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, focusing on ground-breaking research discoveries, and education/outreach activities with a high level of impact.

Erik Goodman (MSU), Kalyanmoy Deb (MSU), and collaborator Dr. Oliver Chikumbo, of Scion, a New Zealand Crown Research Institute, were awarded the prestigious Wiley Practice Prize in June 2013 for their work in multi-objective optimization. The project arose from earlier collaborations between Goodman and Chikumbo beginning in the 1990′s and continuing at a low level ever since. The work is continuing, and the team has been joined by Daniel Couvertier, a BEACON graduate student in CSE at MSU, and Mr. Hyungon Kim, a graduate student in the Human Interface Technology Lab at the University of Canterbury (New Zealand), supervised by Prof. Gun Lee. The project depends heavily on being able to optimize a 14-objective problem,

determining a Pareto set of optimal tradeoff solutions. The Evolutionary Multi-Objective Optimization (EMOO) search technology developed by the team complemented Dr. Deb's R-NSGA-II algorithm with new epigenetic operators developed by the team and to be further studied by Daniel Couvertier. The size of the search space of potential solutions is on the order of 10**600, and with 14 objectives to evaluate, appears at first glance to defy any efforts at optimization. However, the combination of heuristics and decision-making processes used by the team (nicknamed "WISDOM") was able to find a useful Pareto set of solutions that bore up well under critical examination. The team is also working with the University of Canterbury (in New Zealand) to develop virtual reality tools to help users comprehend the set of Pareto-optimal solutions. The decision-making approach given a set of optimal solutions involves allowing individual stakeholders to first express their relative preferences among the 14 objectives, and then to rank four solutions (selected according to their preferences from among the optimal set). These ranks are then combined using a scheme called the Analytical Hierarchy Process (AHP) to identify the solution most compatible with the preferences of all stakeholders. The WISDOM process is applicable to many "wicked" societal problems, and allows stakeholders to address simultaneously economic, environmental and social concerns, to satisfy the "Triple Bottom Line." The team plans to redevelop the platform for integrating the many distinct simulators used to calculate the 14 objective values for each solution into a sophisticated sensor and model integration framework in order to make it easier to generalize the approach for application to many problem domains, in partnership with a company with which negotiations are currently underway. More details on this project can be found in the Research section of this report.

Christoph Adami (MSU) and Arend Hintze (MSU) published a game theory paper in *Nature Communications* that garnered a great deal of media attention, as the take-away message was "evolution will punish you if you are selfish and mean." They tested whether the recently described "zero-determinant" (ZD) strategy in the classic Prisoner's Dilemma game, in which the player always acts selfishly and never cooperates, would be adaptive over the course of evolution. Their simulations demonstrated that ZD strategies are, at most, only weakly dominant, are evolutionarily unstable, are easily outcompeted by common strategies, and over time evolve into more cooperative strategies. This result was covered by many mainstream media outlets, including the *Los Angeles Times*, *BBC News*, *MSN*, and the UK's *Daily Mail*; science media outlets including *National Geographic*, *The Scientist*, *Discovery*, *Popular Science*, and the blog *Why Evolution is True*; political sites like The Daily Kos, who argue that groups with non-altruistic political agendas are "doomed to extinction"; and fashion and beauty blogs and magazines that suggested "mean girls are headed for extinction." (C. Adami and A. Hintze, 2013, Evolutionary instability of zero-determinant strategies demonstrates that winning is not everything, *Nature Communications* 4: 2193.)

Danielle Whittaker (MSU) and collaborators found that the reproductive success of birds – a taxon traditionally thought to have little to no sense of smell – could be predicted by their odor at the beginning of the breeding season. In a study of the volatile compounds contained in preen secretions of dark-eyed juncos, a common North American sparrow species, Whittaker et al found that males who smelled more "male-like" and females that smelled more "female-like" had higher reproductive success. They also found that males that had a higher proportion of compounds typically found in females were more likely to lose paternity in their own nest to extra-pair sires. Moreover, these odors were better predictors of reproductive success than plumage ornaments. This work also received a great deal of media attention, and appeared on the front page of www.nsf.gov, as well as in the news sections of *Science* and *Nature*, plus

mainstream media outlets including CBS News. Whittaker has been invited to give a plenary talk at the 2014 joint meeting of International Society of Chemical Ecology and Chemical Signals in Vertebrates, and is also scheduled to appear on the next season of the NOVA/PBS web series *The Secret Life of Scientists and Engineers.* Whittaker is now collaborating with Kevin Theis (MSU), Heather Goldsby (UW), and Aaron Wagner (MSU) in a BEACON project in which they are testing hypotheses about the coevolution of songbirds and the symbiotic microbial communities in their preen glands which may be responsible for the odors used in songbird chemical communication. More information on this project can be found in the Research section of this report. (D. J. Whittaker, N. M. Gerlach, H. A. Soini, M. V. Novotny, and E. D. Ketterson, 2013, Bird odour predicts reproductive success, *Animal Behaviour* 86(4): 697-703.)

Ben Kerr (UW) and his student Haley Lindsey and postdoc Jenna Gallie published a paper in *Nature* demonstrating that "evolutionary rescue" from extinction (in other words, beneficial mutations that allow the population to survive environmental change) is contingent upon genetic variation already present in the population. When environmental change occurs too rapidly, mutational opportunities are limited by reduced population size, and entire sets of mutations may be eliminated as evolutionary options. The UW researchers evolved hundreds of populations of *E. coli* under environments made ever more stressful by the addition of an antibiotic, which was ramped up at gradual, moderate and rapid rates. Isolates in the "gradual" and "moderate" treatments were likely to have multiple mutations conferring antibiotic resistance, while those in the "rapid" treatment only had a single mutation. Thus, faster environmental change closed off evolutionary paths that were accessible under slower rates of change. The findings have implications for those concerned about antibiotic-resistant organisms as well as those considering the effects of climate and global change. (H. Lindsey, J. M. Gallie, and B. Kerr, 2013, Evolutionary rescue from extinction is contingent on a lower rate of environmental change, *Nature* 494: 463-466.)

C. Titus Brown (MSU) is frequently quoted about the "big data" challenges resulting from the growing use of next-generation sequencing, and he has taken on the task of educating today's graduate students, postdocs, and faculty in how to address these challenges. Brown was awarded funding from NSF of over $200K (supplemental to the main BEACON cooperative agreement) to address the cyberinfrastructure needs of BIO centers and center-like institutions. This project is accomplishing the following goals: (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. These workshops are being designed and offered in partnership with SESYNC (Socio-Environmental Synthesis Center) and NESCent (National Evolutionary Synthesis Center). In addition to workshops and bootcamps offered at BEACON institutions, Brown and collaborators are offering "software carpentry" workshops around the world. For more information, see http://software-carpentry.org/.

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 towards the goals and metrics described in our strategic plan.

GOAL	METRICS	PROGRESS
Integrative Research Goals		
New research collaborations and proposals	Number of interdisciplinary/multi-institutional research projects and publications	54 projects currently underway, 460 publications to date (132 in the current reporting period)
	Service by members on doctoral research committees across disciplines and institutions	We are aware of many faculty members serving on committees of this kind. However, these data are not

		available in any publicly accessible records, making it very difficult to track, and we are removing this metric from our strategic plan.
New paradigms for research in organic and digital domains	Number of new sessions at scientific meetings or scientific meetings hosted at BEACON	At least 1 in 2013
	Number of new journals and societies	None to report yet
	New or increased funding for biocomputational research	BEACON researchers submitted at least 55 proposals for >$25M of external funding relevant to BEACON, and >$12M 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.	Using Google Scholar as a tracking tool, we are seeing a steady annual increase in BEACON publications and in citations.
	High visibility science journalism about BEACON research	12 press releases and >70 media pieces so far in 2013, including high profile pieces in *Los Angeles Times*, CBS News, BBC News, *Discover* magazine, *Psychology Today*, and *National Geographic*
Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	Number of requests for information	~5,600 downloads of Avida-ED, over 4,000 downloads of Avida, over 3,200 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.	Over 90% reported completion by Oct 28, 2013; on track for 100% of participants to fulfill their requirements by December 2013.
	Change in frequency of ethics violations.	No violations to report.
Center participants will	Baseline and follow-up	New Scientific Virtues

embody general scientific norms/virtues, including objectivity, integrity, community, and transparency.	participation in a Scientific Virtues workshop.	workshops piloted in spring and summer 2013, more to come in 2014
Respect for views and ideas "horizontally" and "vertically."	Number of Toolbox seminars and trials	Toolbox workshops have been redesigned for Scientific Virtues training; workshops piloted in spring/summer 2013
	Number of BEACON participants who get cross-disciplinary training	Toolbox workshops have been redesigned for Scientific Virtues training; workshops piloted in spring/summer 2013
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	132 publications submitted, 161 conference or other presentations, 55 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.

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 19 projects are currently supported in this thrust group, which fall into three broad themes: evolution within genomes, the process of adaptation, and the process of speciation. 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 22 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. Thirteen 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	To date, 30 BEACON students have reported receiving degrees (4 Bachelors', 11 Masters', and 15 PhDs). Of the PhD graduates, 60% are currently in postdoc positions, 13% are in faculty positions, and 27% are working in industry. 2 of 3 former BEACON postdocs are in faculty positions (66%), while 33% are in industry.
Increased public literacy in	Development of educational	Testing, presentation, and

evolution and the nature of science	materials.	publication of educational materials across audiences is well underway. Evaluation instruments are being used to assess effectiveness.
	Adoption of materials by teachers; frequency of public use of online materials and visits to museum 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 continues to offer 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. Louise Mead; and Multidisciplinary Approaches to the Study of Evolution taught by Drs. Charles Ofria, Ian Dworkin, and Chris Adami. 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, and especially on involving undergraduates in research through summer REUs but also through opportunities available during the academic year.

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 at Kellogg Biological Station (MSU). Lessons learned here can help in training others to prepare similar programs. BEACON and BioQUEST joined together to offer a 5-day workshop for science educators called

"Unleash your inner scientist: Employing and enjoying inquiry in the classroom and lab." BEACON is developing teacher training and educational materials including evolutionary games for elementary students and software that engages undergraduate students in testing evolutionary hypotheses. We also have a number of educational activities that target the general public, including an evolution podcast and museum exhibits at MSU and UT, as well as a citizen science project in partnership with the Seattle Aquarium.

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**
New collaborative research with industry partners	The number of external industry/government laboratory collaborations with BEACON through its member universities	At least 11
	Number of joint grant proposals submitted with industrial partners	One in progress
	Number of publications submitted that arise from industry provided challenge problems and data	At least 5 in the current reporting period
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.
Dissemination and use of BEACON tools and data	Number of downloads of BEACON tools/data relative to baseline	~5,600 downloads of Avida-ED; over 4,000 downloads of Avida platform
Spinoffs formed	Number of spinoffs formed	No new spinoffs to report in the current period, but foundations are being laid for one

BEACON's Knowledge Transfer model includes 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 these and other collaborative relationships with industry partners.

Several companies are currently working with BEACON, including Ford Motor Company, Northrop Grumman, Continental Automotive, Chrysler, 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.

As noted above, Titus Brown has partnered with SESYNC and NESCent to develop and run workshops offering computer science training to biologists, within and beyond BEACON.

Education Director Louise Mead is working directly with the National Association of Biology Teachers 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. Mead is also working with NESCent on a number of educational activities, and Mead and Diversity Director Judi Brown Clarke held a catalysis meeting at NESCent on the topic of K-12 Evolution Education and the Underserved.

Diversity

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 are pleased to report that we are achieving and sustaining diversity at BEACON through strategic and inclusive recruiting and partnerships, as well as formal professional development opportunities, including ongoing formal mentoring training and support. Our biggest challenge over the past year has been increasing the participation of women at all levels. Participation of women in BEACON at the undergraduate level has long been above the national norms (this year, 43.5%, compared to 36.5%, weighted by field). This year, participation of women at the graduate level also exceeded national norms (36%, compared to 31.3%). Women are still slightly below national levels in BEACON postdocs and faculty (32% compared to 35.5% for postdocs, 29.4% compared to 31% for faculty), but we have seen respective increases of 19% and 33% over the past year. We will continue actively recruiting women at the postdoc and faculty levels in order to meet these goals.

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 due to new 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 has increased from 14% to 23% of all reported publications
	Number of new courses	One new course offered across institutions in Fall 2013
	Number of students enrolled in cross-disciplinary courses	Spring 2013: 15. Fall 2013: 45 in semester-long courses, plus ~100 in 2-day workshops on computational science for biologists
	Number of funding proposals submitted	22 of 55 grant proposals submitted (40%) reported as interdisciplinary (exceeding goal of 10/year); 13 of 55 (24%) inter-institutional
Increase in cross-institutional research and education	Number of paper/conference submissions	Reported cross-institutional publications has increased from 7% to 10% of all reported publications
	Number of new courses	One new course offered across institutions in Fall 2013. In addition, two short courses for biologists introducing them to modern computational tools and techniques were offered at multiple sites around the country, developed under a supplement to BEACON.
	Number of students in cross-institutional courses	Spring 2013: 15. Fall 2013: 45 in semester-long courses, plus ~100 in 2-day workshops on computational science for biologists
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	BEACON researchers submitted 55 proposals for >$25M of external funding, and >$12M in external

		funding has been granted
	Award dollars	BEACONites have been awarded over $12M in this funding period, far exceeding goal of $5M/year
Increase in new participants	Number of faculty, post-docs, and students [Goal: 50%, 100%, 50% increase (respectively) from baseline (November 2010) by October 2015]	This goal has been achieved. Faculty participants increased from 47 to 85 (81% increase); postdocs increased from 14 to 31 (121% increase); grad students increased from 57 to 129 (126% increase)
Effective support of Center operations by Management team	Survey for participants about management team	Year 3 evaluation was positive but revealed areas for improvement, which we are addressing
	Feedback from External Advisory Committee	Feedback has been positive (Appendix C)
Center is perceived by NSF as exemplary	Renewal of NSF funding	Renewal was approved for our fourth funding increment, and we have received positive feedback from NSF
	Number of public mentions made by NSF about BEACON	At least two BEACON studies were featured on the front page of nsf.gov in 2013

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). As a result, we have seen large increases in the percentage of BEACON-related publications and grant proposals that can be considered interdisciplinary and inter-institutional. Details about this process and the results are provided in Section VII (Management).

BEACON Organizational Formative Evaluation Report. Each year since its inception, BEACON has charged a team of experts on organizational evaluation, led by Drs. Patricia Farrell-Cole and Marilyn Amey, to study BEACON and report on the attitudes of participants, practices of management, and other related issues that might reveal desirable changes in BEACON's structure or procedures. We have gained a great deal in the early years from these studies, particularly about how BEACON is perceived by students and postdocs at partner (non-MSU) schools. We have taken many steps to try to improve the sense of connectedness among all BEACON participants. In spring, 2013, the evaluation team surveyed a large number of graduate students and postdocs across all 5 BEACON schools about BEACON's management, policies, organization, and communications. Results of that survey confirmed that the vast majority of BEACONites were very satisfied with BEACON's operation and glad to be associated with BEACON. At the same time, we learned some things that can be improved in the

future, and we are working to address these. More details are provided in Section VII (Management).

Center-Wide Outputs

Publications submitted: 132 reported

Conference presentations and other dissemination activities (including lectures, seminars): 161

Awards and Honors: 33 awards and honors reported

Students that graduated (reported): 4 PhD's, 1 Master's, 1 Bachelor's

General outputs of knowledge transfer activities: 1 invention disclosure, 4 patent applications

Participants: 300 participants, plus another 309 affiliates (under 160 hours/year in Center activities), for a total of 609 BEACONites

Media publicity: In 2013, we have put out 12 press releases so far. Over 70 features on BEACON research appeared in the mainstream and online media in the last reporting period.

Indirect/Other Impacts

International activities: Two faculty members from China (Professor Lihong Xu, Tongji University and Meng Yao, East China Normal University) visited in BEACON in 2013, each funded primarily by the visitor's host institution or a grant from their government; they brought 3 students with them. Dr. Oliver Chikumbo also visited from New Zealand. All of these researchers engaged in collaborative research with Director Erik Goodman and other BEACON participants on three projects described under Research. 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 to grow into larger projects. The Center's overall goals and objectives have not changed since the last reporting period.

In the current reporting period, a total of 54 research projects were supported by BEACON, including 24 projects that just began in summer/fall 2013. 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	54 projects currently underway, 460 publications to date (132 in the current reporting period)
	Service by members on doctoral research committees across disciplines and institutions	We are aware of many faculty members serving on committees of this kind. However, these data are not available in any publicly accessible records, making it very difficult to track, and we are removing this metric from our strategic plan.
New paradigms for research in organic and digital domains	Number of new sessions at scientific meetings or scientific meetings hosted at BEACON	At least 1 in 2013
	Number of new journals and	None to report yet

	societies	
	New or increased funding for biocomputational research	BEACON researchers submitted 55 proposals for >$25M of external funding, and >$12M 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.	Using Google Scholar as a tracking tool, we are seeing a steady annual increase in BEACON publications and in citations. (See figure below.)
	High visibility science journalism about BEACON research	12 press releases and >70 media pieces so far in 2013, including high profile pieces in *Los Angeles Times*, CBS News, BBC News, *Discover* magazine, *Psychology Today*, and *National Geographic*
Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	Number of requests for information	~5,600 downloads of Avida-ED, over 4,000 downloads of Avida, over 3,200 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.	Over 90% reported completion by Oct 28, 2013; on track for 100% of participants to fulfill their requirements by Dec 2013.
	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.	New Scientific Virtues workshops piloted in spring and summer 2013; more to come in 2014
Respect for views and ideas "horizontally" and "vertically."	Number of Toolbox seminars and trials	Toolbox workshops have been redesigned for Scientific Virtues training; workshops piloted in spring/summer 2013
	Number of BEACON participants who get cross-	Toolbox workshops have been redesigned for Scientific

	disciplinary training	Virtues training; workshops piloted in spring/summer 2013
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	132 publications submitted, 161 conference or other presentations, 55 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 challenge 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 and networking sessions for students and postdocs: We held our fourth annual BEACON Congress in August 2013. This year's Congress was lengthened to a total of 4 days (one day is student/postdoc only), which was well received. Feedback from participants in previous years suggested the need for more structured interaction opportunities, so we piloted "Meet the Professors" lunches. Faculty signed up to host a small group of 4-5 students and postdocs for discussion about research and career mentoring. Students and postdocs signed up for specific faculty members. The program was extremely popular and will be refined and repeated.
- **BEACON Intranet profiles**. We are continuing to upgrade 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. Significant progress towards this goal was made in 2013, and we anticipate full completion by early 2014.
- **Weekly seminars**. We hold weekly meetings 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.

These strategies, combined with ongoing attention to the need for clear communication and inclusiveness, are working well, and we will continue to use these methods and refine as needed.

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 19 projects are currently supported in this thrust group, which fall into three 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 focuses on evolution within genomes – for example, understanding why certain genes cluster together. 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.

Evolution within genomes

Several BEACON projects are focused the evolution of genomes and the way genes interact, including describing patterns of epistasis in biological systems, coevolution of genome sections, and the evolution of the genetic code.

Scott Harrison (NCAT), Julius Jackson (MSU), and Justin Zhan (NCAT) are **investigating coevolution of genome sections in gram-negative bacteria**. Recombinational change is associated with how bacterial populations succeed in switching between environments. To investigate the impact on physiologic function and association with microbial habitat, the team is examining the arrangement of genes associated with the biosynthesis of the cytoplasmic membrane, cell wall and outer membrane in Gram-negative bacteria. As a case scenario, prophages have been identified as a cause of change in some emergent disease-causing enteric bacteria. They seek to specifically address the likelihood by which prophages affect genomic organization. A final objective was to establish a scalable infrastructure by which this analysis may apply to all fully sequenced Gram-negative genomes across an even wider range of recombinative mechanisms. Significant odds ratios were calculated based on pathogenicity status and proximity to a prophage 2x2 contingency tables across the various different COG categories. Proximities that were evaluated were for a series ranging from 500 bp to 10,000 bp. COG category “M” (cell wall/membrane/envelope biogenesis) was the most distinctive category found in this analysis. A GALAXY tool was developed to allow for features of strain selection, prophage heuristic, statistical method, and series of proximities to be evaluated. This tool establishes an extensible software framework for incorporating a wider range of bacterial genomes and prophage-associated attributes for further analysis.

Julius Jackson (MSU) and Erik Goodman (MSU) are **modeling metabolic gene clustering in bacterial chromosomes using a custom-crafted computational evolution platform**. Although many models have been proposed to explain the presence of gene clusters in prokaryotes, scientific consensus has not been reached on the validity of these models. In order to elucidate the origin and selective pressures for gene clusters a computational model has been made which simulates the evolution of prokaryotic chromosomes. By changing the selection and mutation mechanics in the simulation, the models of gene clustering can be assessed. In particular, the persistence model, and the protein immobility model (PIM), which was proposed by Julius Jackson, have been investigated with this simulator. The code has been updated to examine dozens of organisms at once to explore trends in populations instead of just one organism. Multiple trials can be run in parallel to efficiently examine the effects of changing a parameter within the program; each one of these trials also outputs a record of the data generated in the run and plots of the variables of interest. By changing which organisms are selected to reproduce, the team noticed that organisms that have clusters seem to be more resilient to mutations that delete essential genes than organisms without clusters. Specifically, in simulations where only organisms with significant clustering were allowed to reproduce, there were far fewer deaths due to the loss of an essential gene than under random selection for reproduction. In future work, they will record data regarding likelihood of cluster formation and dissipation under random mutation and reproduction. Additionally, they will record data concerning the expected rates of survival of clustered and non-clustered organisms. Such observations these will be used to support mathematical formulations addressing the benefits of gene clustering under the persistence model. Although the current implementation of the code allows for powerful simulations to be run to investigate the phenomenon of gene clustering, additional features will be added to determine the following clustering dynamics. (1) The rate at which clusters spontaneously appear in non-clustered organisms. (2) The rate at which clusters increase and dissipate in organisms that have gene clusters. (3) The benefits of gene clustering due to the persistence model alone. (4) How horizontal gene transfer effects the transmission of non-clustered and clustered genes. (5) How the inclusion of other models such as PIM effects clustering dynamics. (6) The effect of simulating metabolic pathways with multiple gene interactions.

Robert Heckendorn (UI), Richard Lenski (MSU), and graduate students Sudarshan Chari (MSU) and Maxwell McKinnon (UI) are working to **cross-fertilize of techniques for epistasis from evolutionary computation and biology**. This project strives to blend algorithms from the evolutionary computation world with approaches and knowledge of practical biology to create new techniques for analysis of epistasis and new perceptions of epistasis in the biological world. The specific goals are: 1) Implement an algorithm for epistasis given limited data. Specifically the algorithm will compute epistasis if it is known that there are no epistatic interactions of order larger than some k. 2) Alter the decision point in the algorithm for when to explore higher orders of epistasis. 3) Investigate whether the results from the algorithm for missing data is actually a best fit. 4) From a practical standpoint, test for the best way to interpret missing fitness data or fitness data that cannot be measured because of lethals. 5) Explore whether it is possible to predict higher order epistasis from lower order epistasis because of some underlying biological

mechanism. 6) Apply this work to data from Ian Dworkin's lab on *Drosophila* that specifically has the opportunity for third order effects. 7) Improve the test for zeroness of an interaction.

Jeff Barrick (UT), Shin-han Shiu (MSU), and Chris Waters (MSU) are **searching for self-encoded RNAs -- remnants of the RNA world**. The goal of this project is to test the hypothesis that bacterial cells contain self-encoded RNA molecules (seRNAs). seRNAs are defined as heritable RNA elements that do not have a corresponding DNA template. The team's preliminary analyses of RNA sequences from *Escherichia coli* suggested that this bacterial species contains 13 potential seRNAs as these RNA sequences are not complementary to any known DNA sequences. The team is testing if the 13 potential seRNAs can be detected in *E. coli*, determining if these sequences are found in other RNA sequencing datasets, and identifying additional potential seRNAs. They also plan to collect similar RNA-seq data for exponential and stationary phase cultures of *Acinetobacter baylyi* ADP1 and *Deinococcus radiodurans* DR1 bacteria to extend this study to other species.

Jeffrey Barrick (UT) and postdoc Colin Brown (UT) are studying the **evolutionary origins and engineering applications of bacterial DNA secretion machinery**. Extracellular DNA (ecDNA) is produced by many bacterial species, and plays important roles in biofilm formation and horizontal gene transfer. While most ecDNA is produced by cell lysis, at least one example of active, regulated DNA secretion has been identified, mediated by a Type IV secretion system (T4SS) in some strains of *Neisseria gonorrhoeae*. T4SS-based DNA secretion systems have a wide range of potential bioengineering and synthetic biology applications, but *N. gonorrhoeae* is genetically unstable and difficult to culture. Barrick and Brown's goal is to recreate a similar DNA-secretion system in *E. coli* by modifying the T4SSs used by conjugative plasmids for cell-cell DNA transfer. They are developing assays and selection strategies for identifying and isolating DNA secreting mutants from these plasmids.

Jeffrey Barrick (UT), Scott Harrison (NCAT) and Robert Newman (NCAT) are **illuminating evolution in action with an expanded genetic code**. The triplet nucleotide code for the translation of genetic material was among the most revolutionary innovations in the early evolution of life. It introduced proteins as the dominant functional biopolymer, displacing what may have been an earlier RNA world. Little is known about the origins of the genetic code or about how it continues to evolve today. Is the current genetic code optimal, providing the perfect combination of chemical diversity and robustness to mutation, or is it a "frozen accident", which may have turned out quite differently if the history of the earth was replayed? Under what conditions can the genetic code be stably altered or expanded by ongoing evolution, and with what varieties of amino acid side chains? What yet unforeseen novel functions may non-canonical amino acids (ncAAs) impart on proteins? This team seeks to define the conditions necessary for a stable expansion of the genetic code using mutually informative evolution experiments with digital organisms, fluorescent proteins, and microorganisms.

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, and empirical studies of the response of organisms in natural systems to ongoing climate change.

Charles Ofria (MSU), Ian Dworkin (MSU), MSU postdocs Aaron P Wagner, David Bryson, and Dave Knoester, and MSU graduate student Abhijna Parigi are studying **variability selection, ecological dynamics, and the evolution of adaptive complexity**. Adaptive complexity – heightened capacity for contingent responsiveness – is hypothesized to have evolved in humans as a consequence of an increased tempo of environmental change occurring between 500 and 390 ka. This 'variability selection hypothesis' is supported by Paleolithic records showing pronounced jumps in human brain size and behavioral flexibility corresponding with unusually large climate shifts and correlated turnover in the mammal fauna. The hypothesis suggests that climate-linked variability selection at that time favored innovations for traits enabling adaptive complexity, rather than directionally selecting for traits optimized for current (temporary) conditions. Accordingly, the investigators are testing the role of environmental change as a primary mechanism of variability selection, and to resolve sources and patterns of change that significantly impact the evolution of adaptive complexity.

Specifically, the team is testing the generality of the variability selection (VS) hypothesis via: (1) Digital evolution experiments investigating the tempo and modes of biotic and abiotic environmental change that promote the evolution of adaptive complexity. The team used Avida to test whether abiotic environmental change (e.g., climate) over time favors the evolution of adaptive complexity. They tested whether organisms evolved to metabolize either 'arid' or 'moist' climate-sensitive food resources under different simulated conditions of climatic change, and found that populations experiencing no environmental change or increasing rates of change evolved only to specialize on single resources. However, large proportions of populations evolved to conditionally consume both resources when rates of change were moderate relative to generation time. The results generally support the VS hypotheses. However, in contrast to the hypothesis, an increasing rate of environmental change over evolutionary time does not appear necessary. Another prediction of VS is that it led to the evolution of resource trading strategies among human populations to mitigate resource-level uncertainties, e.g., trade of goods among populations separated by distance or geographical features and experiencing different conditions (drought, etc.). To experimentally examine the relationship between VS and the evolution of resource trade, the team is developing an evolutionary resource competition model that includes multiple populations, time-varying resource levels, and the evolutionary potential for resource sharing. (2) Biological evolution experiments examining how predators, as a dynamic source of biotic ecosystem complexity, can favor adaptively complex organisms. Specifically, can coevolving predators act as a source of environmental change imposing variability selection pressures on prey? Digital evolution experiments suggest that prey coevolved with predators have a greater likelihood of evolving contingent behavioral responses to environmental conditions than those evolved in the absence of predators. To extend this work and test the generality of these findings in biological systems, the team is now in the process of securing populations of the nematodes *Pristionchus pacificus* (predator) and *Caenorhabditis remanei* (prey) for experimental evolution trials. Finally, in a new set of digital evolution experiments, the

team will manipulate predator mutation rates to examine how rates of change in the biotic environment impact the strength of predator-imposed variability selection on prey.

