen-hypothesis
3/27/12: New Scientist: Black Queen tells microbes to be lazy
http://www.newscientist.com/article/dn21629-black-queen-tells-microbes-to-be-lazy.html
3/22/12: Research.gov: Robotic fish could monitor water quality
http://www.research.gov/research-portal/appmanager/base/desktop?_nfpb=true&_windowLabel=researchAreas_11&_urlType=action&researchAreas_11_action=selectAwardDetail&researchAreas_11_id=/researchGov/AwardHighlight/PublicAffairs/19683_RoboticFishCouldMonitorWaterQuality.html
1/30/12: Futurity: After four mutations, new virus attacks
http://www.futurity.org/science-technology/after-four-mutations-new-virus-attacks
1/27/12: RedOrbit: MSU researchers show how viruses evolve, and in some cases, become deadly
http://www.redorbit.com/news/health/1112463504/msu-researchers-show-how-new-viruses-evolve-and-in-some-cases-become-deadly/
1/27/12: ScienceDaily: How viruses evolve, and in some cases, become deadly
http://www.sciencedaily.com/releases/2012/01/120126224526.htm
1/27/12: Carl Zimmer, New York Times: In real time, a virus learns a new way to infect
http://www.nytimes.com/2012/01/27/science/in-real-time-a-virus-learns-a-new-way-to-infect.html
1/26/12: The Scientist: The making of a trait
http://the-scientist.com/2012/01/26/the-making-of-a-trait/

1/26/12: Science Podcast: an interview with Justin Meyer about the experimental coevolution of a virus and its host
http://www.sciencemag.org/content/335/6067/428/suppl/DC2
1/26/12: LiveScience: Viral attacks on bacteria reveal a secret to evolution
http://www.livescience.com/18144-evolution-trait-virus-bacteria.html
reposted on MSNBC, among others:
http://www.msnbc.msn.com/id/46152646/ns/technology_and_science-science/#.TyqvU-NSROQ
1/26/12: LiveScience VIDEO: Virus rapidly evolves to fight bacteria
http://www.livescience.com/18142-viruses-evolving-deadly-mutations-easily.html
12/02/12: SunLive (NZ): Possibilities of Land Use Analysis
http://www.sunlive.co.nz/news/19759-possibilities-of-land-use-analysis.html
11/30/12: New York Times: DNA Sequencing Caught in Deluge of Data
http://www.nytimes.com/2011/12/01/business/dna-sequencing-caught-in-deluge-of-data.html
11/25/12: LiveScience Behind the Scenes: Worms can evolve to survive intersex populations
http://www.livescience.com/17189-worms-intersex-evolution-nsf-bts.html
11/22/12: ScienceDaily: New research on body parts' sensitivity to environmental changes
http://www.sciencedaily.com/releases/2011/11/111121151608.htm

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 (Korea and China) had extended visits in BEACON in 2012, each funded primarily by the visitor's host institution or a grant from their government. They engaged in collaborative research with Director Erik Goodman and other BEACON participants in four projects described under Research. Two additional visiting scholars from China (one pre-doctoral and one post-doctoral) also collaborated in BEACON on two of those projects. One student from China became a BEACON graduate student with support from one of those projects. All of the collaborations are continuing.

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)