Benjamin Kerr (UW), Charles Ofria (MSU), Robert T. Pennock (MSU), Eva Top (UI), Claus Wilke (UT), Larry Forney (UI), and postdocs Aaron Wagner (MSU), Arthur W Covert, III (UT), and Heather Goldsby (UW), plus graduate students Luis Zaman (MSU) and Joshua Richard Nahum (UW) and undergraduate Brittany Harding (UW) are conducting a multidisciplinary study of **adaptation in structured worlds**, specifically asking whether **slow and steady wins the race**. This project has two simultaneous goals: to explore the effect of spatial structure on adaptive evolution and to use spatial structure as an experimental variable to gauge the topography of a diverse set of fitness landscapes. Specifically, if a fitness landscape is comprised of multiple peaks varying in height, then a population that is structured (limited migration/dispersal) is predicted to obtain higher fitness and accumulate more mutations than a population that is unstructured. The team is addressing this prediction in evolving populations of plasmids, bacteria and digital organisms.

Members of the Kerr lab ran evolution experiments with a strain of *Escherichia coli* that was a poor grower (it bore several costly markers), and varied the degree of structure by controlling the topology of migration within a metapopulation. They found that structured populations (with restrictions to migration between subpopulations) obtained significantly higher fitness than unstructured populations (with no such restrictions on migration) after hundreds of generations of evolution, consistent with rugged landscape topography. The same isolates used for fitness assays were also sequenced at the genome level. We found that isolates from the structured populations had accumulated significantly more mutations than isolates from the unstructured populations (despite an equal number of generations). This second result is also consistent with landscape ruggedness.

In the Wilke lab, work with the Avida digital evolution system has revealed that structured populations of asexual organisms tend to improve the exploration and exploitation of fitness landscapes at certain intermediate migration rates. They tested three hypothesis as to the origin of the effect of population structure (I) increased passage through fitness valleys, (II) increased genetic variation, and (III) reduced clonal interference through a process called “leapfrogging.” Only the third hypothesis explains the improvement at intermediate migration rates. Competition between beneficial mutations may lead to clonal interference, resulting in slower evolution. Occasionally, a superior beneficial mutation will emerge on a genetic background older than that of beneficial mutations currently in the population. These superior beneficial mutations may rapidly sweep older beneficial mutations out of the population, a process called Leapfrogging. At certain migration rates, leapfrogging occurs with significantly greater frequency, reducing the effect of clonal interference and allowing structured populations to reach higher fitness. This finding shines new light on classical models of population genetics and suggests that we should reexamine our assumptions about the evolution of structured populations.

Jeffrey Conner (MSU), Ian Dworkin (MSU), James Arthur Foster (UI), Gregory Goins (NCAT), David C. Tank (UI), and graduate students Amanda Charbonneau (MSU) and Simon Uribe-Convers (UI) are studying **the genetic basis of weediness, focusing on the rapid evolution of flowering time in wild radish.** Evolution can be very rapid, especially when there

are major changes in the environment. One such change caused by humans was agriculture. Wild radish is one of the world's worst agricultural weeds, and has spread to every continent except Antarctica. The weedy form of this species differs markedly from their native ancestors from the Mediterranean region. The team is trying to elucidate the mechanisms of this rapid weed evolution using three complementary approaches: (1) phylogenetics to determine how many times weediness evolved in wild radish and what the native ancestor(s) were; (2) common garden studies to demonstrate genetic differentiation between weeds and natives for key phenotypic adaptations to agricultural fields; and (3) whole-genome tests for the signature of differential selection between weeds and natives to discover genes that evolved rapidly as wild radish adapted to agriculture. These results will improve the understanding of the mechanisms of evolution in action, and may be helpful in managing the weeds as well as breeding better crop radishes.

Postdoc Idelle Cooper (MSU), with Thomas Getty (MSU), Chris Klausmeier (MSU), Muraleedharan G. Nair (MSU), Molly Cummings (UT), and UT graduate student Eben Gering studied the **rapid evolution of damselflies in response to anthropogenic change and range shifts**. To integrate the understanding of evolutionary change at multiple levels (population, species, and biochemical), the team had the following goals: (1) quantify *Megalagrion* distribution and selection relative to UV levels, and build computational models to predict range shifts during anthropogenic change, (2) measure variation and selection on coloration in two local damselflies species that underwent a recent range overlap, *Calopteryx maculata* and *C. aequabilis*, and (3) determine the biochemical basis of *Megalagrion* damselfly pigmentation.

The team completed extensive surveys of Megalagrion species distributions and body color relative to UV levels and also measured natural selection on pigmentation in one species in a caged experiment. Seventeen damselflies species were surveyed on the islands of Kauai, Oahu, Maui, Molokai, and Hawaii. While they were interested in how species may persist through trait changes or species distribution changes, these responses will also affect species interactions, particularly because color is often used as a sexual signal for mating or species recognition. Cooper and Getty measured geographic variation in wing and body pigmentation in the overlapping ranges of sister species *Calopteryx aequabilis* and *C. maculata* 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, sexual selection experiments indicate that wing pigment is a signal of species identification, particularly for *C. maculata*. Preliminary work by Nair and Cooper 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. Eben Gering at UT-Austin identified an abundant red species in Texas, *Telebasis salva*, to serve as an alternative pigment source for the biochemical analyses. Continuing work will involve researchers from James Madison University (where Cooper is now a faculty member) to 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.

Postdoc Aditi Gupta (MSU) and Chris Adami (MSU) are **studying the evolution of drug resistance in HIV populations**. Due to their high mutation rate, a population of rapidly evolving viruses is composed of similar variants, termed quasi-species. Evolutionary theory states that in a quasi-species, selection acts on the entire group of similar variants instead of a single dominant variant, because the similar variants are capable of regenerating each other due to the high mutation rate. Gupta and Adami are investigating whether HIV populations show quasi-species behavior by doing serial infection experiments and reconstructing the variants in the population from next-generation sequencing data to determine the population structure and composition at several time-points. Investigating quasi-species behavior for HIV is critical to understand how the virus maintains all the required drug-resistance mutations with an error-prone replication system. They are testing the hypothesis that drug-resistant mutations are maintained at a population level, where similar viral genotypes carry subsets of the drug resistance mutations, with these subsets accessible to each other in close mutational neighborhood. Previous studies have focused on evolution of individual resistance mutations in dominant variants in the population, however, resistance is achieved by cumulative effect of correlated mutations, and rare variants can harbor resistance mutations even prior to treatment and thus are important to consider.

C. Titus Brown (MSU), Billie J. Swalla (UW), postdoc Kanchan Amol Pavangadkar (MSU), graduate students Elijah Kariem Lowe (MSU) and Max Maliska (UW), and undergraduates Kristin Andrykovich (UW), Ceri Weber (UW), Ian Michael Mahone (MSU) are examining the **evolution of heterochronic changes in gene networks to understand how changes in the genotype can radically alter phenotype**. They are developing genomic models for investigating chordate evolution that makes use of two closely related ascidian species (sea squirts, marine invertebrate filter feeders) that have dramatically different larval body plans. *Molgula oculata* eggs develop into freeswimming 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. The team has 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. They have also sequenced the genomes of *Molgula occulta*, *Molgula oculata* and *Molgula occidentalis*, a tailed molgulid ascidian that is gravid all year long from Florida. The genomes have been assembled and are beginning to be analyzed.

Benjamin Kerr (UW), Richard Lenski (MSU), Lauren Meyers (UT), Charles Ofria (MSU), Eric Klavins (UW), postdoc Rob Egbert (UW), and graduate students Rosangela Canino-Koning (MSU), Joshua Richard Nahum (UW), and Eamon O'Dea (UT) are examining the **evolution of evolvability**. Specifically, they are exploring evolvability mediated through contingency loci (locations in the genome that experience higher mutation rates). By engineering tandem repeat sequences in regulatory regions of selectable genes, they built a system in *Escherichia coli* in

which the evolution of contingency loci can be studied. They have also begun exploring ways to incorporate contingency loci in digital organisms (Avida).

Rob Egbert and other members of the Klavins lab have developed a mechanism for studying the mutability of translation initiation rates via the placement of mono- or di-nucleotide sequence repeats in the ribosome binding site spacer. They have characterized the range and resolution of gene expression using multiple Single Spacer Repeats (SSR) libraries driving the expression of green fluorescent protein, demonstrated the utility of the approach by fine-tuning three distinct functional modes of a mutual inhibitory genetic switch, and verified that SSR mutations can be observed in vivo when repeat sequences are propagated in a DNA mismatch repair deficient cell strain. As a demonstration of the utility of this system, the Klavins lab has selected a bacterial strain for better lactose utilization. They began with a strain of *E. coli* with its lacZ at a low level of expression, but possessing a mutable SSR upstream. This strain was cultured continuously in a turbidostat under limiting glycerol and excess lactose. Over 150 hours, they transitioned the environment from high to low levels of glycerol (with glycerol concentrations eventually becoming insufficient for growth as the sole energy source). This yielded a powerful selective advantage to any mutant that could utilize the lactose in the medium. After 50 hours, lactose---utilizing cells appeared and 40% of the culture was expressing lacZ at high levels after 100 hours. This evolutionary change was mediated by a repeat length mutation, demonstrating that adaptive change can be realized by these mutable elements

Grad student Luis Zaman, working jointly with Ofria and Lenski, performed research with Avida on digital host-parasite systems that had an unexpected twist: coevolving parasites promoted increased host evolvability. That is, hosts evolved genetic architectures that had increased rates of generating phenotypic resistance (escape mutants), even though the mutation rate itself was fixed. Members of the Ofria lab have also used Avida to study the effects of cyclically changing environments on the evolvability of digital organisms. Digital organisms have been placed in a environments that switch between rewarding and punishing the performance of the XOR and EQU logic tasks over cycles of 1000 updates. The final dominant organisms were analyzed to measure the number single-step and double-step mutations that would result in a loss or gain of XOR and EQU task expression. Compared to the controls, where organisms were grown in a static environment where one, both, or neither task were constantly rewarded, the treatment organisms had an order of magnitude more possible single-step or double-step mutational paths that resulted in gain or loss of XOR or EQU. This indicates that changing environments affect the mutational landscape of populations, pushing them toward areas that allow them to more quickly adapt to their environment.

Holly Wichman (UI), Tanya Miura (UI), James Bull (UT), and Martina Ederer (UI) are developing **a tractable animal model for experimental viral evolution**. They will develop a *Drosophila*-virus model system for experimental studies of viral evolution in a eukaryote. It will be used to ask whether results from experimental evolution of phage will generalize to other viral systems and will enable us to address new questions about the dynamics of viral evolution within populations of eukaryotic hosts. They have assembled a collection of 5 available *Drosophila* viruses, including infectious clones, and are currently developing tools and protocols for working with the most promising available viruses.

Postdoc Travis Hagey (UI), with Matt Riley (UI) and Parviz Soroushian (UI) is studying the **optimization of the gecko adhesive system**. To consider the biomechanics, patterns of diversity, and evolutionary history of the gecko adhesive system, this study is using computed tomography, finite element models, and genetic algorithm optimization approaches. Broadly, their goals include understanding the causal relationship between setal morphology and performance, incorporating variation in morphology and perch characteristics.

Postdoc Noah Ribeck (MSU), with Richard Lenski (MSU) and graduate student Carlos Anderson (MSU) is working on **incorporating frequency-dependent selection into Fisher's Fundamental Theorem**. The team plans to test a version of Fisher's Fundamental Theorem of Natural Selection that is modified to account for frequency-dependent selection using known examples from Lenski's Long-Term Evolution Experiment (LTEE), as well as Avida digital organisms. The goals are to complete competition experiments for a large number of clones from a particular time point in the LTEE where coexistence of multiple subpopulations is known to exist. They will compare this fitness variance data to newly developed theory to find out whether ecological considerations are enough to explain the known deviation in the data from Fisher's Fundamental Theory. They will do parallel experiments with Avida to test Fisher's Theorem first, and then introduce frequency dependence. They have completed fitness assays at a wide range of initial relative frequencies, and applied the data to our newly developed method for quantifying frequency dependent fitness. The result gives an accurate qualitative result for the ecological interactions that are known to exist in this system. The team now has specific plans for isolating a large number of clones from this population and to proceed with the experiment outlined above. They have also fully developed the theory to which these data will be compared.

Alexander Shingleton (formerly MSU), Jeffrey Barrick (UT), and graduate students Austin Dreyer (MSU) and Carlos Anderson (MSU) are studying the **evolution of canalization mechanisms**. 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. 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. The team 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. Currently they are modifying FOXO expression in vivo using genetic tools of *Drosophila melanogaster* and measuring the effect on genetic canalization; and testing for evolution of canalization mechanisms in Avida by modifying environmental and genetic inputs.

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, the role of environmental change in adaptation, and connecting so-called "microevolution" on a short time scale to the process of speciation over the long term.

Janette Boughman (MSU), Paul Hohenlohe (UI), Luke Harmon (UI), and Bree Rosenblum (formerly at UI, now at UC Berkeley) have been studying **the genetic architecture of multidimensional adaptation and speciation**. The primary case study is of multidimensional selection via sexual selection in sticklebacks. With MSU postdocs Jason Keagy and Liliana Lettieri, they have compared the fitness landscapes generated by male competition under different demographic conditions (high or low density of nesting males). They found different landscapes at different densities, and a rugged landscape at high density; both of which suggest that male competition has generated divergent selection on male phenotypic traits. They also found correlational selection that favors particular suites of male mating traits – the fitness peaks on this landscape correspond to the multidimensional phenotypes of the pure species, suggesting the male competition has played a major role in driving multidimensional adaptation. Currently, they are comparing selection through male competition to that generated by female choice. Graduate student Tyler Hether (UI) has used a set of genetic regulatory network models to explore the influence of network architecture on multivariate genetic variation and adaptation. He found the surprising result that network motifs effectively curve the M matrix of mutational variation across phenotypic space, and this has strong impacts on rates and trajectories of adaptation.

Jack Sullivan (UI), James Foster (UI), David Hillis (UT), and graduate students Emily Jane McTavish (UT) and Brice Sarver (UI) are working on an **integrated approach to testing the divergence-with-gene-flow model of speciation**. 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; e.g., Porter and Johnson, 2002). This second model, divergence-with-gene-flow

(DwGF), predicts that closely-related taxa may continue to differentiate despite high levels of hybridization and introgression. If DwGF is common, hybridization may be an important transient phase in speciation and introgression it also should be heterogeneous across the genome. This team is testing the predictions of DwGF in empirical (*in vivo* [in the chipmunk radiation] and *in silico*) and in simulated systems. So far, 58 mtDNA genomes from the *Tamias* radiation have been assembled. Preliminary phylogenetic analyses of the complete genomes confirm the mtDNA introgression that has been detected using a single mtDNA gene. In addition, Sarver and Sullivan have automated a model-averaging approach to screen for selection. McTavish is developing simulations for this project.

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 22 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.

Risto Miikkulainen (UT), Kay Holekamp (MSU) and graduate students Andrew Booms (MSU) Eliana Feasley, Wesley Tansey, Aditya Rawal, and Padmini Rajagopalan (UT) are studying **social evolution and learning in computational and biological agents**. Spotted hyenas in the wild have many unique social and problem-solving behaviors. In this project, field observations and computational simulations were used to find out how these behaviors may have evolved over time and what role learning from conspecifics might have played; these insights were then abstracted and evaluated as general computational approaches to learning complex tasks. Four aspects of social interactions were addressed: problem solving, general intelligence, social ranking, and communication.

In problem-solving field experiments, hyenas were given a puzzle of having to open a box for a reward, and other hyenas were able to observe such behaviors. It turned out that their abilities to learn and generalize were relatively limited, mostly to allowing them to focus on the

right object rather than specific behaviors. The conclusion is that hyenas possess only a limited ability for general intelligence; their intelligent behavior is largely limited to specific tasks. A possible explanation is that their brain structures that are less interconnected and interactive (as compared to e.g. baboons, which live in the same environment and display more general intelligence). Preliminary computational experiments with neural networks with different connectivities show that dense such interconnectivity indeed makes generalization easier in pattern recognition tasks at least. In future work, this principle will be applied to tasks in simulated predator-prey environments. The origins of social ranking and communication were studied in a series of computational experiments. The ranking experiments focused on identifying the reason why the ranking structure is so strong in hyena clans. The experiments showed that ranking could have evolved as a way to conserve the health of all the hyenas in a clan so that they are better equipped to defend their territory against other hyena clans. The communication experiments focused on the evolution of a common code for communication (especially during hunting), and whether such a code could have emerged from already existing signals for other tasks such as mating. Future work will include simulating different forms of communication (sight, smell, touch and hearing), and integrating these with other simulated behaviors. Social evolution and learning were abstracted computationally into the Egalitarian Social Learning method (ESL), and it was demonstrated to improve on the traditional teacher-based model. A set of computational experiments were further conducted to test the hypothesis that social learning facilitated adaptation to new or changing predators, extending the method to include negative feedback, and to an engineering application of cybersecurity. The initial results were promising, but more work is necessary to obtain conclusive results.

Christoph Adami (MSU), Fred Dyer (MSU), Robert T. Pennock (MSU), and Peter Stone (UT), with postdocs Frank Bartlett (MSU), Arend Hintze (MSU) and Dave Knoester (MSU) plus graduate students Randy Olson (MSU) Jesus Rivera, and Mike Wiesenauer (MSU) are studying the **evolution of cognition, communication, and social coordination** in both biological and artificial systems. The aim is to use digital evolution in multiple platforms, as well as biological data, to explore (1) the emergence of mechanisms for the communication of navigational information (direction and distance of a goal) from one individual to another in a social group, as is done in the guidance of insect swarms or the communication system of honey bee dances, and (2) how the algorithms that evolve for these problems can be used to guide the search for more flexible algorithms for robotic control in the context of multi-agent reinforcement learning problems. The team is using digital evolution (in both Avida and Markov Networks) to examine the evolutionary preconditions and selection pressures that enable behavioral entrainment to arise, and to determine conditions that favor the evolution of more complex symbolic communication of navigational instructions. Observations of bees will be used to test the hypothesis that a common mechanism underlies communication in both swarms and in dances, and to explore the information content of the signalers' behaviors. Data from biological and digital evolution will be integrated in models that combine reinforcement learning and evolutionary optimization to develop improved algorithms for multiagent systems. The team will also enrich both theoretical and applied dimensions of the project by systematically examining the notion of robustness by exploring the evolution of so-called self-* ("self-star") properties, where * is a placeholder referring to several dimensions of robustness, specifically self-healing, self- adapting, self-organizing, and self-managing.

Benjamin Kerr (UW), Charles Ofria (MSU), Wenying Shou (UW), and postdoc Brian Connelly (UW) are collaborating on a project titled **Genetic Niche Hiking: A New Hypothesis for the Evolution of Cooperation**. This project is centered on investigating whether stressful conditions facilitate the evolution of cooperation through a "genetic niche hiking" process, whereby mutations that improve stress tolerance have more chances to arise on the cooperator background in a structured habitat. They are addressing the connections between stress and cooperation in a microbial system (*Pseudomonas aeruginosa*) as well as a digital system (AVIDA). Two technicians (Sarah Hammarlund and Katie Dickinson) are investigating the genetic niche hiking process using the pathogenic bacterium *Pseudomonas aeruginosa*, which mediates cooperative acts through quorum sensing. The project uses two strains of *P. aeruginosa*: a quorum sensing "cooperator" that produces public goods, and a quorum sensing defective "cheater," which benefits from these public goods without incurring the cost of their production. They have confirmed that this social dilemma exists in a minimal medium where public good production is necessary for high levels of growth. Two experimental pilot runs have been performed to test the genetic niche hiking process, with the antibiotics rifampicin and streptomycin as stressors, and procedures have been developed for a control treatment that precisely matches the bottleneck provided by the antibiotic stressors. Conditions for a large-scale experiment are now being determined. In addition, Brian Connelly, a post-doc, has developed a population-level computational model that allows the genetic niche hiking process to be studied. Using this model, the team has begun to examine the effect that initial population composition, propagule size, the number of possible stress tolerance mutations, and fitness effects have on a population's ability to maintain cooperation.

Chris Adami (MSU), postdoc Arend Hintz (MSU), and graduate student Jorden Schossau (MSU) are working on the **thermodynamics of evolutionary games** to improve the game theoretic approach to the study of the evolution of cooperation. Specifically, they are investigating whether an approach based on mathematical physics can make the analogy between phase transitions in statistical physics and the critical dynamics of evolutionary games more formal. For the one-dimensional spin-model (similar to Ising models) that they have investigated, the analogy is perfect, that is, one can derive an analytic formula for the fraction of cooperating players in a well-mixed one-dimensional system that matches the evolutionary simulations almost exactly. In prior investigations of the Public Goods game, the iterated Prisoner's Dilemma, or rock-paper-scissors like games, we always observe that the outcome of the evolutionary process critically depends on a single parameter. Varying this parameter causes an abrupt change in the winning strategy, from defective to cooperative. In some cases it is possible to move the parameter beyond the critical point without experiencing a sudden transition, but instead observed a delayed response—a hallmark of hysteresis. Hauert and Szabo (2005) have demonstrated that the Prisoner's Dilemma can be described using methods from statistical mechanics, applying mathematical methods that are usually used to describe critical phase transitions like the ones found in the Ising model, they showed that these can predict the outcome of the Prisoner's Dilemma. However, for more complex games such as the Public Goods game, such an analogy has not been made. By constructing a Hamiltonian that stands for the payoff matrix of the Public Goods Game, the resulting mathematical description fits the evolutionary simulation almost exactly. This description can be extended to the Public Goods game with

punishment, where the punishment fine plays the role of a magnetic field. In that case, hysteresis is readily observed, and the theoretical formula almost exactly describes the evolutionary simulation.

Kevin Theis (MSU), Kay Holekamp (MSU), Thomas Schmidt (formerly MSU, now University of Michigan), Charles Ofria (MSU), Benjamin Kerr (UW), Tracy Teal (MSU) and Luis Zaman (MSU) are testing hypotheses about **scent marking mammals, their microbial symbionts, and the hologenome theory of evolution**. Each animal species has coevolved with suites of symbiotic microbes, the vast majority of which appear beneficial to their hosts. Symbiotic microbes are critical contributors to animal nutrition and immune health, and they serve as important catalysts for the effective development and function of animal tissues and neural circuitry. It is also becoming increasingly clear that symbiotic microbes can contribute to animal behavior. Specifically, they can protect their hosts from predators, increase their hosts' foraging efficiency and reproductive output, and mediate their hosts' communication systems. As a paradigm-shifting consequence of these realizations, biologists are increasingly viewing animals as holobionts rather than as autonomous entities. The objective of this project was to use microbial mediation of the scent marking systems of African mammals—primarily hyenas and digital models of hyenas—to begin testing predictions of the hologenome model of evolution.

The team has characterized the bacterial communities in the specialized scent glands of spotted, striped and brown hyenas. In each hyena species, these communities are dominated by anaerobic, fermentative, odor-producing bacteria. As predicted, the communities in the scent glands of the three hyena species are markedly different. The communities in the scent glands of spotted hyenas were very different from those in hyenas' other sampled organs. Collaborative meetings laid the foundation for developing digital experiments in Avida to elucidate principles of microbial mediation of animal chemical signaling systems. The team identified relevant elements of chemical signaling theory (e.g. efficacy, persistence, frequency and uniqueness), and determined the functions/operations in Avida that would enable them to model selection on those signaling elements. These models will ultimately reveal apparent principles in the evolution of microbial-mediated chemical signaling that can then be explicitly tested in the field. This work developed into a new BEACON collaboration between Kevin Theis, Heather Goldsby, Aaron Wagner and Danielle Whittaker (see next project).

Kevin Theis (MSU), Danielle Whittaker (MSU), Aaron Wagner (MSU), and Heather Goldsby (UW) are also working to **test the hologenome model of evolution using songbirds and digital organisms**. The specific goal of this project is to test the hologenome model of animal (and plant) evolution using behavioral and bacterial symbiont data on the chemical signaling systems of wild and digital songbirds. The specific research aims are to demonstrate that symbiotic bacteria are responsible for dark-eyed junco (*Junco hyemalis*) social odors, and evaluate the hologenome model of evolution using songbirds and digital organisms. The team is conducting a comparative study characterizing the bacterial communities of free-ranging songbirds, emphasizing their odor-producing preen glands; testing for the importance of bacterial symbiont communities in odor preference tests; and exploring the selective pressures that lead to the evolution of these symbiotic relationships using model preen gland bacterial communities in Avida. The digital experiments are designed to test key hypotheses regarding the evolution of

scent based signaling systems. To that end, three models have been identified: (1) Base model. The community of microbes within an organism must continually exude a high level of scent compounds. (2) Seasonal model. In this model, there is a cost to producing scent compounds, which degrade over time. Additionally, the compounds must be present during "breeding" season. (3) Signature-based signaling model. Microbes must produce scent compounds that communicate their species, gender, reproductive potential, and also specify their individual scent. Thus far, the team has successfully evolved groups of microbes (present within organisms) that meet the criteria defined by the base model. They are expanding our infrastructure to include degrading scent compounds, as well scent mechanisms for specifying species, gender, reproductive potential, and individual signatures. The models will be used to explore how scent communication is used by different organisms within nature, as well as to test hypotheses regarding the inheritance of microbes (and thus scent compounds) from the father, mother, or both.

In another study on the evolution of chemical communication, Heather Eisthen (MSU) and Barry Williams (MSU) are working to **pinpoint the genetic origins and functional co-option of a peptide pheromone**. Pheromones are molecules that evoke discrete behavioral and/or physiological responses from conspecifics. Amphibian pheromones tend to be peptides, affording the unique opportunity to study the evolution of genes coding for communication signals. The first peptide pheromone to be discovered was sodefrin, produced by newts (Cynops pyrrhogaster); genes coding for sodefrin-like peptides have since been found in other salamanders. Eisthen and Williams discovered a homologous gene for a sodefrin-like peptide in the genome of axolotls (*Ambystoma mexicanum*), which belong to a third family of salamanders. Homologs are present but without annotated function in humans, mice, frogs, and zebrafish, suggesting that this gene family is ancient. The evolutionary history and function of the gene family are unknown. The team is using bioinformatics tools to identify homology and copy number dynamics among sodefrin-like genes in animal genomes, and will also measure site- and lineage-specific rates of evolution across the history of the gene family. They will also examine neurophysiological and behavioral responses to sodefrin-like molecules in diverse amphibians.

So far, the team has characterized the evolutionary history of sodefrin-like genes in animals where thorough genome sequence data was available. The gene family is characterized by one or more three-finger domains (TFDs) on the N-terminus, large fluctuations in copy number among even closely related species, and the subset of the family consisting of sodefrin-like genes in salamanders are unique in harboring an additional C-terminal unstructured region. RtPCR cloning was combined with next-generation sequencing to identify ten homologous proteins expressed from the cloacal gland of adult male axolotls. Interestingly, the rate of evolution in the unstructured region of the protein is unmeasurably high, suggesting strong selection pressure for rapid diversification of these proteins, consistent with their roles as pheromones. This work constitutes the first large-scale examination of the evolution a family of pheromones.

In addition, all TFD-containing pheromone proteins in salamanders fall into three distinct families, suggesting the possibility that the proteins serve diverse functions. They are currently pursuing work to determine whether some of these proteins might function as antimicrobials in addition to or instead of functioning as pheromones. The team has also initiated electrophysiological studies with axolotls, and found that commercially-available newt sodefrin does not evoke neural responses from axolotls. This result is important as it demonstrates the

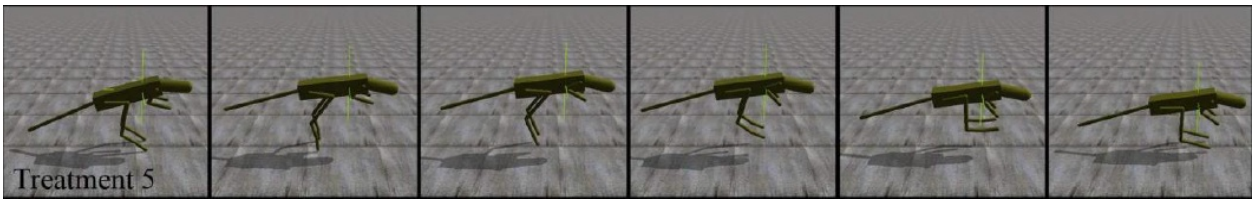
expected species-specificity of pheromone responses, and indicates that the olfactory periphery does not respond indiscriminately to all potential odorants.

Similarly, Heather Eisthen (MSU), Harold Zakon (UT), Luke Harmon (UT) and graduate student Ben Liebeskind (UT) are studying the **evolution of mechanisms enabling the use of a neurotoxin as a pheromone.** Many species of newts produce a neurotoxin called tetrodotoxin (TTX) that blocks the pore of voltage-gated sodium channels (VGSCs), causing paralysis and death in potential predators. Newts and other animals that produce TTX have evolved substitutions around the VGSC pore so that TTX no longer binds. Garter snakes that prey on newts (*Taricha granulosa*) are also evolving resistance to TTX, driving an arms race that is a paradigmatic example of evolution in action: in some areas of heavy predation pressure, *Taricha* produce more TTX than any other known organism. Complicating this scenario, experiments in the Eisthen lab indicate that newts can also smell TTX and are attracted to it, suggesting that TTX plays additional roles in intraspecific signaling. This project combines electrophysiological and pharmacological work to be carried out at MSU with sequencing and bioinformatics work to be carried out at UT, with help from scientists at UI. The focus on a single molecule that is known to interact with well-understood ion channels (VGSCs) in a specific way should reveal insights into the ways in which molecular evolution contributes to behavioral evolution.

Craig McGowan (UI), Philip McKinley (MSU), postdoc Anne Gutmann (UI) and graduate student Jared Moore (MSU) are working to **understand morphology, mechanics, and natural selection involved in the evolution of a locomotor trait: bipedal hopping**. The goal of this project is to understand why animals as diverse as kangaroos, wallabies, kangaroo rats, and jerboas all hop bipedally. 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.

The McKinley and McGowan Labs have conducted an initial study to examine which selective pressures lead to bipedal hopping and how these pressures shape general morphology and biomechanical parameters that relate to underlying muscle-tendon design. Specifically, they conducted a series of evolutionary treatments to investigate the effect of different initial (and evolvable) tail configurations on the evolution of effective hopping gaits. Using the Open Dynamics Engine, a library for simulating rigid-body dynamics, they developed a kinematic model that roughly approximates the function of muscles and joints using hinges with appropriate constraints. The team initially started with a fixed morphology resembling a kangaroo rat, but allowed evolution to modify the morphology, joint limits, and control (see figure below). The results showed that, first, even this simple model evolved locomotion patterns similar to those of natural organisms. Second, they found that a tail is essential to bipedal hopping, but that different configurations can lead to very different gaits, some closely resembling those of biological counterparts (namely kangaroo rats and wallabies), and others different from any known species. Third, while a close coupling among tail movement and the oscillation frequency of leg joints was observed, they discovered multiple configurations that

produced effective bipedal hopping behavior. Finally, they were surprised that many evolved tails had relatively low mass, as it is hypothesized that a heavy tail helps maintain a high moment of inertia in animals, producing a more stable gait. This result might represent a combination of morphology and behavior that could be effective in robotics, but is not exhibited in natural organisms today.



Sequence demonstrating bipedal hopping in an evolved individual from one of 5 treatments reported in the BEACON study (Moore, et al. 2013); video available at http://y2u.be/TniK0VHDAyU.

The McGowan lab continues to make progress toward developing a detailed musculoskeletal model of a kangaroo rat. Laser scans of kangaroo rat bones were used to construct a 3-D skeletal model. They currently in the process of refining the technique for measuring tendon travel to get more accurate muscle moment arm vs. joint angle curves for the leg muscles. These moment arm curves will be used to adjust muscle attachment sites in the model to ensure that the muscles produce realistic joint moments. Then the model will be implemented in forward dynamic simulations to quantify the influence of muscle-tendon architecture on normal hopping mechanics. The leg design will also be adjusted to match the designs that emerge in the physics-based simulator and compare the effect of different limb designs on muscle-tendon dynamics.

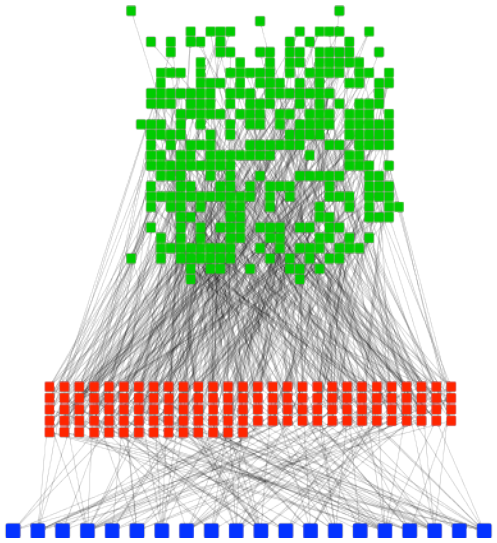
Evolving smarter electronic and robotic systems

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

Kalyanmoy Deb (MSU) and Erik Goodman (MSU) are working with Dr. Oliver Chikumbo, of Scion, a Crown Research Corporation in Rotorua, NZ on **robust evolutionary multi-objective optimization of practical rural land-use strategies, taking into account environmental impacts**. This project, now named the "WISDOM" system, has resulted in the development of a capability for processing the results of multiple computer simulations, producing a total of 14 measures or objectives as outputs, using evolutionary multi-objective optimization methods being developed in BEACON. It has now been extended to include the use of multi-criterion decision-making methods (MCDM) before and after the Pareto optimization step, to constitute a decision-making system that can accept input from multiple stakeholders and allow them to negotiate on the basis of the underlying scientific models. In a "wicked" land use problem in Rotorua, NZ, the process was tested with a very positive outcome, being embraced by the stakeholders as how they want to conduct such negotiations in the future. The evolutionary innovations that enabled finding a reasonable Pareto hypersurface on a problem with 14

objectives included changing from Matlab's built-in MOGA optimizer to a specialized version of Deb's NSGA-II called R-NSGA-II, then biasing the mutation operators away from solutions generally dominated by others and including a probabilistic, neighborhood-based "repair" operation to improve clustering of adjacent parcels to the same land use. Results on the Pareto hypersurface were plans that bore up very well under scrutiny by the stakeholders involved. Visualization of this Pareto hypersurface was aided by use of Hyper-Radial Visualization, a technique for mapping multiple dimensions into fewer (in this case, various subsets of the 14 dimensions to three dimensions at a time). This process helps to identify reference points for use in R-NSGA-II. After Pareto optimization, solutions (land use plans) in desirable areas of the hypersurface can be compared using a classical MCDM technique, AHP, the Analytical Hierarchy Process, to combine ratings by various stakeholders into an overall consensus ranking of the set of plans. Three papers have been published so far describing this work—one in the 2012 IEEE Congress on Evolutionary Computation (at IEEE World Congress on Computational Intelligence, Brisbane), one in Journal of Multi-Criterion Decision Making (forthcoming, 2013)—winner of the Society of Multi-Criterion Decision Making's Wiley Practice Prize for 2012-13—and one in the Genetic and Evolutionary Computation Conference, 2013, Amsterdam. The work is the subject of a proposal submitted to Living PlanIT, LLC, a British company that wishes to sponsor the team to re-implement the WISDOM system in their Urban Operating System, or UOS, so they can market the joint services for addressing large-scale "wicked" problems globally. Should this work be funded, it would represent a major transfer of technology from BEACON research into industrial practice.

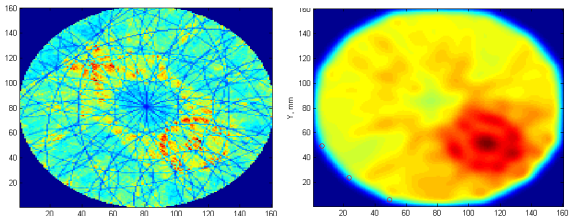
Chris Adami (MSU) and Risto Miikkulainen (UT), with postdoc David Knoester (MSU), postdoc Arend Hintze (MSU), and graduate student Samuel Chapman (MSU), are evolving a **256-node neural controller** to recognize human handwriting in a project they named **Darwin vs. DARPA**. The goal of this project 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. Adami and Miikkulainen's project is focused on evolving a Markov brain that recognizes the numerals 1-10 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



The structure of the Markov network from 250,000 updates with the highest individual testing accuracy. The green squares are the inputs corresponding to the pixels of the 28x28 image field. The red squares are the gates. The blue squares are the output nodes

deforming the initial images. The 6-layer network with 2500+2000+1500+1000+500+10 neurons achieved an error rate of 0.38% (misclassify 38 out of 10,000 test images) after 115 hours of computation time. The current world record architecture misclassifies 23 images. More realistic comparisons are non-parallel approaches that do not use image deformation. The famous deep-learning result 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. BEACON's evolutionary approach could not be any more different than what the literature has tried. Instead of massive neural nets, Markov brain networks, that is, networks of hidden Markov gates whose connectivity and function are evolved, are used. For this task, Adami et al. uses deterministic logic gates, which implies that the evolved networks are classical logic circuits. Because these circuits use digital inputs, the team converts 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 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, see figure above). 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. Using these tools, the BEACON team can evolve committees of brains that have, on average, an error rate of 6.5% on the test set. Because the network is essentially a digital circuit, it is easily transferred from one computational environment to another; for example, the team has used it on an Apple iPad to recognize digits drawn by the user on the screen. While the accuracy is probably sufficient for usage in mobile agent navigation, we believe that the image recognition accuracy can be improved significantly.

Other projects have important medical applications. John Deller (MSU), Erik Goodman (MSU), and Yao Meng (East China Normal University, visiting in BEACON) are **using evolutionary computation for the detection and classification of breast tumors using the Breast Tumor Microwave Sensor System (BRATUMASS)**. 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. The team's MATLAB code can now create 2D reconstructed contour images for a given dataset; however, due to the nature of the signal, certain artifacts persist, and removal of the "shadow" signal is currently being investigated using classical signal processing techniques. The figure above demonstrates the effects of "shadow signal" removal.



Simulated Dynamic Inversion Image (DII) before "shadow signal" removal (left) and contour image after "shadow signal" removal (right)

Results using Haralick features appear promising. Haralick features are a collection of statistical textural analysis terms based on the gray-level co-occurrence matrix. The team developed an image representation that illustrates the concentration of changes in dielectric constants by summing energy across arcs, which represents the behavior of the reflected microwave signals at a set of antenna locations. The doctor's surgical diagnosis is used as ground truth for defining each subimage as cancerous or normal. Then, using 5-fold cross validation with a linear classifier, every possible Haralick feature combination can be computed and the performance of each classifier evaluated based on (1) the classification accuracy and (2) the Matthew Correlation Coefficient.

System models that are linear in parametric structure, but arbitrarily nonlinear in signal operations, are identified using an approach with two novel components. The fundamental parameter estimation task (the "linear" part) uses a set-theoretic analysis of the data to deduce feasible sets of solutions in light of certain model assumptions. In turn, measurable set solution properties are used to assess the viability of nonlinear regressor functions that compete for "survival" as components of the model best fit to represent the system. The solution is formulated as a somewhat unconventional exercise in evolutionary computation.

In a related project, a team led by Chris Adami (MSU), Charles Ofria (MSU), and postdoc David Knoester (MSU) is **detecting and diagnosing breast cancer with evolutionary algorithms.** The goal of this project is to use evolutionary algorithms (EAs) to discover breast cancer detection and diagnosis strategies. They are specifically focusing on evolving Markov and neural networks to classify regions of mammograms into normal vs. cancerous tissue types. While the initial focus is on breast cancer, we anticipate that the techniques we develop will translate to other types of cancer. EAs are an ideal tool for cancer detection because of their ability to produce a population of disparate diagnosis strategies. These amount to many "digital second opinions" that can be used to inform radiologists' diagnoses. This project is the result of a partnership between the Departments of Computer Science and Engineering, Microbiology and Molecular Genetics, and Radiology, and the Clinical and Translational Sciences Institute at Michigan State University.

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 algorithm is based on a new multilevel selection framework that suits

computational needs, and applies Traulson's group selection model in biology to promote cooperation. This new algorithm improves both solution accuracy and evolutionary speed.

In another robotics project, Xiaobo Tan and Kalyanmoy Deb (MSU) are working on an **evolutionary design of artificial lateral line systems.** The lateral system is an important hydrodynamic sensory system for fish and many amphibians and plays an essential role in various behaviors of these animals. Inspired by the lateral line system, recent years have seen emerging interest in engineering artificial lateral lines, consisting of arrays of flow or pressure sensors, as a new noiseless sensing modality for the navigation and control of underwater robots and vehicles. Optimal design of artificial lateral lines is critically important for practical applications, but it is also challenging due to sophisticated flow-structure interaction dynamics and the vast design space for system parameters. This project is focused on evolutionary design methods for the engineering of artificial lateral lines.

Postdoc Joel Lehman (UT), with Risto Miikkulainen (UT), Chris Adami (MSU), and graduate student Randy Olson (MSU) is l**everaging human computation markets to evolve complex behaviors**. The focus of this project is to leverage markets for human computation (e.g. Amazon's Mechanical Turk) to advance the state of the art in automatically evolving complex behaviors in a computer. The central idea is to pay for the human judgment of non-experts to exert selection pressure for an algorithmic evolutionary process. The overarching goal of this project is to test whether purchasing human judgment can sometimes overcome the problem of deceptive local optima induced by mechanical fitness functions. This main goal can be subdivided into several sub-goals: (1) to create infrastructure for driving an evolutionary algorithm through purchased human judgment, (2) to implement appropriate domain experiments where success is limited by lack of effective fitness functions, (3) to implement control optimization algorithms against which to measure the proposed algorithm, and (4) to conduct experiments that compare optimization with a control algorithm with evolution driven by human judgment.

In a multidisciplinary spinoff of previous 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. The team at NC A&T has created a novel technique that is a hybrid of genetic and evolutionary computations and Local Binary Pattern (LBP) feature extractors; this technique is known as Genetic and Evolutionary Feature Extraction (GEFE). Whereas LBP partitions an entire image into patches and extracts features from each patch, GEFE evolves feature extractors represented by the dimension, locations and number of patch areas. The fitness function for feature extractors is the number of errors attained on a dataset of images plus the percentage of features extracted. In addition to GEFE being applied on a training set of images, a validation set can also be introduced that is mutually exclusive from the training set. During the evolutionary process, feature extractors from each generation will be applied on the validation set and the extractor with the best performance will be recorded. This feature is utilized in an effort to record

extractors that generalize well to unseen data. After evolution, optimized feature extractors as well as the recorded generalized feature extractors can be applied on a test set to of mutually exclusive images to test effectiveness. The generalized feature extractors had an accuracy of 73.16% on the testing set, while PCA obtained 43.58% accuracy and standard LBP obtained 56.41% accuracy. An Estimation of Distribution algorithm was used to evolve extractors due to the results of previous experiments with GEFE. The research is further extended by the application of a hybrid feature selection/weighting and GEC technique known as Genetic and Evolutionary Feature Weighting/Selection (GEFeWS). This technique evolves a mask for features, where features are either given a weight or completely masked out. GEFeWS was applied on the templates created by the optimal extractor evolved by GEFE. A group of students from Guildford Tech Community College (GTCC) worked on a summer project of applying GEFeWS on the fly wing dataset using a suite of Particle Swarm Optimizing algorithms (PSO) as well as EDA. The results show that all instances of GEFeWS outperforms GEFE. In addition to outperforming in terms of recognition accuracy, GEFeWS reduces the percentage of features by more than 50%.

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**. This is a joint project between BEACON Center for the Study of Evolution in Action, Michigan State University, and Tongji University, Shanghai, China. The goal is to develop greenhouse climate control strategies that balance between maximizing yield and minimizing resource consumption. The team uses NSGA-II, a multi-objective evolutionary computing approach developed by BEACON's Prof. Kalyanmoy Deb. NSGA-II performs Pareto optimization, which does not have bias for one objective over another, thus allowing them to explore broadly in the solution space. Models of greenhouse environment and crop are derived from Bram Vanthoors's A Model-based Greenhouse Design Method, and are used to train a custom-designed greenhouse controller. Real-world data that can validate the control strategies are being sought. The simulation of the greenhouse needs to be fast, so that it can be used as the evaluation method for the evolutionary computing algorithm to parameterize the controller. It must also be accurate, so that the solutions obtained can be applied in an actual greenhouse with desirable results. The current control strategy works by setting an environmental range (such as greenhouse internal temperature) that the greenhouse should operate in, rather than maintaining a single setpoint. The range is based on the current environment (such as light level and crop developmental stage), and could also (but does not yet) vary with external air temperature. The greenhouse controller will maintain those environmental parameters within the ranges dictated by the control strategy, ensuring maintenance of conditions that favorably tradeoff productivity of the crop versus energy costs. The solutions obtained using this approach performed better than benchmark solutions with a more conventional setpoint controller.

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.

Abdollah Homaifar (NCAT), Gerry Dozier (NCAT), Dukka KC (NCAT) and their graduate students are working on **biologically inspired solutions to computational problems.** The goal is to evolve network topology for classification, dynamic system parameter identification, and classification based on hierarchical structures. These applications are challenging and provide great opportunity to extend the domain of the applicability of the Markov Network Brain. They have worked on a diverse set of problems, incuding:

- *Hierarchical Multi Label Classification (HMC)* for computational prediction of protein function
- *Crowding niching-adaptive mutation (CAM)* method to handle HMC problems in gene function prediction using a sequential evolutionary crowding algorithm
- *System Identification and prediction* to understand the relationship between observed input-output data without having access to the dynamics of the system
- *Artificial neural networks with evolvable topology (ANNET)* to deal with system identification and time series prediction
- *Multiplexer Problem*: The team has applied Markov Network Brain (MNB) to a multi-level classification problem known as the multiplexer problem. The goal is to extend the application of MNB to evolve hierarchical structures for the multiplexer problem. A multiplexer is an electronic circuit that accepts n inputs and gives one output. For n inputs, there are 2n data lines. The goal is to learn the system to select one of the n inputs according 2n to the data line.
- *Gene regulatory network model inference*: Due to advents in high throughput technologies for measuring gene expression levels, it is now possible to infer (model) gene regulatory network. The team is comparing various evolutionary algorithms for quantitative gene regulatory network modeling, using both synthetic and real gene expression data, to find the fitness values of the best individuals at the end of optimization, robustness of fitness values, robustness to noise and scalability analysis.

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 develop the variable-length genetic algorithm in a general sense such that it could be applied to practical engineering design problems. The team is collaborating with the Composite Vehicle Research Center at Michigan State University to improve the impact resistance of composite plates through the inclusion of graphene. BEACON will help achieve this goal by using the variable-length algorithm findings to optimize the placement of graphene throughout the composite plates.

Evolutionary algorithms can even help with emergency response planning. Erik Goodman (MSU), with Robert Till of John Jay College of Criminal Justice, using **evolutionary optimization to improve emergency response planning using agent-based models to model human behavior**. This study uses Agent-Based Modeling to simulate the evacuation of urban traffic in the event of a chlorine spill. A commercial evolutionary optimizer controls execution of the simulator, seeking to optimize the behavior of traffic lights in the area in order to minimize deaths and injuries from the spill. Each time the NetLogo-based simulation runs, it calculates an impact: the number of drivers impaired plus ten times the number killed. A controller is evolved that manipulates the traffic light timings at each of the 64 intersections. Each time the simulation is run, the initial locations of cars and the location of the chlorine spill are determined by a random seed, allowing a traffic light timing to be tested under a variety of initial conditions. The team implemented stochastic optimization using the HEEDS Multidisciplinary Design Optimization Software originally designed by the PI. The multi-objective optimizer in HEEDS, called MO-SHERPA, is used to optimize for both mean Impact and its standard deviation. Using this strategy, the team was able to determine an optimized design with the fewest number of deaths.

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. Thirteen 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. 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.

Josephine Chandler (UW), Ben Kerr (UW), Ajai Dandekar (UW), Philip McKinley (MSU), John Mittler (UW), E. Pete Greenberg (UW), and Chris Waters (MSU) are asking, **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 focus is on populations of bacteria that cooperate conditionally based on density, through a process termed "quorum sensing" (QS). Through a set of genetic manipulations and evolution experiments, the team is 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). *P. aeruginosa* uses quorum sensing to regulate the production of many public goods. The wild-type "cooperator" produces a costly protease (public good). The mutant "defector" strain does not produce protease but benefits from these public goods without incurring the cost of their production. They have confirmed that this social dilemma exists in a minimal medium where public good production is necessary for high levels of growth. When grown alone in a medium requiring protease, the cooperator reaches a higher density than the defector. When grown together, the defector outcompetes the cooperator. This proof of principle sets up the approach for several studies currently being carried out in the Kerr lab and the Chandler/Dandekar labs. Postdoc Brian Connelly (UW) developed a biofilm formation system in Avida. He used this system to show that increasing resource abundance led to the evolution of cooperative biofilm formation. This increase showed a step-like response whereby populations above a certain threshold resource level evolved cooperation to the same extent. To test if a similar conclusion could be drawn from living systems, the experiments were repeated in the laboratory studying the evolution of biofilm formation in *Vibrio cholerae* grown in different resource levels. Indeed, the data derived from bacteria closely matched that observed for Avida. Graduate student Eric Bruger (MSU) is conducting a study of the evolutionary principles and dynamics of quorum sensing (QS) using *Vibrio harveyi* as a model system, and has found that QS, a putative cooperative behavior in bacteria, is more stable in high resource conditions. Eric was also able to develop a defined media that relied on QS for robust growth, and he has since used this media to show that the wild type QS system is more resistant to cheater invasion compared to a constitutively cooperating strain.

In a related project, Josephine Chandler (UW), Ajai Dandekar (UW), Ben Kerr (UW), Chris Waters (MSU), John Mittler (UW), postdoc Brian Connelly (UW) and graduate students Eric Bruger (MSU) and Becky Scholz (UW) are **exploring Hamilton's Rule in quorum sensing systems.** According to Hamilton's Rule, cooperation is favored in conditions where the cost of cooperation (c) is less than the multiplied effects of the benefits (b) and relatedness of the actor and recipients (r) (c<rb). Hamilton's Rule is a centering theme to address how quorum sensing

promotes cooperation by altering cost, benefits and relatedness in microbes. Using a combination of mathematical modeling and molecular and evolution approaches in experimental model systems (*Pseudomonas aeruginosa*, *E. coli*, *Burkholderia thailandensis*, and *Vibrio harveyi*), the team is 1) investigating how QS allows for cost-savings in cooperative traits, testing whether QS stabilizes cooperation by mitigating the cost to cooperators and/or 2) co-regulating 'private' or other goods; 2) investigating how benefit structure affects QS-regulated cooperation, to test the hypothesis that quorum sensing is likely to evolve when the benefit of cooperating increases with cell density; and 3) investigating how QS allows cooperation to occur among relatives, by co-regulating aggregation factors with cooperative traits like proteases. In the process of doing this work, the team has developed or adapted several critical techniques: 1) Freq-seq (Chubiz et al. 2012) to determine allele frequency by next-generation sequencing in natural and lab-evolved bacterial communities (Drs. Dandekar and Chandler and Ms. Smalley); 2) Digital PCR to enumerate variant alleles within a population without need for a marker (Dr. Chandler); 3) Mini-stats (Miller et al. 2013) to control population density for analysis of the cost-savings of quorum sensing systems (Ms. Scholz).

Maitreya Dunham (UW), Ben Kerr (UW), Charles Ofria (MSU), postdoc Heather Goldsby (UW), and graduate students Peter Conlin (UW), Elyse Hope (UW) and Anya Johnson (MSU) are studying the **evolutionary origins of phenotypic plasticity.** Briefly, the goals of the project are to select upon a clumping trait using yeast experimental evolution and to use this system as a model for understanding how environmental cues could direct the evolution of plasticity. The team is using both experimental approaches and computations modeling to accomplish this goal. Graduate students Peter Conlin and Elyse Hope are developing the laboratory procedures and experiments. Charles Ofria and Heather Goldsby have been exploring three key aspects of the evolution of phenotypic plasticity in digital organisms. First, they are continuing to explore the evolution of multicellular developmental programs with digital cells. They have developed infrastructure to provide the cells with additional capabilities that can be used to coordinate phenotypically plastic behavior. Second, they are in the midst of designing an environment that rewards organisms for exhibiting division of labor and phenotypic plasticity in a visual striped pattern. Such an environment will be invaluable for understanding and communicating the results. Third, they are identifying the central factors that govern the success of the team's problem decomposition algorithm and are working on applying this algorithm to problems in other domains. As the project proceeds, these results will be integrated with the experimental work.

Postdoc Jeffrey Morris (MSU), with Rich Lenski (MSU) and Ben Kerr (UW), is **using mathematical and experimental approaches to investigate the Black Queen Hypothesis**. The Black Queen Hypothesis (BQH) describes a scenario in which the loss of "leaky" biological functions, driven by fitness advantages gained by resource savings, can lead to stable ecologies that have the outward appearance of cooperation. The BQH was originally proposed to explain the dependence of marine cyanobacteria on "helper" bacteria to tolerate reactive oxygen species at the ocean's surface, but in principle could apply to many other interactions including nutrient transformations, habitat generation, and toxin removal. The focus of this project is to test the BQH using both wet lab and computational experiments, as well as to develop a more rigorous mathematical framework for understanding what conditions allow BQH interactions to develop

and persist. The specific goals are to test the hypothesis that hydrogen peroxide detoxification is a Black Queen function, to explore other putative Black Queen functions, and to develop a mathematical/computational framework for understanding the limits of the BQH. The team has completed a 1,200-generation evolution experiment following the dynamics of peroxide detoxification in a population of *Escherichia coli* in which a stable equilibrium arose and persisted between detoxifying "helper" cells and dependent "beneficiaries." Ongoing experiments use similar methods to explore the impact of added trophic complexity on the system: two different, mutually exclusive limiting resources in one case, and a heterotroph/autotroph system in another. The team's first BQH paper hypothesized that nitrogen fixation might be a Black Queen function, and they are now testing this hypothesis in two ways: first, by engineering mutants of the N2-fixing cyanobacterium *Anabaena variabilis* that are deficient in N2-fixation, and competing fixers with non-fixers to see if a stable equilibrium can develop in N-free media. Second, they are cloning the nitrogenase operon from *Klebsiella pneumoniae* into *E. coli*, and will experimentally evolve the resulting strain in the absence of fixed N to see if non-fixers can invade and co-exist with fixers. They are also interested to see how the rest of the *E. coli* genome adapts to the presence of the novel, highly demanding nitrogenase function. In addition to these specific examples, the team wishes to develop a more rigorous, abstract theory for the evolution of leaky functions. To these ends, undergraduate S. Papoulis and graduate student L. Zaman are adapting the Avida code to accommodate leaky interactions. Beginning soon, B. Kerr and a University of Washington graduate student will begin efforts at describing a "generic" BQH scenario using systems of differential equations and computational simulations.

Graduate student Octavio Campos (UW) is working with Ben Kerr (UW) to **integrate rapid prototyping, machine vision, and experimental evolution to explore floral phenotype diversification**. Campos is using a mathematical model of floral shape and computer-aided design software to produce 3-dimensional computer models of flowers, and a 3D printer to fabricate these as physical objects. Populations of artificial flowers will then be subjected to visitation by real pollinating animals, and behavioral data of animal visitation will be recorded. Visitation behavior will then be used to calculate measures of fitness for each flower morph present in the artificial flower population, and this information will be passed through an evolutionary algorithm to determine the phenotypic composition of the next generation of the flower population. By iterating this process, the team intends to make use of an experimental evolution approach to study whether different types of pollinating animals select for different floral shape evolution trajectories, and the extent to which these trajectories agree with published accounts of the traditional "pollination syndromes." The pollination syndromes are hypotheses regarding the association between specific pollinator types and specific combinations of floral phenotypic traits, implying coevolutionary links between pollinator type and floral phenotype. However, the pollination syndrome concept has seldom been rigorously tested. The team currently has a prototype system for automatically logging pollinator visitation events at artificial flowers. The system consists of infrared emitter and infrared detector diode pairs attached to each artificial flower in the population to log feeding events by pollinators. The system also makes use of custom position-tracking computer code for automatically tracking sequences of pollinator visitation during foraging trials. They are currently working on confirming that this system functions as intended when used with actual freely flying pollinators in a laboratory setting.

Heather Eisthen (MSU), James Foster (UI), Luke Harmon (UI), postdoc Kevin Theis (MSU), and graduate students Janet Williams (UI) and Patric Vaelli (MSU) are investigating **the role of symbiotic bacteria in a predator-prey coevolutionary arms race**. In their predator-prey coevolutionary system, prey (rough-skinned newt) possess tetrodotoxin (TTX) and are highly toxic, and predators (common garter snake) have evolved toxin resistance. Asymmetrical selection for increasing toxicity and toxin resistance have escalated these phenotypes to extreme levels such that a single newt prey is many times more toxic than necessary to kill several adult humans. TTX is found in many diverse animal lineages including dinoflagellates, nematodes, arthropods, molluscs, echinoderms, and vertebrates. This wide phylogenetic distribution suggests an exogenous origin for TTX in these animals, and indeed many distinct genera of TTX-producing bacteria have been found living symbiotically among toxic animals, or are present in the animal's diet by which TTX accumulates through biomagnification. Despite the identification of TTX-producing bacteria, the origin of TTX in amphibians remains controversial as some studies suggest that rough-skinned newts are capable of producing TTX on their own; however, the empirical evidence to support this claim is tenuous. This project has two aims: 1) Characterize the bacterial communities associated with newt tissues using next-generation sequencing and develop ecologically-guided cultivation media to effectively isolate putative TTX-producing bacteria (in progress). 2) Modify existing protocols for identifying TTX in biological samples to enable accurate and precise quantification of TTX in extracts from bacterial cultures (protocol designed, and experiments will being soon).

Benjamin Kerr (UW), Charles Ofria (MSU), graduate students Luis Zaman (MSU) and Sonia Singhal (UW), and undergraduate Mairin Chesney (MSU) are studying the **role of spatial structure in shaping coevolutionary patterns and processes**. Natural communities are rarely either well-mixed or in truly isolated subpopulations. Instead, communities spread across fragmented space with limited migration. Host-parasite metacommunities are of particular interest because of the economic and medical implications of understanding pathogenic evolutionary dynamics in a more realistic spatial context. This team is using computational experiments to address key questions about coevolution in metacommunities. Using the host-parasite system in Avida, they are exploring how metacommunity structure shapes both ecological interactions at the subpopulation and metacommunity level, and evolutionary dynamics across space and time. The results of these experiments will lead to novel hypotheses that are sufficiently well defined to be tractably studied with comparative and/or laboratory explorations.

Paul Hohenlohe (UI), Barry Williams (MSU), and graduate student Tyler Hether (UI) are developing **an experimental evolution model for genomic islands of speciation.** An important conceptual model in the emerging field of speciation genomics is that of genomic islands of divergence – regions of the genome showing elevated genetic differentiation between populations. Despite comparative data and some theoretical modeling, a mechanistic understanding of genomic islands is still lacking. This team is exploring the feasibility of experimental evolution systems for studying the formation, dynamic behavior, and topology of genomic islands. They are testing whether yeast and/or AVIDA could serve as experimental

evolution systems for studying genomic islands, and working to establish the methods and approach that would be needed to conduct and interpret experiments. Work so far has focused on establishing generations of an admixed yeast population by crossing two divergent strains from North America (YPS128) and Europe (DBVPG1106) that differ in growth rate in response to environmental salt and/or glycerol, conducting population-level whole-genome resequencing at two admixed generations to estimate frequencies of parental haplotypes and confirm the proposed method for quantifying genomic islands. The team will analyze these data in a Hidden Markov Model to precisely map breakpoints for both recombination and gene conversion. A reference genome-wide map of recombination rate specific to these parental strains is critical to delineating genomic islands in divergence with gene flow experiments. They have initiated a replicated experiment in divergent selection with gene flow, varying strength of selection and migration rate, starting from the F2 generation of the yeast cross. Each replicate includes a pair of populations, one in normal media and the other in different concentrations of NaCl, that exchange migrants. They are estimating growth rate parameters as measures of fitness to identify parameter combinations that may produce genomic islands of divergence.

Rich Lenksi (MSU), Charles Ofria (MSU), Ian Dworkin (MSU), Ben Kerr (UW), and Gerry Dozier (NCAT), with graduate students Alita Burmeister (MSU), Luis Zaman (MSU), and Michael DeNieu (MSU) are studying the **evolutionary dynamics of traits that mediate predator-prey/host-parasite interactions**. The Lenski lab has studied the coevolution of *E. coli* bacteria and Lambda phage that infect them. Led by former graduate student Justin Meyer they published an article in *Science* on how populations of Lambda repeatedly evolved sets of four mutations that confer the ability to infect *E. coli* through a novel receptor in coevolution experiments (Meyer et al, 2012). Because all four mutations were required for the phage to exploit the new receptor, they hypothesized that the intermediate steps allowed the phage to better exploit the ancestral receptor. Joined by current graduate student Alita Burmeister, they have now tested and confirmed the hypothesized benefits of the intermediate mutational steps, with the benefits usually being even greater after the host bacteria had evolved reduced expression of the ancestral receptor. Also, Burmeister and undergraduate student Rachel Sullivan are examining changes in virus stability (viability in the absence of host cells) that are associated with the mutations involved in changes in receptor specificity. Work in the Kerr lab has followed up on the Meyer et al. 2012 study, in which lambda phage evolved (through a series of mutations in the host-recognition protein, J) the ability to use a novel receptor, OmpF. This receptor innovation occurred after the host evolved reduced expression of LamB (the canonical lambda receptor). Using a scar-free allelic replacement technique on lambda prophage, they have now constructed a total of 13 combinations of mutations in the J receptor. These combinations cover nearly all the genotypes along the actual evolutionary path of one of the evolving populations from the Meyer et al. study. Eight of the 13 genotypes have been restored as lytic phage (via the introduction of the cI mutation). The team is now gearing up to run competitions for all the phage genotypes under different bacterial hosts (i.e., differing in LamB expression) to gauge the effects of different mutations on the receptor switch and whether/how the fitness landscape of the virus depends on the genotype of its social partner (the bacterial host). Graduate student Luis Zaman, working jointly with Ofria and Lenski, has performed research with Avida that examines whether host-parasite coevolution drives the emergence of host complexity. Results support that hypothesis, with the very interesting twist that coevolving parasites also promoted increased host evolvability, i.e., hosts evolved genetic architectures that had increased rates of generating

resistance, even though the mutation rate itself did not change. Postdoc Aaron Wagner (MSU) has worked with Dworkin and Ofria to examine traits that mediate predator-prey co-evolution in the Avida system and have found a reciprocal promotion between prey sensor use to avoid predators and their sensor use to find environmental resources. Specifically, in environments where prey evolved in the context of needing to forage for food, they were better at sensing and avoiding predators than when no foraging was needed, even when food was made plentiful. Likewise, when predators were removed, prey were better at foraging than organisms that evolved without predators ever having been present.

Xiaobo Tan (MSU), Philip McKinley (MSU), and Jenny Boughman (MSU) are working together to **understand and synthesize collective behavior with mixed robotic and live fish school**s. Exploiting synergy between robotics, evolutionary computing, and fish biology, the project aims, in long term, to create mixed robotic and live fish schools to understand sophisticated group behavior of live fish, and to guide the synthesis of complex autonomous behavior for robotic fish schools. The team has 1) developed a robotic fish with high-precision maneuverability, energy-efficiency, and realistic swimming behavior; 2) co-evolution-based joint design of the morphology and controller for the robot; and (3) application of such robots to investigate the predator inspection behavior in live fish. This project will lead to insights into the new paradigm of applying animal-robot interactions, mediated through evolutionary computation, and will advance the knowledge base in both biology and engineering.

The team designed and developed a robotic fish with both pectoral fins and caudal fins. A dynamic model for robotic fish with flexible pectoral fins was developed, where blade element theory was used to capture the hydrodynamic forces on the fins. The flexible fin was modeled as a series of rigid panels connected via rotary springs and dampers, and the team further investigated the design and modeling of a flexible passive joint for the pectoral fins, which enables forward thrust even when the power stroke and recovery stroke are actuated in a symmetric manner. Joint design of robotic fish morphology and controller was investigated with a multi-objective evolutionary optimization approach. The dynamic model for a robotic fish with flexible caudal fin was used, where the Young's modulus of the fin material (flexibility), dimensions of the fin, and the actuation pattern constitute the design space. The design objectives include the maximization of propulsion efficiency (the ratio between the useful power producing thrust and the total mechanical power) and the speed, under a constraint on the total power consumption. The Pareto front of the resulting optimal designs was analyzed to gain insight. Experimental validation of these designs is underway. Predator inspection experiments with live sticklebacks and model predators were completed under the direction of postdoc Liliana Lettieri (MSU). Useful data were generated in terms of which species had tendencies to perform predator inspection and their specific behaviors. In addition, postdoc Jason Keagy (MSU) completed a set of experiments comparing social cognition between stickleback species.

Gerry Dozier (NCAT), James Foster (UI), and graduate student Daniel Beck (UI) are developing **genetic algorithms for detecting microbiome and behavioral features associated with bacterial vaginosis**. Specific microbial communities have coevolved with human beings to be exquisitely tailored to the various niches in the human microbiome. These symbiotic relationships are so well tuned by evolution that community disturbance is often correlated with

human diseases. This team is developing a machine-learning algorithm that determines when a disturbance in the vaginal microbiome, coupled with patient behavior, leads to bacterial vaginosis (BV). It is currently unknown how specific changes in a patient's vaginal microbial community or her behavior lead to BV. Specifically, they are analyzing quantitative, semi-quantitative, and qualitative longitudinal data about relative microbial abundances over time and daily journals with a modified feature extraction genetic algorithm from the Dozier lab (GEFEml). The team will then refine accurate predictive models from the Foster lab (using genetic programming, linear regression, and random forests) by rerunning them with the features that GEFEml has determined to be significant. The result will be more streamlined models that are more likely to reveal hypotheses about the relationship between BV and the vaginal microbiome, and which are more likely to be useful clinically. The long term objective is to develop a methodology for building computational models that predict or at least recognize when a person has a disease with a microbial community etiology, using data about the relevant microbiome and behavioral metadata.

Engineering applications of biological collective dynamics

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

Terence Soule (UI), Robert Heckendorn (UI), Philip McKinley (MSU), Scott H. Harrison (NCAT), and Justin Zhan (NCAT) are developing **distributed, onboard evolution in a robotic cloud**. This project will determine how large-scale distributed evolution can be implemented in a web-enabled world, with evolution taking place on-board robots in the field, but also distributed, via the web, across populations of robots. It will identify the benefits and drawbacks of exchanging genetic material among robots, and demonstrate a feasible approach to such functionality. Biologically this project will make it possible to perform controlled experiments addressing different mechanisms of genetic dispersal and exchange using physical systems, rather than pure simulation. Similarly (and independent of the distributed aspects of the project) COTSBots (Commodity-Off-The-Shelf robots) are powerful enough research platform to model complex behaviors allowing for physical modeling of complex animal interactions. The team has developed a framework for on-board evolution using COTS robots and is currently developing a framework for on-board evolution across geographically dispersed (literally at separate BEACON sites) teams of low-cost, computationally powerful, robots. They will also model different mechanisms of genetic exchange, such as horizontal gene transfer (bacteria), long range pollinators (plants), and roaming bachelors (social mammals) by changing the rules for exchanging genetic material via the cloud. The team will then test the hypothesis that robotic teams which exchange evolved results via the cloud perform better and more robustly that teams that adapt individually. Finally, they will create a central web location for faculty and students wanting to build COTSBots, with parts lists, assembly instructions, library code, sample projects, and sample curricular materials. Designs, code, etc. are being up-loaded to two publicly accessible, inter-linked sites (http://www.cotsbots.wordpress.com and https://bitbucket.org/uidaholair) as they finish testing them.

Paul Stanfield (NCAT), Justin Zhan (NCAT), and graduate student Patrick Wanko (NCAT) are assessing **biologically and socially inspired computational evolution for product life cycle management**. Increasingly, the design of durable products, such as automobiles and aircraft, has expanded from traditional mechanical design to include more biologically inspired capabilities - learn, morph, communicate and sustain. This same transition is making its way to high value assemblies and parts on such products. The transition is enabled by Sensor-Integrated Automatic Identification Technology (SIAIT), which can provide data collection, storage, processing, and communication capabilities with minimal power requirements. Intelligent use of these enhanced capabilities depends primarily on the development of integrating processes. Processes are needed to use the collected data to improve design and operating parameters across a variety of environments in order to minimize costs, extend life cycles, and enhance sustainability. The federal government spends $100 of billions annually on these issues. Due to the biological nature of the parts, bio/eco systems are expected to be the primary sources of process innovation. Patrick Wanko has adapted genetic algorithms in two ways, one inspired by the dynamics of fish schooling and the other by social networks. Though justifiable based on the significance of product life cycle management, such algorithms are likely to be expanded to other complex service systems and might serve as examples of ways to use evolutionary computation to model biological/social phenomenon not typically considered evolution-based.

2b. Progress towards metrics listed above.

Integrative Research Goals

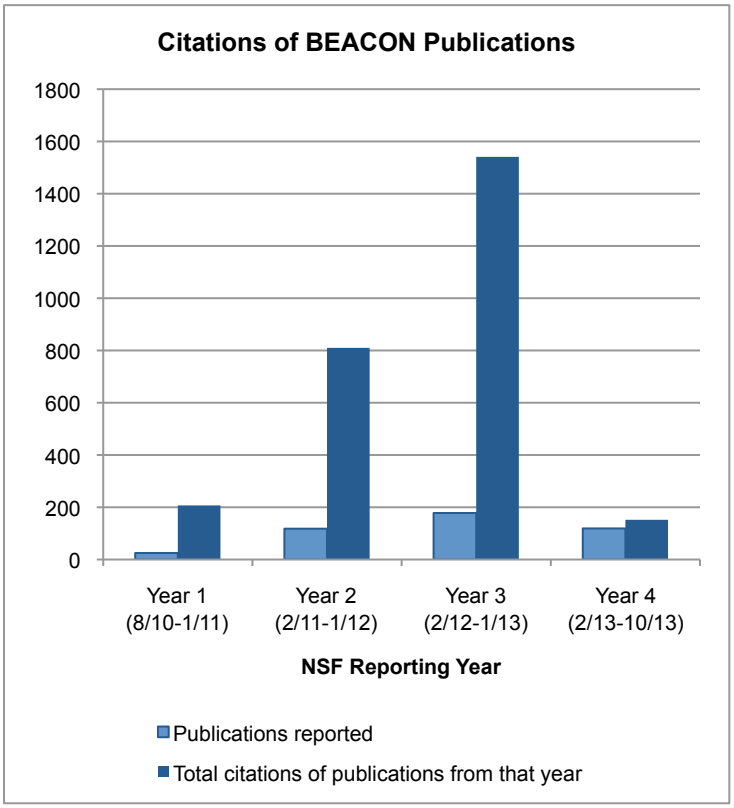
1. New research collaborations and proposals

- Of the 54 projects currently underway, 24 are new projects and include new collaborations.
- 127 publications submitted this reporting period, of which about 25% are categorized as multidisciplinary and 10% can be categorized as multi-institutional
- Many projects include funding for students/postdocs/faculty to travel between partner institutions.
- We are aware of many faculty members serving on doctoral research committees committees across disciplines and institutions. However, these data are not available in any publicly accessable records, making it very difficult to track, and we are removing this metric from our strategic plan.

2. New paradigms for research in organic and digital domains

- Number of new sessions at scientific meetings or scientific meetings hosted at BEACON: Louise Mead and Rob Pennock organized a symposium for the 2013 National Association of Biology Teachers annual meeting. 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 2013 featured dozens of BEACON talks. BEACONites gave keynote addresses at 4 engineering/CS conferences, which will increase the community's interest in evolutionary methods: IEEE CEC (Miikkulainen), GECCO (Adami), ALife13 (Kerr), and IEEE IDEAL'2013 (Goodman).

- 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 55 proposals for over $25M of external funding, and >$12M in external funding has been granted.



3. Increase in publications related to evolution in action

- Number of publications: 132 publications submitted by BEACONites to date in 2013
- *Increase in BEACON publications and citations.* MSU graduate student Rosangela Canino-Koning created a Python script to query Google Scholar to 1) find publications that BEACONites reported for each reporting period and 2) count the total number of citations of those publications. The graph at right summarizes the results. The increasing trend of citations of papers from previous years clearly indicates growing impact, and we anticipate that this impact will continue to grow. Because Google Scholar does not index every publication in which BEACON work is published, these numbers are an underestimate of BEACON's impact.
- High visibility science journalism about BEACON research: In 2013 to date, we put out 12 press releases. Over 70 features on BEACON research appeared in the mainstream and online media in 2013, including NBC News, CBS News, BBC News, MSN, the *Los Angeles Times*, the *Daily Mail*, *National Geographic*, *Discover*, Daily Kos, and *Nature*.

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

- ~5,600 downloads of Avida-ED
- over 4,000 downloads of Avida: Tracking Avida downloads from GitHub is difficult because once someone downloads it, they can install it on other computers. We have had a total of 17 forks (someone has chosen to create their own copy of an Avida repository on GitHub - similar to cloning it locally, but they can also use it to share changes publicly and to submit changes back to the project) and 44 stars of Avida-related repositories on GitHub (a means for individuals to follow activity on a project, allowing them to receive notification of updates, while keeping it separate from projects they actively contribute to).
- over 3,200 visits to BEACON website monthly, where all resources are linked

- C. Titus Brown is leading an effort to develop training materials and curriculum and run workshops to train biologists (faculty, postdocs and students) outside BEACON on development and use of computational tools in support of their research. This work is funded by two NSF supplements to the BEACON Cooperative Agreement. More details can be found in the education section under "Materials and Workshops for Cyberinfrastructure Education in Biology."

Ethical Research Goals

1. Responsible Conduct of Research (RCR) training

- We are meeting our goals for compliance with RCR training. As of October 28, 2013, over 90% of trainees have reported completing the required training. We anticipate that our goal of 100% will be reached by December 2013.
- No ethics violations to report.

2. Scientific norms/virtues, respect across disciplines

- Robert Pennock and Michael O'Rourke have redesigned the Toolbox sessions to include Scientific Virtues training. Initial workshops were run at BEACON in spring and summer 2013 and will be refined and repeated.
- 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

- Toolbox/Scientific Virtues sessions have been piloted and will be repeated.

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

- Toolbox/Scientific Virtues sessions have been piloted and will be repeated.

Research Output Goals

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

- Number of publications submitted: 131 reported to BEACON (goal is 150 per reporting period – we are on track to meet this goal by the end of January)
- Conference presentations: 175 reported (goal is 150)
- Grant proposals submitted: 56 submitted (goal is 40)

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

- Third External Advisory Committee meeting will be held November 2013
- Feedback from last External Advisory Committee meeting 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 2014. We will hold our project selection process for Year 5 (see explanation in VII. Management) in February 2014 in order to choose projects that will be conducted August 2014-August 2015. 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	To date, 30 BEACON students have reported receiving degrees (4 Bachelors', 11 Masters', and 15 PhDs). Of the PhD graduates, 60% are currently in postdoc positions, 13% are in faculty positions, and 27% are working in industry. 2 of 3 former BEACON postdocs are in faculty positions (66%), while 33% are in industry.
Increased public literacy in	Development of educational	Testing, presentation, and

evolution and the nature of science	materials.	publication of educational materials across audiences is well underway. Evaluation instruments are being used to assess effectiveness.
	Adoption of materials by teachers; frequency of public use of online materials and visits to museum 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

1c. Problems encountered in making progress towards goals

Internal education activities: We continue to discuss and evaluate the effectiveness of our educational programs. Our graduate training courses create unique inter-institutional challenges such as different academic calendars (for example UW is on a quarter system whereas MSU is on a semester system). During the Fall 2013 semester, Titus Brown restructured CSE 801 in order to improve the logistics of participation at BEACON's partner institutions by holding intensive on-site workshops. The change also addressed another concern pointed out by the 2012 Site Visit Committee: that we need to make our interdisciplinary training more broadly available. The on-site workshops allowed many more faculty and students to receive training.

The other challenge we are working to address is rigorous assessment of Evolution in Action tools and activities. We've had success in assessing the effectiveness of Avida-ED, and have plans to include assessment in projects currently under development (i.e., Data Nuggets). However continued assessment of other tools still needs to be completed.

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 Biologist (CSE 801, Fall) taught by Dr. Titus Brown; Evolutionary Biology for non-Life Scientists (ZOL 890) taught by Dr. Louise Mead in the Fall of 2013; and Multidisciplinary Approaches to the Study of Evolution (CSE 891, Spring) taught by Drs. Charles Ofria, Ian Dworkin, and Chris Adami. We initiated an evaluation of 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	Chris Adami, Titus Brown, Ian Dworkin, Louise Mead, and Charles Ofria (MSU)
Intended Audience	Beginning graduate students
Approximate # of attendees	~30 per year

Computational Science for Evolutionary Biologists: Based on feedback and discussions from the 2012 class, the 2013 "Computational Science for Evolutionary Biologists" course (now CSE 801 at MSU) was adjusted to match the UW class schedule of 10 weeks. As part of this adjustment, we ran two 2-day workshops, one at MSU and one at UW, to announce the course and motivate the course topics. Each of these workshops had 50 attendees (the room size limit) and was well attended on both days. As a result we now have 40 enrolled and auditing students across MSU and UW for this year's course (about 25 at MSU and 15 at UW), a significant increase over 2012. The course has been modularized more so that the first five weeks is on data analysis and programming, with the second five weeks (taught by Arend Hintze and Randy Olson) on modeling. Next year we plan to extend the intro workshop model to other campuses that want to participate, and perhaps move to a more team-taught course. We are also discussing refocusing the graduate education efforts based on a workshop model, given the significant interest in these topics at the advanced graduate and postdoc level.

Evolutionary Biology for Non-Life Scientists: ZOL 890-601 is being taught during the Fall 2013 semester at Michigan State University. Four students from Michigan State University and one student from University of Idaho are currently enrolled. 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 instructor exceeds all evaluation criteria. We are also using the course to provide professional development for two graduate students at BEACON (Caroline Turner and Emily Weigel) who are co-instructing the course with Dr. Louise Mead.

Multidisciplinary Approaches to the Study of Evolution: In Spring 2013, 15 students enrolled in the course (one later dropped 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. As part of the final project, students first formulate individual research proposals, the best of which (voted on by students and faculty) are then selected as group projects. The class selected and tackled four projects in teams of 3-4 students: "Evolution of functionally modular codes in the absence of recombination," "Standing genetic variation versus historical

contingency in the evolution of anti-predator traits," "More bucks for your bang: How quorum sensing improves suicidal altruism in Artificial Life," and "From cues to signals: Evolution of interspecific communication via aposematism and mimicry in a predator-prey system." All four final project reports were turned in formatted as a submission to a PLoS journal. One of the four ("From cues to signals") has already been submitted for publication in PLoS Computational Biology, and the other three manuscripts are in preparation for submission. One paper from last year's class was published in the Proceedings of the European Conference on Artificial Life (ECAL 2013).

Dr. Claudia Vergara of the Center for Engineering Education Research (CEER) at MSU led the external evaluation of the BEACON graduate course sequence. An executive summary of the evaluation begins on the following page.

BEACON External Evaluation

Findings from Evaluation Activities: Educational Component
Evaluation Period: Fall 2012 – Spring 2013

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 2012 -2013 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 students enrolled in the fall and spring courses. In addition we conducted a focus group at the end of the spring course (Table 1).

Table 1: BEACON Courses Evaluated (2012-2013) and Data Collection Summary

	Fall 2012		**Spring 2013**
	Evolutionary Bio. for Non-Life Scientists	Computation for Evolutionary Biologists	Multidisciplinary Approaches to the Study of Evolution
Students Enrolled	12	13	12
Data Collected. Term. (Response Rate)	*Start survey*. Start Fall 2012. (80%)		*End survey*. End Spring 2013. (91.6%) *Focus group.* End Spring 2013 (100%)

From the 25 students enrolled in the Fall courses, only 6 enrolled in the Spring course.

Participants' Expectations

- The start-survey data indicated that respondents enrolled in the computation for Evolutionary Biologists course (N=11) chose "learning programming" as the most prevalent category (54.5%), followed by "data processing" (36.3%) and "computational methods" (27.2%); the category less populated was "communicate/work better/collaboration" (18.1%). (*These percentages were calculated for each course separately. Numbers do not add to 100% because a single response can fall into more than one category.*)

- Start-survey data from respondents enrolled in the Evolutionary Biology for Non-Life Scientists course (N=10) indicated that the large majority (90%) of respondents chose "improve biology knowledge" as the prevalent expectation.
- Comparing the expectations at the start of the fall courses and the self-reported gains at the end of the spring course 63.6% participants reported gains in programing skills. Specifically improved R programming skills including improved ability to use R to design and analyze experiments and to run statistical analyses. (*These percentages do not add to 100% because a single response can fall into more than one category.*)
- Notably, improved statistical abilities--not mentioned in the start survey-- was reported as a gain by 72.7% of students enrolled in the Multidisciplinary Approaches course (N=11).

Interdisciplinary applications

Responses about participants' ideas on interdisciplinary applications were similar in both the start and the end surveys and also across groups (Computer Scientists (CS) and Biologists). Common themes related to the application of evolutionary biology to other disciplines included:

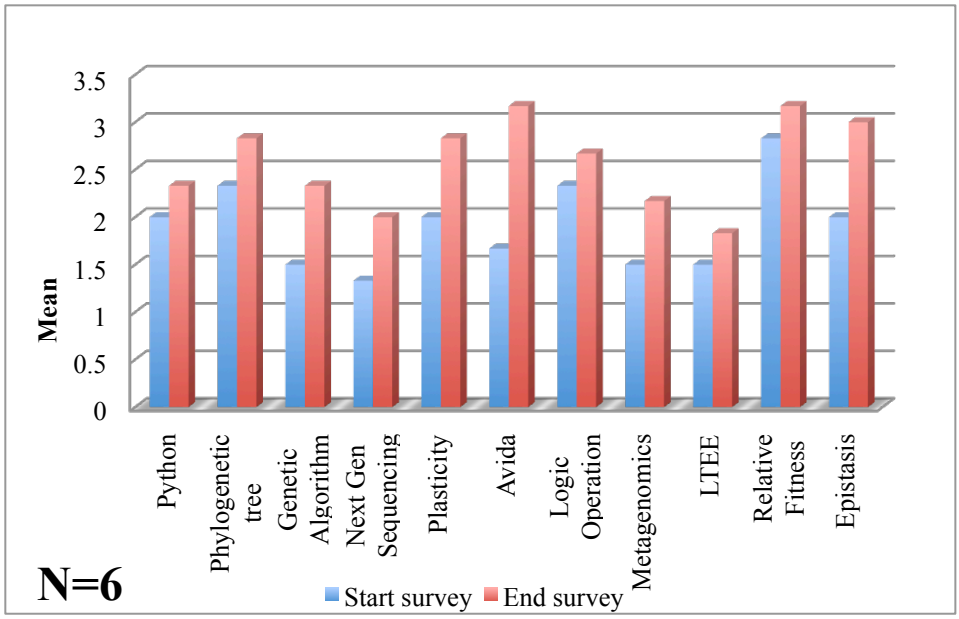
- Principles of evolutionary biology informing disciplines such as computer science, medicine, psychology, engineering, ecology and anthropology.
- Application of evolutionary concepts and principles towards understanding biological patterns and processes.

With respect to the application of Computer Science and Engineering to Evolutionary Biology, responses centered around themes such as modeling of evolutionary process through the design and application of computer programs. Other responses included data management (in particular high throughput sequencing) and data analysis in particular statistical analyses.

The following sets of analyses correspond only to students who participated in both the fall and the spring courses and who responded to the two surveys (start and end) (N=6).

Evolutionary Concepts

When asked about the level of comfort with evolutionary concepts/terms participants enrolled in the spring course (end survey) reported gains in their "level of comfort" with all the concepts listed in the question as compared to their responses in the start survey (fall courses) (figure 1).

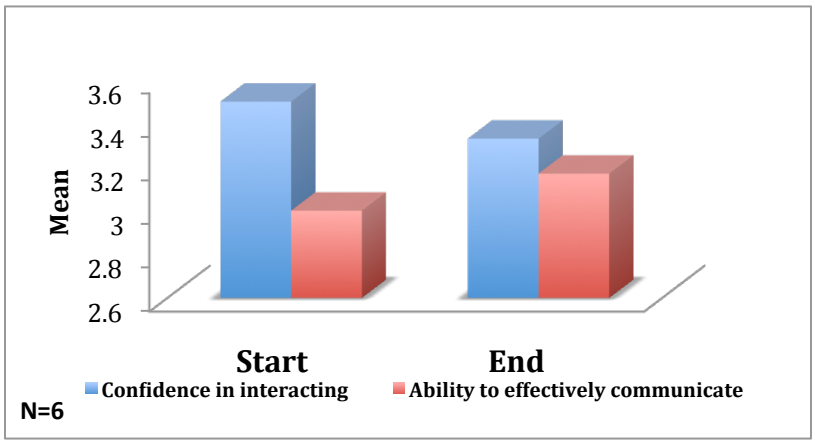


1=none; 2=a little; 3=some; 4=a lot.

Figure 1. Comparison of start and end survey responses. Mean values related to comfort with evolutionary concepts.

Peer Interaction

Participants were asked to rate their confidence and ability in various aspects related to interaction and communication with peers in other disciplines, and their interest in learning about and grasping concepts in the alternate discipline. In general participants reported a moderate improvement in their ability to interact with peers from other disciplines. The focus group analyses (below) give us additional information related to these characteristics (Figure 2).



1=none; 2=a little; 3=some; 4=a lot.

Figure 2. Comparison of start and end survey responses. Mean values related to interaction and communication with peers.

When asked about the roles that evolutionary biologists and a computer scientists and/or engineers undertake in a collaborative project, both biologists and CS indicated that biologists are more involved in the "question generation process" (largely based on their biological

knowledge) as well as the "experimental doing" and CS are involved in providing tools to help in the problem-solving process for example programming and modeling tools, and dealing with large data sets and statistical data interpretation.

Focus groups

The focus group was conducted at the end of the spring course (Multidisciplinary approaches). The main themes resulting from the focus group include:

- The course objective was to take a multidisciplinary approach to proposing and working on an evolutionary biology project.
- Participants had different levels of ability and experience with Avida. This made for—sometimes—difficult interactions within a group and a division of tasks that were not beneficial to all.
- There was a sense of misalignment between some components of the "lecture portion" to the "project portion"; some examples mentioned included statistical lectures unrelated to projects; and limited discussions about Avida and the types of projects where the system can be used.
- Participants have different opinions about the level of collaboration while completing the projects. For some there was no real collaboration within the group and to complete the projects they resorted to task division according to their abilities. Others indicated gains related to improved ability to understand and apply concepts (from the alternate discipline) as they progressed through the project.
- Participants reiterated the idea that "biologists come up with the question" and CS "will provide tools to test it"

*****

Activity Name	Materials and Workshops for Cyberinfrastructure Education in Biology
Led by	C. Titus Brown (MSU)
Intended Audience	Graduate students, postdocs, and faculty
Approximate # of attendees	Hundreds

This NSF supplement to the main BEACON Cooperative Agreement is the result of our application to a call from the NSF Office of Cyberinfrastructure to address pressing Cyberinfrastructure (CI) needs across multiple NSF centers. The supplement proposes to tackle the increasing need for computational training in the biological sciences. In collaboration with the SESYNC center, C. Titus Brown proposed to build training material, run both teaching and coordination workshops at the various centers, and develop assessment materials. After the initial award, we also received an extension to the original supplement to run "train the trainer" workshops in collaboration with NESCent.

The first of the planning workshops were held at SESYNC in July, with approximately 30 attendees from North America and England, including representatives from EBI and TGAC in England, iPlant, rOpenSci, Mozilla Open Science Labs, and multiple BEACON institutions. At this workshop the team decided that there were two significant gaps that needed to be filled: first, there was a lack of coordination between the far-flung interests in the space of "biology education in computing"; and second, there was a significant lack of starter material. The group proposes to address both of these in a workshop they are planning for February 2014, which will bring together approximately 20 people for a "hackathon" in Puerto Rico.

In the past year, the team has have also run several experimental workshops, including two "zero-entry" workshops at the MSU and UW BEACON institutions and a Software Carpentry bootcamp at iPlant Collaborative in Arizona; funded a workshop at the Ecological Society of America; and helped fund a "Women in Science" workshop in Boston. The zero-entry workshops were great successes in that approximately 100 people attended and over 50 people signed up for a follow-on course taught through BEACON. The "train the trainers" supplement is still in the planning stages.

Titus Brown wrote two blog posts about these workshops (http://ivory.idyll.org/blog/2013-teaching-workshops.html and http://ivory.idyll.org/blog/2013-sesync-meeting.html).

Activity Name	Undergraduate Education in Computational Evolutionary Biology
Led by	Claus Wilke and Art Covert (UT)
Intended Audience	Undergraduates
Approximate # of attendees	27

Drs. Claus Wilke and Art Covert continue to receive funding to run the computational evolution stream of the UT Freshman Research Initiative (FRI). An FRI stream is a year-long inquiry-based class centered on in-silico experimental evolution with digital organisms. Students earn credit towards their degree while learning how to perform research in a computational lab. In the spring semester freshmen take a lab-based course taught as an inverted-class model, to

learn the basics of python programming, data analysis, running experiments on high-performance computing clusters, and constructing and testing a well reasoned hypothesis. In the summer and fall semesters, students carry out individual research projects in the Wilke lab, supervised either by Dr. Covert or a graduate student in the lab. At the completion of the stream, students will have worked on a research project intended for publication, and will have gained extensive experience in programming, data analysis, high-performance computing, and evolutionary biology. This year Wilke and Covert conducted a detailed assessment with the goal of publishing a case study of their methods and applied for a grant based on this successful and innovative style of teaching evolution. In addition, they have exchanged a number of undergrads from our stream with other BEACON schools to begin bringing the FRI experience to students all over BEACON. These students have also begun presenting their original and novel research at the BEACON congress and, in doing so, have set an example for undergraduates from every corner of BEACON.

In the spring 2013, Dr. Covert taught the FRI (Freshman Research Initiative) course to 27 UT undergraduates. During the summer of 2013, three FRI students visited MSU for the summer, working on projects related to evolution, behavior, and education. Nine undergraduates from the stream attended the BEACON congress. In the fall of 2013, Covert is teaching the follow-up FRI course to 17 UT undergraduates, with the help of 5 undergraduate mentors (only the more successful students from the spring course tend to continue in the fall). Each student pursues a different research project independently.

Activity Name	**BEACON REU Field Experience**
Led by	Kay Gross (MSU)
Intended Audience	Undergraduate Students
Approximate # of attendees	8

The BEACON Field Research Experience project funds undergraduates to pursue cross-disciplinary research at the Kellogg Biological Station (KBS). The undergraduate research program at KBS supports undergraduate research at multiple levels and involves BEACON faculty working in a variety of thematic areas. The program supports both advanced undergraduates (as REUs) and early career students (as Undergraduate Research Apprentices, URA). The URA program addresses the lack of preparedness that hampers the participation of students from under-represented groups in research experiences or pursuing STEM careers. The KBS REU/URA program supports the educational goals of BEACON by increasing their understanding of evolution and the nature of science, better preparing them for careers in the scientific workforce, and increasing the opportunities for students from underrepresented groups to participate in research. In 2013, we expanded marketing for the KBS REU/URA program to include tailored emails to over 300 schools with an emphasis on minority serving institutions and BEACON partner schools. We increased both the total number of applicants and those from our target audiences from 98 in 2012 to 408 applicants in 2013. From these applicants, we admitted and provided research experiences for 6 students at KBS, 3 REUs and 3 URAs (Table 2), including students from 3 partner schools. Two additional students recruited to KBS from NC A&T were supported by other BEACON funds. Students participated in professional development that included RCR training in addition to their individual research projects. Students presented their research at the Undergraduate Symposium; one student presented a

poster at the national meeting, ESA (August 2013). We have also submitted an NSF REU Site Proposal: Ecological and Evolutionary Dynamics in a Changing World: A Scaffolded Undergraduate Research Experience in August 2013.

Activity Name	**Reforming a Large Undergraduate Non-majors Biology Course (Part 1 of Infusing Evolution Through an Entire College Biology Curriculum)**
Led by	Randall Hayes (NCAT)
Intended Audience	Undergraduates
Approximate # of attendees	100s

The primary goal of this project was 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 overall goals of the project have largely been met. Accountability and oversight of the 100-level non-majors class have increased dramatically. The course now includes sections on both evolution and ecology. Students are performing short, authentic research projects, using themselves as subjects. This semester they are tracking their intake of calories and other nutrients, in connection with the book *Salt Sugar Fat*, which is the "campus read" for this year. Two master's students (not involved in the fall) did paid laboratory rotations with Hayes in spring 2013, where they were trained in Criterion and human subjects issues. Criterion has been implemented in fall 2013 in the senior projects course, taught by Hayes, where 12 senior students and 10 of the faculty will be exposed to it through their mentoring relationships with the seniors. Chad Rohrbacher will continue to work with students and faculty to expand the use of Criterion. 300 individual licenses have already been paid for. This portion of the project, which will track the change in students' written understanding of evolution, will go into effect in spring 2014.

2b. Professional development activities

Activity Name	**Developing a Virtue-based Approach to RCR Training**
Led by	Robert Pennock, Michael O'Rourke, Chet McCleskey (MSU)
Intended Audience	Undergraduates, Graduates, Faculty
Approximate # of attendees	~100

BEACON's Ethics Goal, as articulated in the Strategic plan, 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 of the Center." This project aims to fulfill that goal. 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. They have begun pilot testing these modules in BEACON weekly meetings and the annual Congress, which will also help grad students and post-docs fulfill their RCR requirements. They are coordinating with Pennock's national SV survey and using its data to support RCR curriculum development. BEACON funding supported Pennock's successful external proposal to the Templeton Foundation to fund the implementation of a survey on the ethical views of scientists about the scientific character of virtues. The funding from the Templeton Foundation allows BEACON researchers to carry out the first national survey on this topic, and BEACON is benefiting directly from the effort.

2c. External education activities

The report from the National Academies of Science Convocation on Thinking Evolutionarily (National Research Council and National Academy of Sciences 2012) made it clear that we need more research in evolution education, and that all students will benefit from more active engagement in evolutionary biology. BEACON is working to address this call. Across our consortium, participants are engaged in education and outreach efforts, both formally through the development and testing of novel tools and lessons, the implementation of Evolution in Action focused programs for students, and a range of training workshops. Faculty and students are active in more informal education as well, through our participation in community and public outreach events, all with the aim of providing participants with an experience of evolution in action – showing them that evolution is an ongoing process happening now, that evolution can help us solve complete problems, and that evolutionary science is a good example of how science works.

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

Michigan State University (MSU) College of Engineering Recruitment, Scholarships, and K-12 Outreach and BEACON collaborate to offer a summer program focused on exposing a diverse group of high-achieving high school students to concepts, activities, and tools related to evolution-in-action. The program's goals are: (1) to introduce students to evolutionary science and its applications in engineering and computational science; (2) to educate students about BEACON related science and engineering college majors; (3) to educate students about BEACON related science and engineering careers; (3) to teach students about evolutionary science; (4) to educate students about the importance of conducting scientific research. The summer 2013 program was held at Kellogg Biological Station from July 7-11th, with 30 students participating. Students were exposed to a variety of activities and experiences including field exercises in evolutionary biology, classroom exercises using BoxCar2D, a statistics bootcamp, Avida-ED, presentations from engineering faculty, and completion of an inquiry project that concluded with the creation and presentation of their research. The BEACON High School Institute has been a role model program combining uniquely diverse faculty, staff, and students each year. This year, unlike previous years, the program included approximately 70% women, but less than 25% underrepresented students. Overwhelmingly, participants report good research experiences, good balance between classes and activities. In addition, most report that they

would recommend BEACON High School Institute to others. However, a continuing challenge is the recruitment of pre-engineering students who come with an expectation of an engineering camp, with the reality that BEACON research requires an understanding of how evolutionary processes work in order to apply them in computational and engineering environments. The team hopes to address some of this mismatch by recruiting more students interested in biology to the program, as well as using the program to introduce students to a new Biomedical Engineering degree program currently under development at Michigan State University

This program was evaluated by Sheila Coressel, with pre- and post-survey instruments, with both student understanding of evolutionary concepts as well as programmatic evaluation carried out. A few highlights from the report are below:

BEACON Summer Program for High School Students Evaluation Report
July 7th –11th , 2013
Kellogg Biological Station

General Student Satisfaction: Of the 30 students who attended the summer program at Kellogg Biological Station (KBS), 20 (66%) were female and 10 (33%) were male. Four students (13.8%) were entering grade 11, 19 (65.5%) were entering grade 12, and 6 (20.7%) were entering college.

Student ratings of their experience in the program.

	Response Percent	Response Count
Poor	0.0%	0
Below Average	3.3%	1
Average	6.7%	2
Good	40.0%	12
Excellent	50.0%	15

Ratings for how well sessions prepared students to answer evolution questions.

	Poor	Below Average	Average	Good	Excellent
Understanding variation in natural populations: measuring natural selection in milkweeds	0	0	3	17	10
Experiments in engineering with evolution: BoxCar2D	0	1	3	12	14
Damselfly adaptations in nature: selection on color and behavior	0	1	2	13	14
Seeing evolution happen: observing and experimenting with Avida-ED	1	1	3	18	7

Aggregate responses regarding inquiry projects.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The project was interesting.	0	2	2	13	13

The project allowed me to use knowledge I learned this week.	1	0	1	17	11
The project allowed all group members to contribute.	1	0	3	8	18
Inquiry projects should be included in next year's BEACON summer program.	1	0	3	10	16
The inquiry project topic was relevant to the BEACON summer program.	0	0	3	10	17
The inquiry project made me feel like I was doing science.	0	4	2	12	12

Recommendations for future years include:

1. Provide computers with updated memory and processing abilities.
2. Nametags for all participants.
3. Incorporate more engineering faculty and connections into program sessions.
4. Use post-test results to guide future sessions.
5. Provide additional structure for the REU lunch.
6. Continue to include fieldwork and hands-on activities.
7. Continue holding the program at Kellogg Biological Station.
8. Continue to include free time with planned, unstructured activities
9. Ensure all program staff understand their responsibilities.
10. Continue to do careful hiring of undergraduate mentors.

Activity Name	**Unleash Your Inner Scientist: Employing and enjoying inquiry in the classroom and lab**
Led by	Louise Mead (MSU) and Kristin Jenkins (University of Wisconsin-Madison)
Intended Audience	K-12 Teachers
Approximate # of attendees	10

BEACON and BioQUEST joined together to offer a 5-day workshop for science educators that ran from June 28th-July 3rd 2013 at Kellogg Biological Station. Twenty participants registered for the workshop, a total of eight attended, in addition to Lazarius Miller, an REU SROP student with BEACON. Participants (1) explored lessons focused on teaching inquiry and using data (BioQUEST/DataNuggets); (2) carried out a field-based experiment, collecting and analyzing data, and creating a poster/presentation on their research; (3) identified ways to incorporate inquiry-based lessons into the curriculum that address specifically evolutionary topics; (4) gained experience with Avida-ED and other model programs that can be used to carry out investigations focused on evolutionary science; (5) heard about recent research by BEACON scientists (Zachary Blount, Jen Lau, Danielle Whittaker). Participants completed an evaluation at the end of the program indicating overall enjoyment in the scheduled activities with most scoring between 1 and 2 on a 5-point scale with 1 indicating excellence and all participants indicated they will incorporate the information, materials, and inquiry approach presented throughout the workshop.

Activity Name	Continuation for Podcast
Led by	Randall Hayes (NCAT)
Intended Audience	K-12 Teachers
Approximate # of attendees	~ 90,000

As of August 2013, 62 episodes of *VSI* have been produced. Year Three Guests have included 4 academic scientists at various stages of their careers, including two BEACON members (Dinitra White, Luke Harmon), as well as various artists, naturalists, and activists. 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 3000 times, and hits to the blog site are still accelerating.

Year	Number of Visitors
2013	93,796
2012	51,839
2011	8774

The website for the podcasts 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. The podcast now has a Facebook page (facebook.com/vsibeaconpodcast) which is the major way that Hayes's own students engage with the podcast. 153 of the 187 Likes (followers) of the page are young African Americans, most but not all of them Hayes's students. 13 are international, mostly from Spanish- and Arabic-speaking countries.

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

The goals of this project were threefold. First, include cutting BEACON research in classroom modules for a Science, Technology, & Society class at the undergraduate level. Second, 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. And third, reach into the elementary schools with simple, fun, scientifically responsible computational models of evolution. Accomplishments to date include the production of lesson plans and, testing of these with K-12 teachers and students. Melissa Kjelvik used these lessons with the GK-12 partnership and collected enough data to write a short paper, now in revision. 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 of stories in the *Origins: Tales of Human Evolution* anthology. As of August 2013, the book is now finished and being distributed by BEACON and by Hadley Rille Press, the publisher of the anthology on which it is based. High school teacher and NCAT graduate student Marcia

Moore-Lyons tested one of the stories with her inclusion class during spring 2013 and found a decrease in problem behaviors during this unit.

Activity Name	**Avida-ED Curriclum Development and Assessment Study**
Led by	Rob Pennock (MSU), James Foster (UI), Joseph Graves (NCAT), Randall Hayes (NCAT), Ben Kerr (UW), Louise Mead (MSU), Jim Smith (MSU), Charles Ofria (MSU), Claus Wilke (UT), Diane Ebert-May (MSU), Billie Swalla (UW)
Intended Audience	AP Biology, Undergraduate Biology, Upper level Evolution
Approximate # of attendees	Unknown

Avida-ED is BEACON's digital evolution software designed for educational use in undergraduate and graduate courses. The goals of the project for the past year included (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.

Software development: The Mac version of Avida-ED 2.0 was completed and released in February 2013. The main improvement was a complete revision of the basic code and a restructuring of the relationship of the GUI to the Avida core, but this team also implemented a variety of improvements to the user interface (see http://avida-ed.msu.edu for a list of the changes). Porting these changes to Windows has run into various technical difficulties; a working version of Avida-ED 2.0 is not yet available for the PC. Over the summer, UT BEACON undergraduate Miranda Grabowski, came to MSU for a research internship and worked with the group on adding the ability to graph changes in function evolution over time. This work should be completed by the end of 2013.

Curriculum Development and Assessment Pilot Study: Pennock, Mead and Smith hold a weekly curriculum development meeting with graduate students Amy Lark and Wendy Johnson. The team designed a template for instructor support materials to show how to use Avida-ED for inquiry-based learning, and developed several new model exercises. Lark has completed a national multiple-case classroom effectiveness study, including several BEACON partners. The most significant findings are from the student assessment outcomes. Student content scores increased significantly from pre- to post-test in six of the ten cases—all lower-division courses (Lark et al. in prep). Student acceptance of evolution increased significantly from pre- to post-test in the same six lower-division courses. These results suggest that Avida-ED succeeded in improving student understanding and acceptance of evolution in lower-division courses. Interestingly, there was a significant, positive relationship between the change in content and acceptance scores from pre- to post-test across the ten cases, suggesting that student learning of fundamental evolutionary concepts via Avida-ED is associated with increased acceptance of evolution. This result is significant because other studies investigating the effects of learning on acceptance have shown the opposite pattern or no relationship at all. Other notable outcomes include: Insight regarding best practices when using Avida-ED specifically, and other instructional technologies more generally, to teach about evolution; feedback from instructors regarding the affordances and limitations of using Avida-ED and the degree to which it aligns

with their instructional goals and practices; feedback from students regarding their experience with using Avida-ED and what aspects were most and least helpful to their learning.

Activity Name	**Evolutionary Games in Action**
Led by	Laura Crothers (UT), Arend Hintze (MSU), Thomas Hladish (UT), Edward Theriot (UT), Christina Cid (UT), Julie Fick (MSU), Ammon Thompson (UT)
Intended Audience	General Public
Approximate # of attendees	100,000

This project seeks to finish developing and to evaluate two digital games for touchscreens designed to address several "intuitive" but inaccurate conceptions of evolution. Both games tie in to BEACON research projects (epidemics & evolution of host systems; Texas Longhorn evolution and phylogenetic inference) and will be featured in the evolution exhibits of the Texas Natural Science Center (UT-Austin) and the MSU Museum, as well as on their websites. Evolution, as a process of change, is best depicted in motion. The games are being designed with simple, appealing interfaces to enhance interactivity in the museums' exhibits and to reinforce understanding of central evolutionary processes (evolution happens to populations, not individuals; evolution is not teleological; variation exists not only between species but within species as well). The specific goals and steps of this project are as follows: (1) Develop entertaining, simple, and educational game outlines and beta versions of the "*Tree Thinking*" and "*Clickademic*" games; (2) Evaluate the educational value of these beta versions through interviews and observations of focus groups of different ages and scientific backgrounds; (3) Finalize development of the games and install them in TNSC and MSU Museum's evolution exhibits; (4) Complete a summative evaluation of the educational value of the games for different target age groups.

A beta version of the *Clickademic* game has already been developed. Dr. Tom Hladish will work with members of Dr. Lauren Meyer's lab at UT to finalize the programming of the *Clickademic* game after formative evaluation has been performed (by the end of 2013). Ammon Thompson, Laura Crothers, and Christina Cid are working with *PowersCombined* (a software development company) to develop a beta version of the *Tree Thinking* game by late November. The beta version of the game will consist of 3 difficulty levels, which will be evaluated for ease of use and educational value.

Activity Name	**Data Nuggets**
Led by	Louise Mead, Melissa Kjelvik, Elizabeth Schultheis (MSU)
Intended Audience	K-14
Approximate # of attendees	100s

This project focuses on the development of Data Nuggets, an educational tool that brings data collected by scientists into the classroom. Data Nuggets are worksheets designed to help students practice interpreting quantitative information and make claims based on evidence. The standard format of each Nugget provides a brief background to a researcher and their study system and a small, manageable dataset. Students are then challenged to answer a scientific question, using the dataset to support their claim, and are guided through the construction of

graphs to facilitate data interpretation. Graphing and content levels allow for differentiated learning for students with any science background. Because of their simplicity and flexibility, Data Nuggets can be used throughout the school year as students build confidence in their quantitative skills.

Data Nuggets are built around data from recent and ongoing research, providing several benefits for researcher and student alike. BEACON researchers who create Data Nuggets will improve their communications skills; the challenge of unearthing the story within their experiments is a difficult but rewarding process. Working with science education researchers to develop our assessment of Data Nuggets, the team is also writing a proposal to NIMBioS to hold a workshop, which would allow them to gain national feedback, guidance, and collaboration. They have presented Data Nuggets at several teacher workshops and conferences and will be contacting teachers interested in assessing Data Nuggets in their classrooms. The template has been finalized, through work with Anna Thanukos from Understanding Science. A new website is being developed to host the materials, at the addresses www.datanuggets.com and www.datanuggets.org (previous website located at http://kbsgk12project.kbs.msu.edu/data-nuggets/).

Activity Name	**Citizen Science: Monitoring Evolutionary Change and Biodiversity in the Puget Sound Intertidal Zone**
Led by	Billie Swalla (UW), Karen Matsumoto (Seattle Aquarium), Bryan Bartley (UW)
Intended Audience	High school teachers and students
Approximate # of attendees	30-100's

In collaboration with Seattle Aquarium, BEACON is working to bring Evolution in Action to a Citizen Science Project. Seattle Aquarium's "Citizen Science" program monitors the health of local Marine Reserves of Puget Sound in partnership with local high schools. Urban development in the Puget Sound is causing pollution and changes in the environment in Puget Sound. Long-term effects of global warming and ocean acidification in Puget Sound are part of the research in the project. Fourteen Seattle high schools are part of the program. Two of these schools are Tribal schools, and many of the students are low income. BEACON graduate students worked with the Karen Matsumoto from the Seattle Aquarium and high school teachers participating in the Citizen Science program, to make research experiences available to interested high school students. These students carried out projects during the 2013 summer on ecological succession in invertebrates, Pacific oysters, and phytoplankton indices monitored by PCR, and participated in a public symposium where they presented their research. In addition, a teacher workshop was held in early August focusing on the connection between evolutionary change and the marine environment. A collaborative team from the University of Washington and Seattle Aquarium worked with Louise Mead to hold a workshop for teachers from communities in rural and coastal Washington and Puget Sound. Components of the workshop included effects of climate change, ocean acidification, "Evolution in Action" lessons developed by BEACON, and interactions between research scientists and high school teachers. Continued work will include collaboration with Elizabeth Schultheis and Melissa Kjelvik to develop and present Data Nuggets based on the Citizen Science data as well as a second teacher workshop focused on statistical training.

A comprehensive evaluation of all programs up to date was carried out by Andrea V. Anderson of SoundView Evaluation and Research. To evaluate the Citizen Science-BEACON project, students were given pre and post-tests on Citizen Science skills, knowledge and attitudes toward environment and science, resulting in statistically significant improvements on 20 of 29-scaled items. In addition, Citizen Science and coastal Washington teachers attended a weeklong teacher workshop, *Think Evolution*, about evolutionary biology. A total of 16 teachers participated. The teachers were given pre-test, post-test, and retrospective pre-test surveys (i.e., pre-post/then) to assess changes in understanding about the concepts of evolutionary biology and comfort levels with teaching concepts to students. The results showed statistically significant differences for 5 of 7 items.

Three graduate students from the University of Washington participated in the Citizen Science-BEACON program and the *Think Evolution* workshop. But their most significant involvement was in mentoring six high school students selected from the Citizen Science student population. The graduate students gained experience in teaching and communicating their research to non-scientific audiences. They honed their mentoring skills.

For the most part, the high school interns were successful in achieving goals. The interns were "excited and entranced" with the work, they were "never bored" and "were able to figure things out on their own." They learned how to extract RNA, calculate biodiversity indices, skillfully use Excel, shuck oysters, take accurate measurements, and speak knowledgeably and confidently about their research to parents, friends, and faculty in a public presentation. For these students it was a transformative experience: "*I am thankful for the opportunity. I never knew I could do something like this. I never thought about doing something like this – I didn't know this was an option.*"

The Citizen Science program has matured and improved during the past eight years. The quality and quantity of data from the monitoring efforts continues to improve. Students are gaining knowledge, skills, and improved attitudes about the Puget Sound environment. The addition of BEACON activities—to expand teachers' understandings of evolution and genetics—will catalyze a new group of teachers and students into studying and assessing the marine environment differently. In the end, this collaboration shows potential for bringing into the classroom what can be a challenging topic for schools (i.e., evolution).

Activity Name	**Developing ribozyme evolution assay for undergraduate education and K-12 outreach**
Led by	Andrew D. Ellington, Gwendolyn M. Stovall,
Intended Audience	Undergraduates and high school students.
Approximate # of attendees	100s

The goals of this project are to work with the UT Freshman Research Initiative (FRI) to develop, test, and distribute a new hands-on inquiry activity for students, so they may gain a practical understanding of evolution and selection. The activity involves selecting for ribozyme catalytic function and rapidly evolving populations of ribozymes coding for faster catalysis. With the help of the UT FRI, which recruits students from diverse backgrounds and underrepresented groups, the activity will cater to high school and entry-level college students of a wide range of

backgrounds and interests. In essence, the students will show that they can perform a test tube evolution that results in an observable signal.

An evolution scheme based on the original Wright and Joyce (1997) selection was developed and tested on a pool of T500 ligase ribozymes randomized at the 3 nucleobases composing their catalytic core ("T500 N3" pool). With only 3 mutations at essential positions, improved catalytic function in populations seeded by this pool is evident after only one round of selection, thus suitable for classroom periods/timeframes. This continuous evolution scheme was paired with a strand displacement based fluorescent reporter assay in order to minimize the equipment requirements for observation of catalytic function. Student evaluation surveys (both pre- and post-demonstration) have been developed and high school coordination efforts are pending, as are efforts to offer kit training exercises over the holiday breaks.

Activity Name	**Cross-institutional iGEM synthetic evolutionary biology team**
Led by	Greg Goins (NCAT), Jian Han (NCAT), Scott Harrison (NCAT), Randall Hayes (NCAT), Robert Newman (NCAT), Jeffrey Barrick (UT), Andrew Ellington (UT)
Intended Audience	Undergraduates.
Approximate # of attendees	25

The International Genetically Engineered Machine (iGEM) Foundation is dedicated to education and competition, advancement of synthetic biology, and the development of open community and collaboration. The iGEM Foundation fosters scientific research and education through organizing and operating the iGEM Competition, the premier student synthetic biology competition. The goals of this BEACON project include (1) carry out education and outreach activities related to synthetic biology and evolution; (2) participate in iGEM 2013 as a BEACON sponsored joint UT and NCAT iGEM; (3) prepare NCAT for participation in the 2014 iGEM as an independent team. In June, one graduate student and three undergraduates from Austin visited NCAT to give a series of workshops lasting a week. Each day's workshop started with a "dry-lab" tutorial on generating project ideas, experimental design, or using computational design tools. This was followed by a "wet-lab" application, such as transformation, PCR, and cloning. In July, four undergraduates from NCAT and Dr. Newman visited Austin for another series of workshops. More advanced techniques were demonstrated, such as advanced primer design, plasmid assembly, and the use of non-canonical amino acids for protein engineering. Participants have remarked that these workshops gave them a much deeper understanding of synthetic biology techniques and iGEM participation.

In Austin, the team had tables at a "Hot Science, Cool Talks" event and during student orientation sessions, where they educated passers-by about topics related to synthetic biology and evolution. Likewise, in Greensboro, the team participated in the North Carolina Biosciences Symposium and hosted a table during freshman orientation. The team also plans to discuss their project at the monthly "Geeksboro Science Café" public outreach in the near future. For the human practices component of their iGEM project, the team examined what is being done to screen DNA synthesis requests to prevent bioterrorists from ordering the genomes of harmful viruses and select agents. As a result of this activity, they made contact with the FBI and were able to host an official Academic Biosecurity Workshop on the UT Campus. This event took

place on Sept. 18th, and included ~40 participants from the Austin community. Finally, a journalism student has been shadowing the NCAT team during its inception. To date, he has posted several blog articles chronicling the team's progress and plans to publish a series of articles in the university newspaper.

Participation in the BEACON iGEM team was greater than expected, with 12 undergraduates at UT and 13 undergraduates at NC A&T. Fourteen participants (10 UT and 4 NCAT) to the North American Jamboree (Oct. 4–6) to present their research. Their main research projects were: **GluE.coli** – a biological part for incorporating the "sticky" noncanonical amino acid L-DOPA into Mussel adhesion proteins; **Bacto-Art**—a multicomponent, inducible gene expression system that can be used as an educational tool to introduce middle and high school students to fundamental biological concepts; and **D. odori**, where they expressed genes capable of degrading odorous compounds present in swine manure in *E. coli*. The iGEM competition uses "BioBricks," which are well- characterized genetic sequences that can be combined to make larger systems with novel functions. However, the current BioBrick rules (from 2003) make it difficult to submit parts that consist of large, novel sequences. The team surveyed other iGEM teams about whether they thought these restrictions should be removed in light of newer DNA assembly techniques and proposed a Request for Comments (RFC 95: Open Sequence Initiative) to the iGEM community.

Activity Name	**Reinvigorating a 1980s Microbiology Course via Evolution in Action**
Led by	Alita Burmeister, Jim Smith, Richard Lenski (MSU)
Intended Audience	Undergraduates.
Approximate # of attendees	72

As a field, microbiology has often overlooked evolution as a core concept and process. Even in obvious cases where it could and should be integrated, like antibiotic resistance, microbiologists often speak of the "development of resistance" rather than its evolution. One such instance is in the microbial genetics laboratory course MMG 408 at Michigan State University. While the core evolutionary concepts of variation, selection, and inheritance are encountered daily in the course, the link to evolution and natural selection has been absent from course materials. They have created a formal plan to integrate evolutionary thinking into MMG 408 and to assess whether evolutionary instruction increases student learning of microbiological and evolutionary concepts. They developed a classroom laboratory exercise and protocol in the Lenski Lab during summer 2013, with the help of MSU undergraduate and BEACON REU student Rachel Sullivan. The activity uses experimental evolution of *Escherichia coli* in media containing the antibiotic rifampicin and requires approximately three weeks of instructional lab time to complete using standard MMG 408 course techniques. They have re-written the course syllabus to include a detailed outline of the traditional and new experiments, standard course lecture material, and the new evolution-related lecture material. These new lectures introduce basic evolutionary concepts focusing on populations and relate evolution to future careers via material grounded in the scientific literature. New lectures began on September 25, 2013 and are developed on an ongoing basis. They also presented a poster for this project at the MSU CREATE for STEM Mini-Conference in April and written a formal assessment plan for this project including methods, a content-based assessment, and an attitude-based assessment. The

content-based assessment includes three open-ended questions about microbial genetics and evolution. The attitude assessment includes two constructs of Likert-scale questions that assess acceptance of microbial evolution as a natural process (six-question construct) and the perceived likelihood of using evolutionary concepts in future careers (five-question construct).

Activity Name	**Finger Painting Fitness Landscapes, PicBreeder, and Rhyzobium**
Led by	Tom Getty (MSU), Heather Goldsby (UW), Luis Zaman (MSU), Tomomi Suwa (MSU), Anya Johnson (MSU)
Intended Audience	K-12
Approximate # of attendees	Unknown

In collaboration with scientists from diverse disciplines (computer science, plant biology, biology, and zoology), this team is developing several course modules with two main education goals: 1) to foster a deep understanding of evolutionary mechanisms and 2) hands-on exposure to inquiry-based science. Using two computational tools (Finger-painting Fitness Landscapes4 and Picbreeder) along with living organisms (plants and soil bacteria), they are developing interactive, engaging, and fun educational tools for the high school level. They are modifying the Finger-painting Fitness Landscape program to support iPads, thus allowing for wider distribution within high school classrooms. Additionally, they will extend the application to support a second perspective on evolution that makes the fitness landscape more tangible. To complement the Finger-painting application, they will also use Picbreeder, an interactive online tool, to teach key concepts such as recombination and selection. Students can "evolve" graphics by selecting several pictures as parents for the next generation and view the evolutionary process in real time. To cement the connection with evolution in action in nature, they will use plants and rhizobia to conduct a simple classroom experiment, as well as raise broader questions about ecological and evolutionary implications. Computational tools combined with living organisms are ideal inquiry based learning tools that allow students to form evolutionary hypotheses, conduct simple experiments, and draw conclusions based on their observations.

Activity Name	**LadyBug and Aphid Game**
Led by	Terry Soule (UI), Tom Getty (MSU), Melissa Kjelvik (MSU), Josh Rubini (UI)
Intended Audience	K-8th Grade
Approximate # of attendees	Unknown

Prior to the project, the LadyBug software had one user interface and few options of changing parameters to explore the concepts (natural selection) programed into the simulation. Joshua Rubini (graduate student, UI) created a classroom-friendly program with five modules that each highlighted one component of natural selection (e.g. variation, inheritance, predator selection, change over time). Melissa Kjelvik (graduate student, MSU) designed lesson plans to accompany each interface along with supplemental activities to introduce new ideas and reinforce concepts from the lessons. An additional lesson plan with live lady beetles and aphids is offered as an inquiry experiment as a follow-up on predator selection.

The lesson plans have been piloted with Michigan students, teachers, and parents both during school hours and through outreach events such as science nights and MSU's Science Festival. Interestingly, many parents find this resource valuable and encourage their children to continue exploring at home. The activities and lesson plans will be presented at the National Association for Biology Teachers (NABT) meeting this November in Atlanta, Georgia. NABT is a great avenue to reach teachers from across the United States and will provide a resource to address their concerns about teaching evolution in classrooms. Plans for assessment are now underway and a more comprehensive study of effectiveness in the classroom being developed, as well as creation of a BEACON linked website for distribution of program and lessons. Terry Soule is also collaborating with Julie Fick at the MSU Museum, to modify the program and make it usable in the museum environment.

Activity Name	**Evolved Art Competition**
Led by	Randal Olson
Intended Audience	Adults
Approximate # of attendees	36 entries

BEACON hosted an online evolved art competition, open to the public, from March 1st through May 31st, 2013. The goal of this competition was to evolve an alternative lighthouse to the BEACON lighthouse on the collaborative art evolution web site Picbreeder. The top three lighthouses submitted received Visa gift cards of $200 (1st place), $100 (2nd place), and $50 (3rd place). The awards were presented at the BEACON 2013 Congress. Entries can be viewed here: http://picbreeder.org/search/showcategory.php?visited=3172. The winners can be viewed here: http://beacon-center.org/blog/2013/06/14/beacon-evolved-art-competition-results/.

2d. Integrating research and education

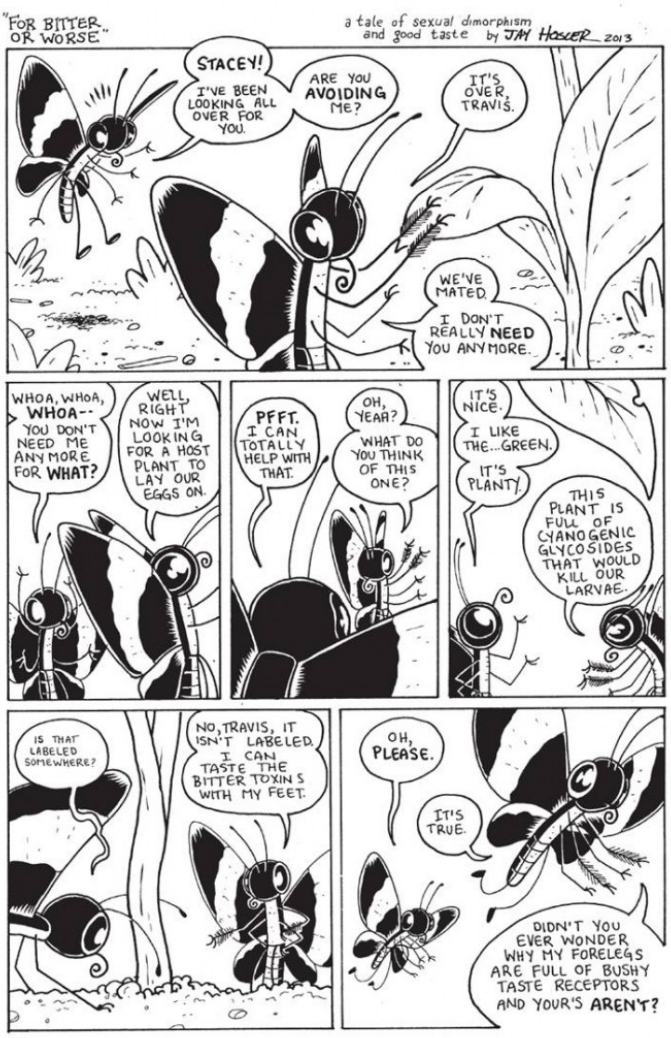
Across our entire consortium, our programs seek to integrate research and education, both by bringing current BEACON research on Evolution in Action to various audiences, as well as bringing research approaches to our education projects.

The Michigan State University Museum continues to work on exhibits that highlight BEACON research, adding two hands-on components to the exhibit: Mutation Station engages the visitor in building "Spartybug" genetic code mutations with Lego bricks and comparing the effects of those mutations in the Bugworld environment where Spartybug lives. In the 50,000 portion of the gallery, visitors can see for themselves the results of competitions between ancestral and modern *E.coli* populations. Plates of *E. coli* colonies from the Lenski lab (MSU) have been preserved and sealed for viewing under a magnifier and the Natural History Museum at UT Austin is engaged in developing resources for outreach as well. BEACON members also routinely bring their research to general public audiences, through programs such as Darwin Discovery Day at Michigan State University and iGEM, not to mention science festivals and science nights. A few programs below are wonderful examples of BEACON efforts to integrate research and education.

A number of our faculty and graduate students are involved in evolution education research efforts. Emily Weigel (MSU) completed a FAST Fellowship project last year examining how the

order of the presentation of genetics and evolution influence students' understanding of evolution. At MSU, faculty have been involved in the submission of a university-wide grant to HHMI focused on reform of undergraduate classrooms, which would include further integration of Avida-ED across biology courses. Similarly, UW faculty have teamed up with biology education specialists there to also submit a proposal to HHMI that would include bringing Experimental Evolution to Introductory Biology courses. Graduate students interested in evolution education meet regularly with Louise Mead, who is actively involved in working with a group outside of BEACON to develop the GeDI (a genetic drift inventory for measuring what advanced students have mastered about genetic drift) (Andrews et al. 2012; Price et al. in revision), and is working with BEACON graduate students on a review of all instruments that measure understanding and acceptance of evolution.

Adriana Briscoe, a BEACON Faculty Affiliate from UC Irvine, worked with Jay Hosler to create a public outreach cartoon "For Bitter or Worse: A Tale of Sexual Dimorphism and Good Taste" (at right), based on discoveries reported in a paper published in PLoS Genetics (Briscoe et al. 2013).



Randall Hayes (NCAT) organizes the Greensboro Science Café, a monthly series of discussions with STEM professionals (https://www.facebook.com/GreensboroScienceCafe). These events are attended regularly, with a maximum of 75 individuals. Of the 6 sessions thus far, two have been evolution-related: Corbin Jones from UNC-Chapel Hill discussed speciation in March. Charles Mitchell from UNC-CH discussed invasive species and plant diseases as models of human disease in August.

BEACON sponsored two week-long workshops for high school teachers. **Think Evolution Teacher Workshop** in Forks, Washington; and **Unleash Your Inner Scientist** at Kellogg Biological Station in Hickory Corners, Michigan. Both workshops included research presentations by guest speakers, particularly focused on Evolution in Action related research. The Think Evolution workshop included presentations by Dr. Jason Hodin, postdoc, Hopkins Marine Station, Stanford University; Dr. Carolyn Friedman, Professor, School of Aquatic & Fishery Sciences, UW; Dr. Steven Roberts, Assistant Professor, SAFS; Dr. Abby Swann, Assistant Professor, Atmospheric Science & Biology, UW; Dr. Robin

Waples, Senior Scientist, Northwest Fisheries Science Center, NOAA. Unleash Your Inner Scientist workshop included presentations by Dr. Jen Lau, Dr. Zachary Blount, and Dr. Danielle Whittaker (all BEACON). Feedback from the participants indicates these links to scientists doing science are what helps them understand what they need to be doing in their classrooms to open these types of careers up to their students.

2e. Progress towards metrics described above

1. Multidisciplinary Ph.D. graduates and postdocs placed in faculty positions at rates approaching averages across engineering, computer science, and biology.

- We are just now seeing appreciable numbers of graduate students complete their degrees and seek positions in academia. So far, 33 BEACONites have reported receiving a degree or completing a postdoc, and their placements are summarized in the table below.

	Bachelors	Masters	PhD	Postdoc
Graduate School	1 (25%)	6 (55%)		
Postdoc			9 (60%)	
Faculty Position			2 (13%)	2 (66%)
Industry	3 (75%)	3 (27%)	4 (27%)	1 (33%)
Government		1 (9%)		
K-12 Education		1 (9%)		
Total # graduates	4	11	15	3

- We continue to make progress in training multidisciplinary students. All three interdisciplinary graduate courses continue to be offered across our consortium, and we continue to respond to the feedback we receive from students as to how best to improve these courses.
- Continued funding of REU/FRI students during the summer as a way of introducing potential students at early stages in their careers.

2. Increased public literacy in evolution and the nature of science

- Our Year 4 budget for Evolution in Action education projects increased to 18%.
- Faculty across our consortium are involved in reform efforts across the STEM disciplines, with faculty bringing BEACON related approaches to experimental evolution and evolution in action to these initiatives.
- The BEACON funded multi-case national study of Avida-ED is well underway, with Amy Lark preparing data for publication.
- We have increased our presence at the National Association of Biology Teachers annual professional development conference. We are co-sponsoring with NESCent the Evolution Symposium and an education workshop based on the Evolution Symposium topic (honoring Alfred Russel Wallace's contribution to biogeography at the Atlanta meeting in November 2013). We are also co-sponsoring the NESCent/BEACON Evolution Scholars Program that is providing an opportunity for four teachers (two high school and two community college) to attend NABT.
- BEACON continues to have a strong involvement with all education and outreach efforts of the Society for the Study of Evolution, with presenters participating in both the Evo101

workshop for K-12 science educators as well as a new Professional Development workshop offered in 2013.

- We continue to keep the Evolution in Action gallery at the MSU Museum dynamic – new stations, specific development of Ladybug/Aphid interactive for the museum. Rose Canino-Koning invented and built an LED-based installation that illustrates a population of light sequences being evolved by a genetic algorithm. BEACON was an active participant in the MSU Science and Engineering Festival. BEACON faculty and staff have participated in Elementary Science nights at local schools.

3. Increased interest in STEM careers

- We have responded to a call for proposals by NESCent on K-12 Evolution Education and Underrepresented Minorities by holding at catalysis meeting at NESCent in April 2013 and initiating a research project, funded through BEACON, to examine barriers to URM students entering disciplines related to evolutionary science.

2f. Educational plans for next reporting period

We continue to test and review all our educational projects, working to bring curriculum developed at one institution to other institutions across the consortium. Cross-fertilization of Data Nuggets and Citizen Science program is one example of how our education materials are being developed at one institution and distributed at other institutions. We are also providing training for our graduate students interested in education in both DBER and knowledge of current science education reform. We will be submitting a number of proposals during the coming months in response to the NSF HER Core Research RFP and the CAUSE RFP. We will also continue to gain notoriety in evolution education field through publication of lessons, review papers, and through the development of our web resources.

IV. KNOWLEDGE TRANSFER

1a. Overall knowledge transfer goals

BEACON's **Knowledge Transfer goal** is to develop and practice effective mechanisms and pathways to facilitate intellectual exchanges among BEACON partners and industry that will support the sharing of knowledge and application of new technology. Based on its interactions with industry to date, BEACON has revised its approach to knowledge transfer to concentrate on collaborative relationships with individual companies rather than to work with an industrial consortium, as companies have found it burdensome to navigate their respective organizational bureaucracy. Instead, it is mutually beneficial and more resource-efficient to BEACON and to the companies to work directly with BEACON participants.

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**
New collaborative research with industry partners	The number of external industry/government laboratory collaborations with BEACON through its member universities	At least 11
	Number of joint grant proposals submitted with industrial partners	One in progress
	Number of publications submitted that arise from industry provided challenge problems and data	At least 5 in the current reporting period
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.
Dissemination and use of BEACON tools and data	Number of downloads of BEACON tools/data relative to baseline	~5,600 downloads of Avida-ED; over 4,000 downloads of Avida platform
Spinoffs formed	Number of spinoffs formed	No new spinoffs to report in the current period, but foundations are being laid for one

1c. Problems encountered and resultant changes

As was described in the previous Annual Report, BEACON's initial plan to create an industrial consortium ("Industrial Affiliates Program") turned out not to be an effective way to organize collaborative research with industry for a center with potential applications as broad as those of BEACON researchers. There is too little commonality of needs among the very diverse companies with which BEACON researchers have established contact. Therefore, although considerable effort was invested by BEACON's Industrial Affiliates Manager, Dr. Betty Cheng, to create the legal framework for such a consortium, working with the IP and sponsored research offices of all of the BEACON partners, and such an agreement has, in fact, been signed by all of the partner universities, we have decided to abandon this thrust in favor of the much more successful approach of working with individual companies on evolutionary applications that are of immediate interest to them. Dr. Cheng's title in BEACON will be changed to the Manager of Industry Relations in recognition of this organizational change.

In parallel with the development of the general IP agreement planned for use with the Industrial Affiliates, Dr. 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 BEACON's areas of expertise. Dr. Cheng is also working with the PIs at the BEACON partner institutions to coordinate industrial contacts to avoid redundant efforts. Dr. Cheng is also providing BEACON students and postdoctoral researchers with information about industrial career opportunities, as well as assistance with resume preparation appropriate for industrial careers. Several BEACON participants are engaged in knowledge transfer activities (see below) and are also actively recruiting industrial partners. To help to promote such industry involvement, Prof. Cheng organized a Sandbox Session at the 2013 BEACON Congress on the topic "Working with Industry." There, several BEACON participants with experience working with companies described how their work was structured and funded, and answered questions on the topic. Also, during the 2013 BEACON Congress, Dr. Cheng also met with several student/postdoctoral groups to share her industrial experience and offer advice and guidance for working with and in industry.

BEACON's posture toward industry has been and continues to be to cooperate first and not stress legal 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 an agreement and funding can be negotiated to continue the work.

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. He returned for a second month-long visit in April 2013. Since 2011, he has collaborated regularly via videoconference and email with Goodman and Deb. The team made a breakthrough during his first 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, Mr. Daniel Couvertier. Deb and Goodman 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 that was not funded. 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. The team published a conference article in June, 2012, and their entry in the Multi-Criterion Decision Making Conference (Malaga, Spain), won the Wiley Practice Prize, a prestigious award in the field. They are in negotiations with a major firm for support continue their research and to produce a commercial tool to apply to large, "wicked" problems globally, as part of the firm's offerings in support of "smart cities" and related projects.
- **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 is exploring 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.
- **Chrysler:** Led by Betty Cheng. Cheng is in the preliminary stages of negotiating a project with Chrysler to investigate the next generation of networking for automotive systems (i.e., automotive Ethernet).
- **Continental Automotive**: Led by Betty Cheng. Cheng has been collaborating with Continental Automotive on the use of evolutionary techniques for algorithms to assist in the prevention of backup rollover accidents. In addition, they have received two challenge problems, including the backup rollover prevention system and another one on automated pedestrian collision avoidance system.
- **StoneAge Robotics**: Led by Risto Miikkulainen. Miikkulainen is working with this startup company to transfer neuroevolution technology to the intelligent robotics industry.

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

Xiaobo Tan filed an invention disclosure on Gliding Robotic Fish in February 2013. This is a technology that integrates key advantages of robotic fish with those of underwater gliders, and is expected to result in underwater robots with high locomotion efficiency and high maneuverability. The technology has a myriad of applications in aquatic environmental sensing, and it was highlighted at the third annual MSU Innovation Celebration in June 2013. A provisional patent is expected to be filed in late October 2013. Tan's group has received two grants, one from Spartan Innovations and the other from NSF, to advance the market readiness of the technology. These projects will make the technology easier to service and customize with longer operational time. Spartan Innovations and MSU Technologies are working with them closely on this commercialization effort. They are planning to start up a company once the current phase of development is complete, around early 2015. A few videos of the technology (including field tests at KBS with BEACON researcher Elena Litchman and at Kalamazoo River) are available at http://www.youtube.com/user/smartmicrosystems. Some pictures can be downloaded at http://msutoday.msu.edu/360/2013/faculty-voice-xiaobo-tan-robofish-grace-takes-a-road-trip-1/.

2c. Progress towards indicators/metrics listed above

1. Establishing collaborative research relationships with industrial sponsors.
BEACONites are working with at least 11 external industrial/governmental organizations at this

time. At least 5 publications submitted in this reporting period have resulted from collaborations with industry partners, including 2 by Goodman's team working with Scion, Inc, and 3 by Cheng.

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. Dissemination and use of BEACON tools and data.

We are currently developing a web page repository for these tools and data.

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 2011 – Jul 2012)** (*Previous reporting period)*	**No. of Downloads (Aug 2012 – Jul 2013)**
Avida-ED		
For Windows	2903	3421
For Mac	1174	2237
Total	*4077*	*5658*
Avida		
SourceForge.net	4405	4032

4. Spinoffs formed. While no spinoffs were originally anticipated in the first five years of the Center, one spinoff was successfully established by Risto Miikkulainen in the 2011 reporting period, and a second one is planned for 2015 by Xiaobo Tan.

2d. Knowledge Transfer plans for the next reporting period

- Continue to collect additional challenge problems from current and new industrial collaborators.
- Encourage and support travel by BEACON participants to visit industrial organizations and other external organizations to describe their industrially-relevant work.
- Encourage BEACON participants to give tool demonstrations at their respective conference venues to publicize and obtain feedback on their tools and techniques.
- 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.

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 was 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. More details are available in the Education section of this report.

Activity: BEACON External Faculty Affiliate Program

Organizations/people involved: University of California Irvine/Adriana Briscoe, Yale University/Paul Turner

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 was our first Affiliate and continues to be active with BEACON. Dr. Briscoe recruited a student, Aide Macias Muños, who was trained in DNA sequencing with BEACON support, and was consequently

awarded an NSF Graduate Research Fellowship. Dr. Briscoe's initial BEACON led to a proposal to NSF for external funding, which was funded at $440K. Our second Affiliate, appointed in 2013, is Paul Turner from Yale University. This program is described in greater 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: Unleash your inner scientist: Employing and enjoying inquiry in the classroom and lab.

Organizations/people involved: BioQUEST

Narrative: BEACON and BioQUEST joined together to offer a 5-day workshop for science educators that ran from June 28th-July 3rd 2013 at Kellogg Biology Station. Twenty participants registered for the workshop, a total of eight attended, in addition to Lazarius Miller, an REU SROP student with BEACON. Participants (1) explored lessons focused on teaching inquiry and using data (BioQUEST/DataNuggets); (2) carried out a field-based experiment, collecting and analyzing data, and creating a poster/presentation on their research; (3) identified ways to incorporate inquiry-based lessons into the curriculum that address specifically evolutionary topics; (4) gained experience with Avida-ED and other model programs that can be used to carry out investigations focused on evolutionary science; (5) heard about recent research by BEACON scientists (Zachary Blount, Jen Lau, Danielle Whittaker). Participants completed an evaluation at the end of the program indicating overall enjoyment in the scheduled activities with most scoring between 1 and 2 on a 5-point scale with 1 indicating excellence and all participants indicated they will incorporate the information, materials, and inquiry approach presented throughout the workshop.

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

Organizations/people involved: NESCent

Narrative: Drs. Judi Brown Clarke, Joseph Graves and Louise Mead received funding from the National Evolutionary Synthesis Center (NESCent) to hold a catalysis meeting at NESCent focused on Evolution Education and the Underserved. They brought together 18 people from across the country to discuss the underrepresentation of minorities in evolutionary sciences. This group is continuing to work together to collect preliminary data on potential barriers to students considering careers in evolutionary sciences and have plans to submit a EHR Core Research Proposal to NSF in January.

Visiting researchers during this reporting period: Dr. Benjamin Kerr (from BEACON at UW), Professor Lihong Xu (Tongji University), Chenwen Zhu (Tongji University), Haiqiang Nie (Tongji University), Professor Meng Yao (East China Normal University), Weiming Ji (East China Normal University) and Dr. Oliver Chikumbo (Scion Crown Research Institute, Rotorua, New Zealand).

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

Proposal in development: One proposal is under development for submission to Living PlanIT, a UK corporation, for $4.5 million over a 3-year period for commercialization of the WISDOM multi-criterion decision making technology developed in BEACON in a collaboration between Profs. Goodman and Deb (BEACON) and Dr. Oliver Chikumbo (Scion, New Zealand).

Visiting speakers: BEACON has hosted a number of visiting speakers in 2013, who traveled to Michigan State to meet with researchers and students, and gave presentations at the weekly Friday seminars which are videoconferenced across all five partner institutions. This year's visitors included:

- Gail Patricelli, UC Davis
- Pekka Malo, Aalto University School of Business
- Lynn Rothschild, NASA
- Joel McGlothlin, Virginia Tech
- Gusz Eiben, University of Amsterdam
- John Long, Vassar College

2c. Progress towards goals

Number of researchers visiting BEACON for sabbatical: 1 in 2013-2014 (Ben Kerr)

Number of sabbaticals supported: 2 (Charles Ofria, 2012-2013, Ben Kerr, 2013-2014)

Number of publications resulting from sabbaticals: 6 so far this year

Number of submitted external grant proposals: 2 so far this year

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

BEACON will issue a third 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 are pleased to report that we are achieving and sustaining diversity at BEACON through strategic and inclusive recruiting and partnerships, as well as formal professional development opportunities, including ongoing formal mentoring training and support.

BEACON is completing its fourth year of funding, and with that comes a need to thoughtfully reflect on our diversity efforts. In the original 2010 proposal, section ***4.e Diversity Program*** page 30-33, BEACON states:

> "The Center will achieve this general goal by starting with diversity at all levels and conducting programs to build on that diversity. It will greatly exceed national norms with respect to underrepresented groups and will demonstrate the value of diversity by fostering active collaboration among all participants."

Overall, BEACON has been successful in accomplishing our diversity goals by leveraging strong partnerships and programming to ensure that our efforts are consistent and sustainable. We always incorporate our *Plans for the Next Reporting Period* outlined in the prior year's annual report, and utilized data-driven results and "lessons learned" into the curent efforts. Here are our most recent accomplishments:

2013 GOAL: BEACON will target its efforts to increase female participation; specifically, we will focus on graduate students, post-docs, and faculty.

Accomplished. BEACON surpassed the national norms for overall female participation; however, we still have opportunities to increase female post-docs and faculty. Currently BEACON has 19 post-docs, with 32% being female. This is a significant accomplishment from last year's (2012) results of 26.9%, which was well below the National Norms (35%). We recruited graduating seniors at our partner schools and within our undergraduate summer research programs, and coordinated with faculty advisors at HBCUs and HSIs to increase the number of females participating in our graduate programs and post-doc opportunities. BEACON actively recruited current female faculty at partner schools to collaborate on research, teach classes, submit grants, and/or write publications.

2013 GOAL: 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.

Accomplished, modified. In 2012, BEACON partnered with Dr. Lizanne DeStefano, the primary evaluator for the Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS), a peer NSF STC, to conduct a collective evaluation across multiple STC's REU sites. Unfortunately we had difficulty navigating a reciprocity agreement between our two institutions in a timely manner. As a result, BEACON conducted the evaluation independently using the *2013 BEACON Organizational Effectiveness & Impact Survey* conducted by MSU evaluators Drs. Patricia Farrell Marilyn Amey, and the results are forthcoming.

2013 GOAL: BEACON will sustain its baseline diversity efforts, with the intention of exceeding National Norms in all participant categories and disciplines.

Accomplished. BEACON has successfully exceeded National Norms in all targeted categories; the only sub-categories for improvement were female post-docs and faculty, and undergraduates with disabilities.

2013 GOAL: BEACON will continue to leverage funding and secure grants to support diversity efforts and research opportunities for URMs.

Accomplished. We found that many URM students were underprepared for the summer research experiences, and therefore created a two-tiered program by funding both REUs (for students with strong lab/research backgrounds) and Undergraduate Research Apprenticeships [URAs] (for student with little to no lab/research background). We blended and leveraged support from multiple funding sources to create summer research opportunities at MSU, NCAT, UT, KBS, and Friday Harbor.

BEACON has travel awards for students to attend professional conferences and present their research; many of our URM students are taking advantage of this funding opportunity and are getting valuable exposure to professional networks, discipline peers, and content experts. BEACON is also providing year-round formal mentoring training for all graduate students and post-docs in direct contact with undergraduate research students.

ADDITIONAL HIGHLIGHTS

BEACON initiates a bi-monthly conference call for the diversity and education directors in all the STCs. This has become an opportunity for problem solving and sharing of best practices among STC colleagues.

Working with MSU's Resource Center for Persons with Disabilities, BEACON audited and made appropriate corrections to its' website to ensure it met the standards for accessibility for people with disabilities. Additionally BEACON has hired a videographer to create our *branding* video and to capture our Friday seminars and other special events; we are in the process of exploring adding *closed captioning* to ensure it meet standards.

BEACON continues to work closely with the MSU College of Engineering's Sloan Program, which recruits, helps fund, and mentors domestic engineering doctoral students, with an emphasis on underrepresented groups. This program now refers to itself as Sloan/BEACON. The BEACON students have access to all the same programming opportunities as the Sloan scholars, including a bi-weekly informational meetings and expert speakers.

The BEACON High School Summer Program is a residential summer education/hands-on research program that runs at the MSU Kellogg Biological Station. In 2013, the program served 32 students, including 70% females and approximately 25% underrepresented students. Over the past three years it has collectively provided a rich, in-depth experience in evolutionary science to 92 rising 11th and 12th grade high school students, with an average of 36% underrepresented minorities and 63% females. This program continues to make its materials and lessons available as open resources to teachers, and acts as a talent pipeline to recruit participants into any of the BEACON schools.

BEACON awarded its second Faculty Affiliate grant, which is a mini-grant of up to $100,000 over a two-year period to conduct research and explore the possibility of becoming a permanent member of BEACON. This grant has a two-year overlapping funding cycle, which now supports 2012 recipient Dr. Adriana Briscoe, Professor of Ecology and Evolutionary Biology at the University of California, Irvine, and our new 2013 recipient Dr. Paul Turner, Professor and Chair of the Department of Ecology and Evolutionary Biology, Yale University.

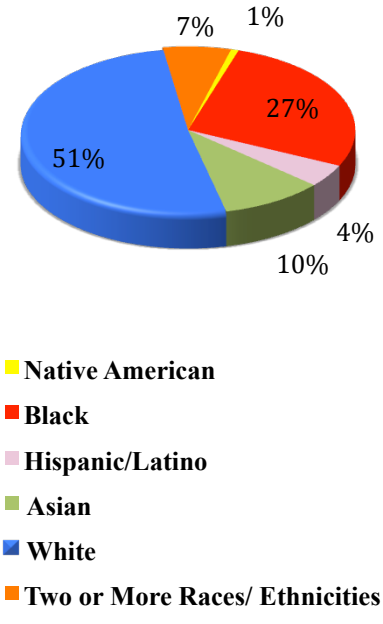
BEACON also awarded its second Distinguished Postdoctoral Fellowship to Dr. Annat Haber, who will study macroevolutionary implications of integration.

Under the direct leadership of BEACON professor Gerry Dozier (NCA&T), the Computer Science (CS) Department at NCA&T launched its own doctoral program this fall 2013. This effort was greatly assisted by collaborations between NCA&T faculty and their BEACON computer science colleagues.

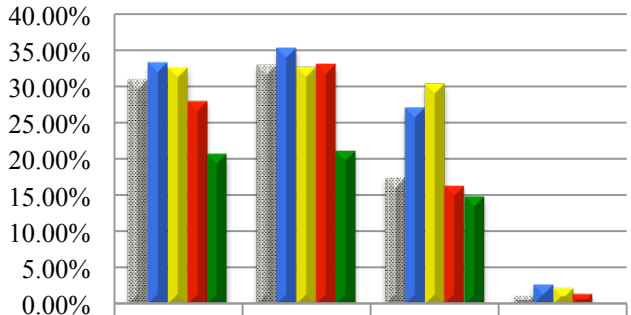
1b. Performance and Management Indicators

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 we captured national norm data for BEACON-specific disciplines only using NSF's 2012 data tables, see http://www.nsf.gov/statistics/wmpd/start.cfm.

Underrepresented minorities (URMS): Our 4-year target was to achieve a 5% increase over the National Norms for BEACON-specific disciplines by October 2013. Currently 33.2% of BEACON participants are self-reporting as URMs, which is a 7.79% increase above the National Norm. This is also an



BEACON URM Participants: Four-Year Baseline Camparison



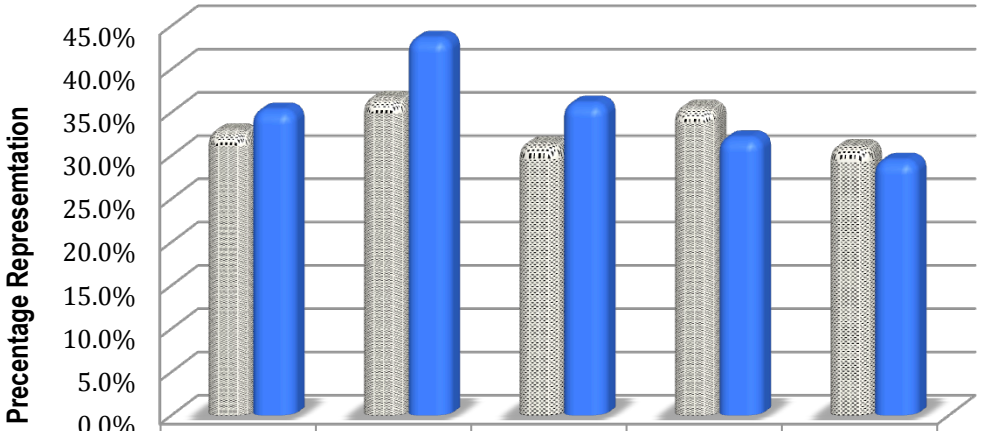
	Total Membership	BEACON Female Participants	BEACON Ethnic Participants	BEACON Participant Individuals w/ Disabilities (Vis/Aud/ Mob)
Weighted National Norms	30.80%	32.8%	17.3%	1.1%
2013	33.2%	35.2%	27.0%	2.70%
2012	32.5%	32.6%	30.3%	2.20%
2011	27.8%	32.9%	16.2%	1.40%
2010	20.5%	20.9%	14.7%	0.0%

impressive 61.9% increase over the Year One (2010) baseline of 20.5%.

Currently BEACON participants are: 51% White, 27% Black, 10% Asian, 4% Hispanic/Latino, 1% Native Indian, and 7% two or more races/ethnicities.

Females: BEACON is pleased to report that the overall percent of females participating is 35.2%, which surpasses the National Norms (32.6%). This is a positive increase from 2012, when BEACON (32.5%) was slightly below the national norms. While we are very happy with these collective results, we are diligently working and creating strategies to increasing female representation in faculty and post-doctoral positions.

2013 BEACON Females vs. Weighted National Norms



	Total	Under-Graduates	Graduate Students	Post-Docs	Faculty
Weighted National Norms	32.8%	36.6%	31.3%	35.5%	31.0%
BEACON	35.2%	43.5%	36.0%	32.0%	29.4%

Undergraduates: BEACON (43.5%) exceeded the National Norm (36.5%) for female undergraduates. This was accomplished by the expansion of the summer research programs, and increased opportunities for undergraduates to work in research labs and take BEACON-specific courses

Graduates: BEACON (36.0%) exceeded the National Norm (31.3%) for female graduate students. This is an area where BEACON had a great opportunity to make progressive strides, we recruited from partner schools and utilized the summer REU programs and graduate recruitment conferences to inclusively recruit female students.

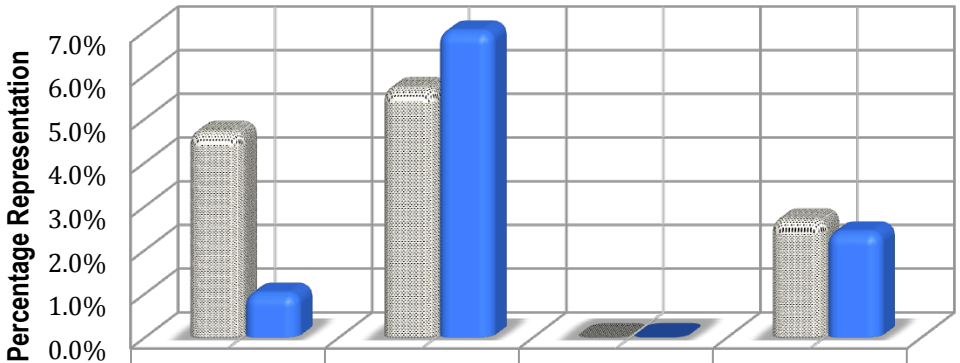
Post-Docs: BEACON (32.0%) is still slightly below the National Norm (35.5%) for female post-docs; however, last year (2012) BEACON was at 26.9%, which well below the National Norm. We see this 19% increase as a positive result from our strategies to recruit Ph.D students from BEACON's partner schools, graduate recruitment conferences, and the BEACON Post-Doc Fellowship Program.

Faculty: BEACON (29.4%) is still slightly below the National Norm (31.0%) for female faculty; however, last year (2012) BEACON was at 22.1%, which well below the National Norm. We see this 33% increase as a positive acknowledgement of our efforts, including

recruiting current faculty at BEACON partner schools to collaborate on research, teach classes, submit grants, and/or write publications; and 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 2.7% of our participants self-reported as having a disability, this exceeds the National Norms (1.1%) and is a 22.7% increase from 2012 (2.20%).

BEACON Participants: Individuals w/ Disabilities



	Under-Graduates	Graduate Students	Post-Docs	Faculty
Weighted National Norms	4.7%	5.7%	0.0%	2.7%
BEACON	1.0%	7.0%	0.0%	2.4%

While we are pleased that more individuals self-reported as having a disability, we acknowledge that our participant numbers are still underreported. This underreporting represents individuals that have verbally disclosed that they have a disability but do not choose to reflect this in their personal profile for various reasons, such as "feeling vulnerable" or "it may be perceived as a weakness." Creating a safe and inclusive environment will be a priority in this year's diversity efforts in attempts to address the underreporting issues.

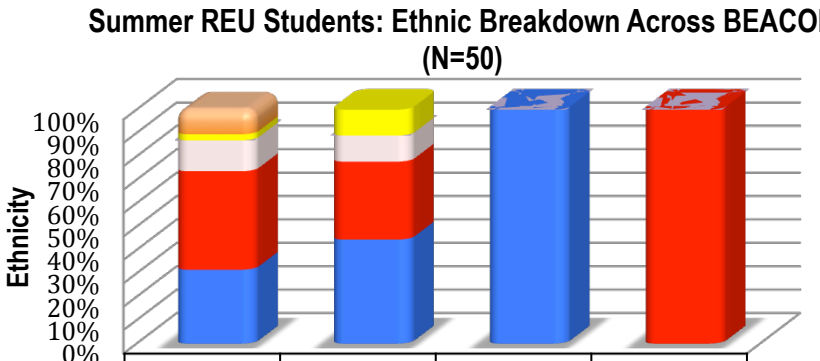
1c. Problems encountered

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 to change the culture to promote open communication, knowledge sharing, and innovation by creating a collegial, mutually respectful environment. This allows everyone to reach his/her full potential in the workplace by fostering a unified community of inclusion. However, we know that affecting cultures is not an easy task and we will continue to diligently support the unique needs of URMs, specifically females and individuals with disabilities.

We are addressing non-programmatic diversity activities with the following two key efforts: 1) BEACON budget requests must address diversity and state how they enhance it (if applicable), and 2) ensure that diversity is represented as a connecting thread through all aspects of BEACON (e.g., social media - website/blogs/Facebook page, professional development training, and adaptive learning/research environments.

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.



	MSU	KBS	UTA	NCA&T
Mixed	4	0	0	0
Native Am	1	1	0	0
Asian	0	0	0	0
Hispanic	5	1	0	0
Black	16	3	0	2
White	12	4	3	0

This past summer, we funded 50 students across the BEACON partner schools, at four different sites. This included wet labs, dry labs, computer/simulations, field experiences, and/or a combination.

Additionally BEACON provided ongoing formal **mentor training** to 48 graduate students and post-docs mentoring REUs and URAs in diverse research settings; with on-going weekly training and technical assistance to address any challenges. This model proved to be extremely effective in strengthen a positive experience for both mentors and mentees.

Evaluation: BEACON partnered with the MSU's Graduate School Summer Research Opportunity Program (SROP) to administered pre-, mid-, and post-surveys to students and mentors, as well as conducted group observations and focus group interviews

- **Respondents' gender**: 50 participants (Reflecting BEACON & SROP students); 26 males, 23 females, 1 other
- **Ethnicity:** 21 Black/African American, 12 White/Caucasian, 6 Hispanic, 2 Asian, 2 Native American, 1 Puerto Rican, 1 Haitian Creole, 5 Mixed Races
- **Preliminary results:** On a 5-point Likert Scale, mean response rates show and overall 4.32 satisfaction rate

Here are some key survey results:

86% 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.

77% 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.

93% of students reported very strong to strong results on a positive *overall experience.*

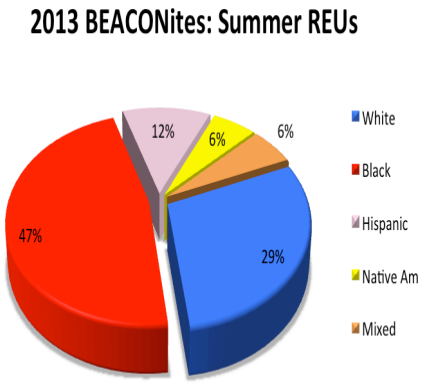
Question	Very Strong	Strong	Neutral/Ave.	Weak	Very weak	Mean	SD
9. Communicate across disciplines	14 25.50%	29 52.70%	11 20.00%	1 1.80%	0 0.00%	4.02	0.733
10. Communicate with my discipline	21 38.20%	22 40.00%	11 20.00%	1 1.80%	0 0.00%	4.15	0.803
23. I plan to pursue a graduate degree	33 60.00%	9 16.40%	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

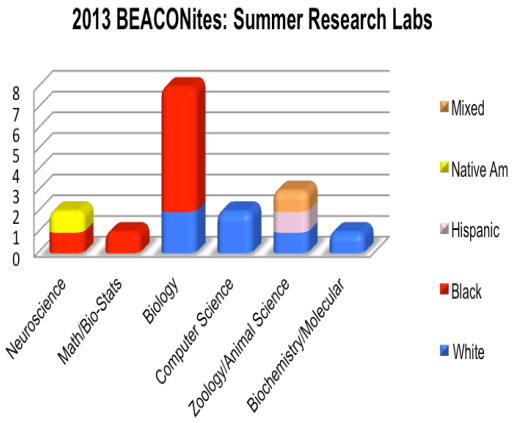
External Funding: In an effort to establish sustainability, multiple grants have been submitted to external funders. Drs. Eisthen & Lonstein were **successfully awarded a NSF REU site grant for the Integrative Biology of Social Behavior (IBSB)**, this funding is for three years to support 10 neuroscience undergraduates in summer 2013-15. In this year's cohort of ten interns, 60% (6) were ethnic minorities, and one was a veteran of the US military.

In 2013, BEACON **submitted a supplemental REU funding proposal to NSF 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.

While NSF did not fund this 2013 proposal, BEACON was able to resubmit the proposal to MSU's Office of the Provost – Undergraduate Education and secured $40,000 of internal funding, which was blended to support sixteen (16) MSU undergraduate students during the summer. The blending of funds represented leveraging an additional $49,990 for a total budget

of $89,980 to support MSU students. This is relevant because BEACON summer research funding targets non-MSU students, which has been very unfortunate for MSU students wanting to stay and research at MSU during the summer.





An additional $20,000 was secured to support four (4) of those students throughout the academic year. MSU students participating in this opportunity become outstanding candidates for direct admission to a BEACON graduate program at one of the partner schools.

BEACON's Diversity Director Brown Clarke and Education Director Mead collaborated with Nevada's submission of a project entitled **The Solar Energy-Water-Environment Nexus to NSF's EPSCoR Track 1 Research Infrastructure Improvement (RII) program**. This proposal was selected and awarded $20 million for five years. Brown Clarke was invited and accepted membership on their External Advisory Committee, and the first meeting will convene this spring 2014.

BEACON was awarded **NESCent support for a catalysis meeting entitled K-12 Evolution Education to Underserved Minorities**. The meeting convened April 18th-20, 2013, and included experts from across the nation in evolutionary science across different disciplines and levels. We identified some key challenges and crucial issues that influence the underrepresentation of minorities in evolutionary science, as well as increase access to overall evolution science literacy in these communities. We broke into key "issues" groups, with on-going strategic tasks.

Internally funded projects targeting diversity: BEACON supported numerous outreach events that exposed K-12 underrepresented students to evolutionary science/STEM education; for example, Girls' Math and Science Day Conference - A one-day, hands-on conference for 120 girls grade 6th -8th providing math and science experiences; and citizen science days that occur at aquariums and in urban & rural classrooms.

BEACON is actively recruiting undergraduates, graduates, and post-docs at regional and national conferences, and identifying/securing partnerships for future pipelines 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.

BEACON High School Summer Residential Program advances three of the four BEACON goals for public and K-12 education. MSU's College of Engineering Recruitment, Scholarships, and K-12 Outreach and BEACON offer a summer program focused on exposing a diverse group of high-achieving high school students to concepts, activities, and tools related to evolution-in-action. The program curriculum content mainly focused on biology and engineering and the intent of the program was to explore the variety of educational and career opportunities within BEACON-related fields and STEM. The program's goals, as described to participants, are:

- To educate students about BEACON related science and engineering college majors
- To educate students about BEACON related science and engineering careers
- To teach students about evolutionary science
- To educate students about the importance of conducting scientific research

BEACON High School Institute each year has been a role model program combining a uniquely diverse faculty staff, and students each year. This year, unlike previous years, program included approximately 70% women, and less than 25% underrepresented students.

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. Three of the five students in 2013 are returning students to the BEACON summer research program. The two seniors reported that they will pursue and/or have applied to graduate school upon graduation. For example, one student has participated in the BEACON Summer REU program for two consecutive summers, and was accepted at MSU and started this fall 2013 in the MMG program. Another URM student will graduate in May 2014 and plans to apply to MSU for fall 2014.

BEACON Day @ NCA&T: Dr. Gerry Dozier (NCAT) hosted a BEACON-wide day on October 3rd-4th 2014, highlighting the accomplishments of the BEACON Center and NCA&T. It introduced and educated NCA&T administration about BEACON, provided a forum for discussion of BEACON research across the Center, provided an opportunity for faculty across the Center to come to NCA&T and discuss possible collaborations, and provided a showcase for getting NCAT students excited about research at BEACON institutions or other universities. The collaborative workgroups have organized efforts to submit three proposals for internal BEACON funds, as a *proof of concept* for submission to a national funding organizations for substantial funding.

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:

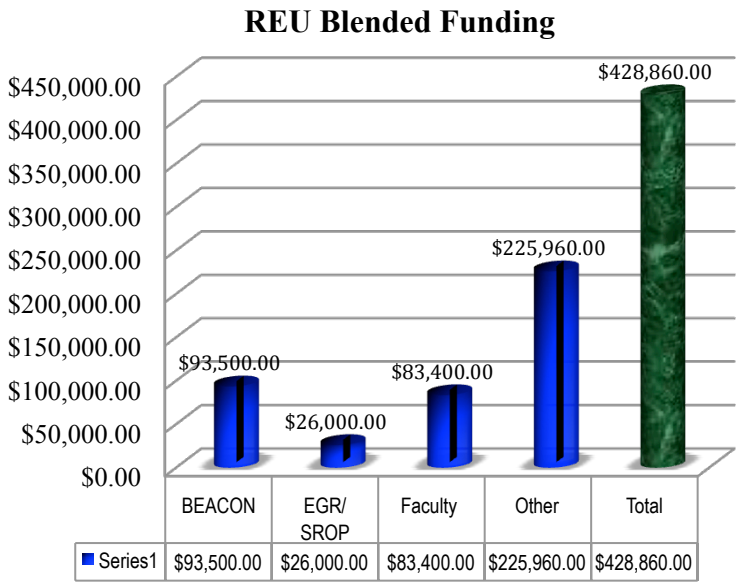
BEACON's Research Experience for Undergraduates (REU) Program is a 10-week intensive residential program targeting the recruitment of underrepresented students to conduct research with a faculty mentors. This past summer, we funded 50 students across the BEACON consortium at six different sites.

The total cost of programming was $428,860; which reflects the following blended funding model:

- Approximate cost per Participant: $8,500
- Total Participants: 50
- Total Program Cost = $428,860.

Blended funding percentages:

- BEACON @ 21.8%
- Leveraged @ 78.2%



Furthermore, 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 10 underrepresented neuroscience undergraduates per summer.

2d. Plans for the next reporting period

- BEACON will target its efforts to increase female participation; specifically focusing on post-docs and faculty positions.
- BEACON will complete its diversity climate survey to 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. Dr. Robert Heckendorn is now the Diversity Coordinator at University of Idaho. Our updated Organizational Chart (Appendix B) reflects this minor change. The Industrial Affiliates Manager position has been retitled Manager of Industry Relations; Dr. Betty Cheng continues in the position.

Project Selection Process. Projects at BEACON are chosen through an annual selection process, in which BEACON members submit "budget requests" in early spring under one of six categories: Thrust Group 1, 2, or 3; Education; Diversity; or Other (which can include infrastructure requests). Research projects are evaluated by the two leads for the respective thrust group, as well as 4 ad hoc reviewers from within the thrust group chosen by the leads, including faculty members from any of the five BEACON universities. Projects focused on education and outreach are evaluated by the Education Steering Committee while those focused on increasing diversity are evaluated by the Diversity Steering Committee. Projects designated “other” are reviewed by the Management team. Each budget request is evaluated on the basis of 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), plus a 9th criterion, Budget Appropriateness:

1. Scientific strength of the proposed project
2. Centrality of project to BEACON’s mission
3. Probability of leading to external funding
4. Degree of multidisciplinarity
5. Impact on education and human resource development
6. Knowledge transfer to industry
7. Impact on achieving the diversity goals of BEACON
8. Multi-institutionality
9. Budget Appropriateness

Additionally, all education and outreach projects are required to include an evaluation plan.

This process continues to evolve as the Executive Committee identifies necessary refinements. In 2014, we will implement some changes to the review process in response to some difficulties noted in 2013. We have updated our internal web pages so that the Thrust Group Leaders/Steering Committee chairs can more effectively assign reviewers to each budget request. They can now easily see the keywords that each BEACON member has chosen to describe their areas of expertise, to better enable them to choose appropriate reviewers that they may not know personally. Additionally, to ensure that the reviewing load is spread out more evenly, they will be able to see how many reviews have been assigned to each BEACON member. Assigned reviewers will now have the ability to decline, and to suggest a different reviewer. Finally, members who submit budget requests commit to reviewing a minimum of 5 budget requests for each one they submit.

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

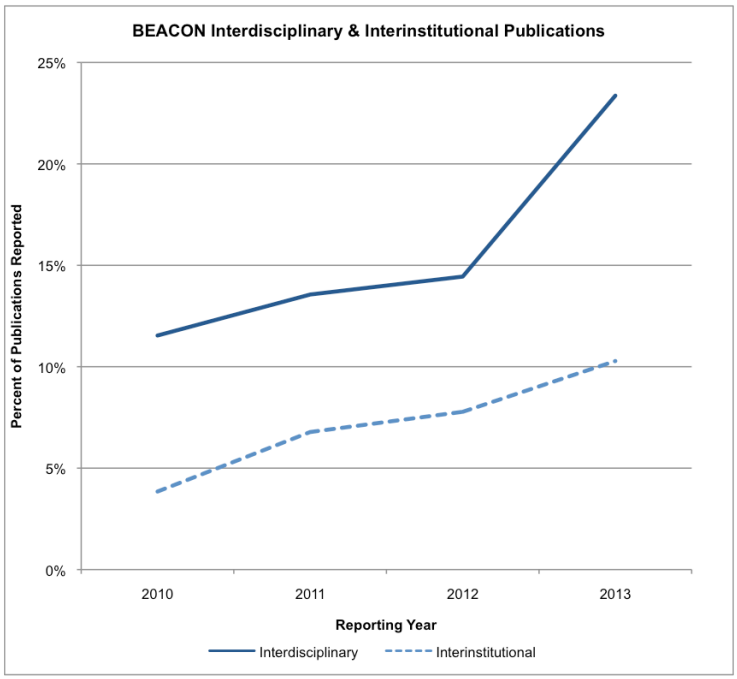
BEACON's overall Leadership and Management goals are to envision and enable the Center's mission through inclusive and transparent decision-making as well as effective and responsible implementation; to inspire Center participants; and to facilitate collaborative efforts within and beyond the Center. 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 has increased from 14% to 23% of all reported publications (see graph below)
	Number of new courses	One new course offered across institutions in Fall 2013
	Number of students enrolled in cross-disciplinary courses	Spring 2013: 15. Fall 2013: 45 in semester-long courses, plus ~100 in 2-day workshops on computational science for biologists
	Number of funding proposals submitted	22 of 55 grant proposals submitted (40%) reported as interdisciplinary; 13 of 55 (24%) inter-institutional
Increase in cross-institutional research and education	Number of paper/conference submissions	Reported cross-institutional publications has increased from 7% to 10% of all reported publications (see graph below)
	Number of new courses	One new course offered across institutions in Fall 2013. In addition, two short courses for biologists introducing them to modern computational tools and techniques were offered at multiple sites around the country, developed under a supplement to BEACON.
	Number of students in cross-institutional courses	Spring 2013: 15. Fall 2013: 45 in semester-long courses, plus ~100 in 2-day workshops on computational science for

		biologists
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	BEACON researchers submitted 55 proposals for >$25M of external funding, and >$12M in external funding has been granted
	Award dollars	BEACONites have been awarded over $12M in this funding period (~$6M for cross-disciplinary proposals), far exceeding goal of $5M/year
Increase in new participants	Number of faculty, post-docs, and students [Goal: 50%, 100%, 50% increase (respectively) from baseline (November 201) by October 2015]	This goal has been achieved. Faculty participants increased from 47 to 85 (81% increase); postdocs increased from 14 to 31 (121% increase); grad students increased from 57 to 129 (126% increase)
Effective support of Center operations by Management team	Survey for participants about management team	Year 3 evaluation was positive but revealed areas for improvement, which we are addressing
	Feedback from External Advisory Committee	Feedback has been positive (Appendix C)
Center is perceived by NSF as exemplary	Renewal of NSF funding	Renewal was approved for our fourth funding increment, and we have received positive feedback from NSF
	Number of public mentions made by NSF about BEACON	At least two BEACON studies were featured on the front page of nsf.gov in 2013

Cross-disciplinary and cross-institutional research, education, and funding. We have recently asked BEACON participants to self-report on our Intranet whether their reported outputs & activities are interdisciplinary or interinstitutional. Our current numbers are likely an underestimate, since we are also asking participants to go back and classify outputs from the past three reporting periods, but it gives us a useful starting point for evaluating our progress in the future.

Research: The graph below illustrates the reported percentage of paper and conference submissions in each year that are interdisciplinary and interinstitutional. Both types of collaborative outputs have increased steadily, with a much sharper increase of interdisciplinary publications between 2012 and 2013.



Education: Based on feedback and discussions from the 2012 class, the 2013 "Computational Science for Evolutionary Biologists" course was adjusted to match the UW class schedule of 10 weeks. As part of this adjustment, we ran two 2-day workshops, one at MSU and one at UW, to announce the course and motivate the course topics. Each of these workshops had 50 attendees (the room size limit) and was well attended on both days. As a result we now have 40 enrolled and auditing students across MSU and UW for this year's course (about 25 at MSU and 15 at UW), a significant increase over 2012. The course has been modularized more so that the first five weeks is on data analysis and programming, with the second five weeks on modeling. Next year we plan to extend the intro workshop model to other campuses that want to participate, and perhaps move to a more team-taught course. We are also discussing refocusing the graduate education efforts based on a workshop model, given the significant interest in these topics at the advanced graduate and postdoc level. Our other interdisciplinary courses (Evolutionary Biology for Non-Life Scientists and Multidisciplinary Approaches to the Study of Evolution) have continued as in the past; more detail is available in the Education section of this report.

Funding sources: BEACON researchers reported submitting 55 grant proposals for a total of $25M during this reporting period, 22 (40%) of which are interdisciplinary, and 13 (24%) of which are interinstitutional. Of these, 24 were funded (9 [38%] interdisciplinary and 6 [25%] inter-institutional) for a total of over $12.5M in external funds, from NSF, NIH, NASA, the Department of Defense, and private foundations including the Templeton Foundation. 10 submitted proposals were declined, and no decision has been reported for another 21 proposals. These totals do not include a $5M NIH COBRE grant to Larry Forney.

BEACON Organizational Formative Evaluation Report. Each year since its inception, BEACON has charged a team of experts on organizational evaluation, led by Drs. Patricia Farrell-Cole and Marilyn Amey, to study BEACON and report on the attitudes of participants, practices of management, and other related issues that might reveal desirable changes in

BEACON's structure or procedures. We have gained a great deal in the early years from these studies, particularly about how BEACON is perceived by students and postdocs at partner (non-MSU) schools. We have taken many steps to try to improve the sense of connectedness among all BEACON participants.

In spring, 2013, the evaluation team surveyed a large number of graduate students and postdocs across all 5 BEACON schools about BEACON's management, policies, organization, and communications. Results of that survey confirmed that the vast majority of BEACONites were very satisfied with BEACON's operation and glad to be associated with BEACON. At the same time, we learned some things that can be improved in the future, and we are working to address these.

A fair fraction of BEACON's grad students and postdocs knew that BEACON had goals regarding outreach to the public, to K-12, and to industry, but many did not know what activities were being carried out to address them. BEACON management will highlight its outreach activities in more of its communications with its members. More articles about outreach activities will be posted in the BEACON blog and in the newsletter, and presented in the weekly seminar. An Outreach site in the public BEACON web pages will features up-to-date information about such activities. Opportunities for participation in such activities will be broadcast more frequently to BEACON members.

Some BEACONites were less than completely satisfied with the quality and specificity of the reviews they received on budget requests that were denied. As noted above, BEACON's Intranet tools for submitting of budget requests have been completely re-implemented, with the intent of making the submission and review processes not only easier, but also better defined. Tools for selection of reviewers by the Thrust Group Leaders and Steering Committee Chairs have been dramatically improved, including allowing them to match keywords between requests and reviewer interest areas, to see how many reviews have already been assigned to a reviewer, and to track progress of the review process. Pre-review meetings with the Thrust Group Leaders will be held each year, from now on. The desired end result is that the maximum number of reviews per reviewer is brought down, reviewers write more specific comments, and Thrust Group Leaders do a better and more uniform job of synthesizing summary review comments for all requests, including some justification for their rankings of the requests.

While most BEACONites rated the feedback from the budget request process as Very Good, some rated it only as Good. The Intranet tools for submission and review of budget requests have been improved, as described above. In addition, we will try to make BEACONites more aware of the whole process, including the deliberations and rankings by the BEACON Executive Committee, so they understand better why overall budget constraints may prevent funding of some very worthwhile requests.

Many BEACON students and postdocs would like a broader range of professional development activities, beyond the usual resources for future faculty. We are working on providing more mentoring and opportunities for professional development for students and postdocs who want to look beyond traditional academic careers. Our Manager of Industrial Relations works to provide networking opportunities and internships with industry, and our Managing Director is developing resources and workshops for those interested in "alternative-academic" careers.

Some newer members of BEACON would benefit from more assistance with becoming integrated into BEACON. At this year's BEACON Congress, we piloted our new "Meet the Professors" networking program, in which we recruited about 25 faculty members to meet with small groups of 4-5 students and postdocs over lunch, to discuss topics ranging from research brainstorming to career mentoring. The program was immensely popular and the feedback was overwhelmingly positive. We will continue to incorporate this program not just into our annual Congress but also into other events such as the NSF site visit, or BEACON Day at NC A&T. Additionally, we will ensure that new students/post-docs/faculty are provided with online "welcome packages" and instructions on how to find and access information, so that they have the same quality communications experience as our longer-term members.

Data Management. BEACON funds and facilitates a wealth of research and educational activities that produce information and data valuable to the scientific community. We are committed to responsibly managing these data both during and following the lifetime of the center. Accordingly, we have developed a data management plan that incorporates the unique, broad, and multidisciplinary nature of BEACON research and projects. The most current draft is provided below.

Data Management Plan

Philosophy: BEACON funds and facilitates a wealth of research and educational activities that produce information and data valuable to the scientific community. BEACON is committed to promoting, educating, and facilitating the responsible preservation and open access of these data. At the same time, we recognize the importance of preserving the professional interests of students, postdoctoral researchers, and faculty, who have worked to fund, organize, and complete complex projects and experiments and must be given reasonable opportunity to analyze and publish results before data are made available to the community at large. The BEACON Data Management Policy strives to balance these competing interests and to provide guidelines for handling the many disparate types of data.

Policy: The BEACON Data Management Policy applies to all researchers supported by BEACON funding, facilities, and resources. The word “researcher” is used to refer to all scientists, students, engineers, educators, staff, and any other persons who develop data, analyses, and/or ideas associated with BEACON projects and research. Research data and information are to be handled and made available in a manner consistent with the guidelines detailed below. Public release of data should be as soon as possible following the first publication based upon or utilizing those data. Other data should be released in a reasonable time frame following development.

Internal BEACON project budget requests should include statements regarding the specifics of how project data will be managed, including details for handling the privacy, confidentiality, security, and intellectual property of research products and their intended distribution at project completion. Project reporting must include statements detailing adherence to that plan and this policy. Adherence to these requirements will be overseen by the BEACON Managing Director.

Data Handling Guidelines: BEACON projects produce and make use of five general types of data: collected data sets and experimental results generated by research; the configuration files and scripts used to run computational analysis and experiments; the source code of software

developed to enable those experiments; information resources, such as curriculum materials and documentation; and administrative materials such as policies or other reported information. Each type requires special care to ensure long term preservation in a useful and functional state. Training, being necessary to ensure compliance and facilitate successful implementation of the data management guidelines, will be provided during appropriate BEACON activities, such as the annual congress and weekly seminars. Researchers must make reasonable efforts to ensure that data subject to these disclosure guidelines is preserved prior to release.

Since each individual research and administrative community within BEACON has its own community standards for data storage and accessibility, the goal of this plan is to provide both flexibility and guidance for its members. Data released in accordance with this plan and associated guidelines must be available for a minimum of 3 years following release. This plan is intended to cover all researchers funded through BEACON as well as technical and administrative employees. Material that is proprietary, under copyright protection, patented, or confidential is not covered under this plan.

These guidelines are not intended to limit the scope of data that should be disclosed.

Collected Data Sets and Experimental Results: Research data and analysis material necessary to replicate, support, and validate research findings must be published to an appropriate third party archiver such as Dryad, GeneBank, or other institutionally supported repositories. Data collected from experiments involving human subjects must be made anonymous and handled with appropriate care and in compliance with regulations. When possible, raw data should be published; otherwise the lowest possible level of aggregated data along with the material required to fully replicate experiments may be substituted. Data file formats should be suitable for long-term archiving, such as human readable formats (e.g. txt, csv, xml), well documented open source formats (e.g. hdf5), or where appropriate, industry standard binary formats (e.g. pdf). BEACON strongly encourages researchers to use open standard file formats and label data using domain-specific ontologies where practical. Metadata including the name(s) and contact(s) of the creator(s) and PI(s) along with a description of contents and purpose should be included as part of the publication record of all materials.

Configuration Files: Complete configuration settings used in published experiments and analysis pipelines should be made available alongside archived data. Detailed setting listings and configuration files must clearly identify the version(s) of the software with which they were designed to be used, and provide basic instructions for their use as appropriate. Non-trivial experiment and analysis scripts should provide documentation and/or comments that explain their operation.

Source Code: The full source code of software developed or modified in the course of BEACON projects should be made publicly available under an OSI-approved open source license, unless existing license or intellectual property protections prevent such distribution. BEACON projects are encouraged to utilize public version control repository hosting services, such as GitHub and SourceForge to host the source code. Developed software should include at least the minimum documentation to build and execute it, along with metadata about authorship, purpose, and licensing.

Information Resources: Education and outreach materials produced and vetted during BEACON-funded projects should be made available to the public via the BEACON website. The materials should include descriptions of their intended use and links to relevant studies.

Administrative Materials: Administrative documents, including official reports, should be posted to either the center's website or wiki. Other administrative data should be kept in secure locations. Data used to generate administrative reports are to be maintained in a manner identical to research data but may be kept in a private location.

Other Materials: Other materials, such as samples, apparatuses, and other materials not explicitly mentioned above that are necessary for the reproduction of the research must be handled according to the standards of the field. Specific plans regarding such materials must be detailed in project budget requests and adherence to those plans detailed in project reports.

1d. Problems encountered

Our primary challenges have always revolved 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. In general we have been very successful in this area; however, it does require constant effort.

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 use our videoconferencing technology 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. In 2012, the Congress was two full days (in addition to the student/postdoc retreat day); in 2013, we added a third full day, which seemed to work very well, and will be repeated in 2014. Beginning with the 2012 Congress, we began holding a Student/Postdoc Retreat day at the beginning of Congress. Topics covered in 2012 and 2013 include communicating science to the public (led by Danielle Whittaker), grant writing (led by George Gilchrist), scientific climate and diversity (led by Pat Hawley from University of Kansas), and a student/postdoc picnic. At the 2013 Congress, we also introduced our "Meet the Professors" networking event (described above), which gave students and postdocs an opportunity to meet and interact with faculty members that they might not normally talk to.

2. Management and communications systems

Management systems. Our central management "engine" is our intranet system, the original 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 continued updating the site to improve functionality and user experience. The upgrade is nearly complete, with only a few pages related to the budget request process remaining. These pages

will be complete in time for the 2014 round of budget requests. Very little of the original infrastructure now remains, and a great deal of additional functionality has been added.

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 primary blog theme is "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. 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 (http://www.facebook.com/BEACONCenterEvolution, 293 "likes" as of 10/28/13, an increase of 156% since the last annual report) and Twitter (@BEACON_Center, 380 followers as of 10/28/13, an increase of 198%). We use these networking tools to announce blog posts and media coverage, to send reminders about Center-wide activities, to share relevant web material, and to help maintain a sense of community. These pages are updated at least 2-3 times a week.

Newsletter. This year, we began producing the "BEACON Buzz," a bi-monthly newsletter reporting on accomplishments of BEACONites and upcoming events. The newsletter is written by MSU graduate student Emily Weigel, who has been appointed as BEACON's first Science Communications Fellow. The newsletter is typically a four-page full-color publication; the PDF is sent out to our mailing list and posted online, and we also provide print copies to visitors to BEACON (including attendees at the annual Congress and other events). Four issues have been produced so far (May 2013, March 2013, Summer 2013, and October 2013. A fifth issue is expected to be completed in early December 2013.

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 Acrobat Connect (for video and content sharing) and an "800" conference phone system (for audio).

BEACON Videos. In December 2012, we worked with Amol Pavangadkar of the MSU College of Communication Arts & Sciences to produce a promotional video titled "What is BEACON?" This high-quality documentary style video is on YouTube (http://www.youtube.com/watch?v=9dgCJ9wetqI), has been featured on our website and social

media, and has had nearly 500 online views to date. This video is a useful tool for many different audiences. We envision producing more videos showcasing BEACON research in the near future. We are also videorecording BEACON Friday seminars (when the speakers consent) and posting them on the BEACON YouTube channel where the public may view them (http://www.youtube.com/user/beaconcenter2010).

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

In 2013, there have been some changes to our External Advisory Board. Scott Edwards (Harvard University) accepted a position at NSF as Division Director of Biological Infrastructure, and Judy Scotchmoor (University of California, Berkeley) has retired, and both have stepped down from BEACON's advisory board. We invited Allen Rodrigo (Duke University, director of NESCent) to replace Scott Edwards, and Ross Nehm (SUNY Stony Brook) to replace Judy Scotchmoor. Additionally, we felt it was important to strengthen the evolutionary computation side of our EAB, and we invited Martin Pelikan (Google) to join the board. We also invited Meghan Duffy (University of Michigan) to join the board. All four have accepted, and we now have a total of 9 members of our External Advisory Board.

External Advisory Board	
Name	**Affiliation**
Meghan Duffy	University of Michigan
John Koza	Stanford University
Hod Lipson	Cornell University
Ross Nehm	SUNY Stony Brook
Una-May O'Reilly	Massachusetts Institute of Technology
Martin Pelikan	Google
Allen Rodrigo	NESCent, Duke University
Kathleen Smith	NESCent, Duke University
Joan Strassman	Washington University in St. Louis

The third meeting of BEACON's External Advisory Board will be held November 22, 2013, at Michigan State University. The summary report from that meeting will be provided to NSF site visitors at the December site visit.

4. Changes to the Center's strategic plan

The goals and optimal outcomes remain the same for the bulk of the strategic plan. We have made some fairly substantial changes to our Knowledge Transfer section of the plan based on lessons learned over the past couple of years (see IV. Knowledge Transfer for a discussion). We have updated the strategic plan to reflect progress already made, and the revisions were approved by BEACON's Executive Committee on October 28, 2013.

VIII. CENTER-WIDE OUTPUTS AND ISSUES

1a. Center publications

Peer-Reviewed Publications

1. C. Adami; A. Hintze. 2013. Evolutionary instability of zero-determinant strategies demonstrates that winning isn't everything. *Nature Communications* 4: 2193.
2. C. Adami; F. Dyer; A. Hintze; D. B. Knoester; R. S. Olson. 2013. Predator confusion is sufficient to evolve swarming behaviour. *Journal of the Royal Society Interface* 10(85).
3. C. Adami; D. B. Knoester; R. S. Olson. 2013. Critical interplay between density-dependent predation and evolution of the selfish herd. *Genetic and Evolutionary Computation Conference (GECCO 2013).*
4. H. K. Allen; J. M. Bunge; J. A. Foster; D. O. Bayles; T. B. Stanton. 2013. Estimation of viral species richness from shotgun metagenomes using a frequency count approach. *Microbiome* 1: 5.
5. J. J. Amarasinghe; R. E. D'Hondt; C. M. Waters; N. J. Mantis. 2013. Exposure of *Salmonella enterica serovar Typhimurium* to a protective monoclonal IgA trigger exopolysaccharide production via a diguanylate cyclase-dependent pathway. *Infection and Immunity.* 81(3): 653-664.
6. A. Anderson; L. Harmon. 2013. Ecological and mutation-order speciation in digital organisms. *American Naturalist.* (In Press)
7. J. W. Atwell; G. C. Cardoso; D. J. Whittaker; T. D. Price; E. D. Ketterson. 2013. Correlated hormonal, behavioral and life-history traits facilitate establishment in a novel environment. *The American Naturalist.* (Submitted)
8. J. R. Barker; B. J. Koestler; V. K. Carpenter; D. L. Burdette; C. M. Waters; R. H. Valdivia. 2013. STING-mediated recognition of Chlamydia trachomatis cyclicc-di-AMP is necessary for the induction of Type I interferon responses during intracellular infection. *mBio.* (In Press)
9. S. L. Bazaz Behbahani. 2013. A dynamic model for robotic fish with flexible pectoral fins. *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics.*
10. S. Bazaz Behbahani; J. Wang; X. Tan. 2013. A dynamic model for robotic fish with flexible pectoral fins. *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* 1552-1557.
11. S. Bazaz Behbahani; X. Tan. 2013. Dynamic modeling and experimental validation of robotic fish actuated by pectoral fins with flexible passive joints. (Submitted)
12. S. E. Benson-Amram; M. L. Weldele; K. E. Holekamp. 2013. A comparison of innovative problem-solving abilities between wild and captive spotted hyaenas (*Crocuta crocuta*). *Animal Behaviour* 85: 349-356.
13. J. J. Bishop; R. Miikkulainen. 2013. Evolutionary Feature Evaluation for Online Reinforcement Learning. *IEEE Conference on Computational Intelligence in Games* 267 - 274.
14. A. J. Briscoe; A. J. Macias-Muñoz. 2013. Female behaviour drives expression and evolution of gustatory receptors in butterflies. *PLoS Genetics* 9: e1003620.

15. C. M. Brown; D. Sen; H. Yano; M. Bauer; L. Rogers; G. A. Van Der Auwera; E. Top. 2013. Diverse broad-host-range plasmids from freshwater carry few accessory genes. *Appl. Environ. Microbiol.* (In Press)
16. D. M. Bryson; C. Ofria. 2013. Understanding evolutionary potential in virtual CPU instruction set architectures. *PLoS ONE.* (Submitted)
17. K. D. Califf; E. L. Ratzloff; A. L. Wagner; K. E. Holekamp; B. L. Williams. 2013. Pervasive gene duplication and positive selection at MHC loci in two hyena species. *Journal of Mammalogy* 94(2): 282-294.
18. J. M. Catchen; P. Hohenlohe; S. Bassham; A. Amores; W. A. Cresko. 2013. Stacks: an analysis tool set for population genomics. *Molecular Ecology* 22: 3124-3140.
19. S. L. Chapman; D. B. Knoester; A. Hintze; C. Adami. 2013. Evolution of an artificial visual cortex for image recognition. *European Conference for Artificial Life (ECAL 2013).*
20. S. Chen; J. Wang; X. Tan. 2013. Backstepping-based hybrid target tracking control for a carangiform robotic fish. *Dynamic Systems and Control.* (In Press)
21. S. Chen; J. Wang; X. Tan. 2013. Target-tracking control design for a robotic fish with caudal fin. *Proceedings of the 32nd Chinese Control Conference* 844-849.
22. B. H. Cheng; A. Ramirez; P. McKinley. 2013. Harnessing evolutionary computation to enable dynamically adaptive systems to manage uncertainty. *Proceedings of the First International Workshop on Combining Modelling and Search-Based Software Engineering.*
23. O. M. Chikumbo; K. M. Deb; E. D. Goodman. 2013. Triple bottomline, hyper-radial-visualisation-based 'decision-making by shopping' for a land use management problem using evolutionary multi-objective optimisation. *Journal of Multi-Criteria Decision Making.* (In Press)
24. T. J. Clark; P. McKinley. 2013. Evolutionary optimization of robotic fish control and morphology (poster summary). *Proceedings of the 2013 ACM Genetic and Evolutionary Computing Conference Companion.*
25. D. J. Colbry; F. Dyer; I. Dworkin; Y. Wang; L. Wang. 2013. Speeding up scientific imaging workflows: design of automated image annotation tool. *User Centered Computer Vision.*
26. I. A. Cooper. 2013. Evolution of sexual dimorphism and species variation in Hawaiian damselflies. *Evolution.*
27. A. W. Covert, III; R. Lenski; C. Ofria; C. O. Wilke. 2013. Experiments on the role of deleterious mutations as stepping stones in adaptive evolution. *Proceedings of the National Academy of Sciences, USA.* (In Press)
28. J. R. Deller, Jr. 2013. Multi-frame super resolution based on sparse representation and matrix completion. *IEEE China Summit & International Conference on Signal and Information Processing* 538-542.
29. B. D. Fleet; M. Yao; H. Wang; J. R. Deller, Jr; Z. Tao; Z. Han; J. Yan; Y. Yao; E. D. Goodman. 2013. The function of phase parameter in the sampling data analysis of BRATUMASS. (Submitted)
30. A. E. Flies; C. K. Grant; E. J. Smith; L. S. Mansfield; S. E. Glickman; M. L. Weldele; K. E. Holekamp. 2013. Development of a hyena immunology toolbox. *Veterinary Immunology and Immunopathology* 145: 110-119.
31. L. V. Forney. 2013. Microbiota of the seminal fluid from healthy and infertile men. (Submitted)
32. L. V. Forney. 2013. Microbiome of the vagina. (Submitted)

33. L. V. Forney. 2013. Vaginal and vestibular bacteria in paired samples from women with vulvar vestibulitis syndrome and healthy controls. (Submitted)
34. L. V. Forney. 2013. The evolution of antibiotic susceptibility and resistance during the formation of *Escherichia coli* biofilms. (Submitted)
35. L. V. Forney. 2013. Effects of tampons and menses on the temporal dynamics of vaginal microbiota. *British Journal of Obstetrics and Gynecology.* (In Press)
36. J. A. Foster. 2013. Introduction to GPEM. Special Section on best of EuroGP/EvoBIO. *Genetic Programming and Evolvable Machines.* (In Press)
37. E. Fredericks; A. Ramirez; B. H. Cheng. 2013. Validating code-level behavior of dynamic adaptive systems in the face of uncertainty. *Symposium on Search-Based Software Engineering.*
38. E. Fredericks; A. Ramirez; B. H. Cheng. 2013. Towards run-time testing of dynamic adaptive systems. *Symposium on Software Engineering for Adaptive and Self-Managing Systems.*
39. E. Fredericks; B. H. Cheng. 2013. Exploring automated software composition with genetic programming. *GECCO.*
40. B. S. Goldman; W. Punch. 2013. Reducing wasted evaluations in Cartesian genetic programming. *European Conference on Genetic Programming.*
41. B. S. Goldman; W. Punch. 2013. Length bias and search limitations in Cartesian genetic programming. *Genetic And Evolutionary Computation Conference.*
42. L. M. Grabowski; D. M. Bryson; F. M. Dyer; R. T. Pennock; C. T. Ofria. 2013. A case study of the *de novo* evolution of a complex odometric behavior in digital organisms. *PLoS ONE.*
43. J. L. Graves, Jr. 2013. A new functional genomics. *Target Meeting 2nd World Genetics and Genomics Online Conference.*
44. J. L. Graves, Jr. 2013. Genome-wide transposable element insertion frequencies change with selection for accelerated development. *Society for the Study of Evolution.*
45. J. L. Graves, Jr. 2013. Maintenance of genome-wide polymorphism in replicated outbred populations of *Drosophila melanogaster* under directional selection regimes. *Society for Molecular Biology and Evolution, Annual Conference.*
46. A. K. Gutmann; D. Lee; C. McGowan. 2013. Collision-based mechanics of bipedal hopping. *Biology Letters* 9(4).
47. J. F. Han; S. H. Harrison. 2013. Application of circuit simulation method for differential modeling of TIM-2 iron uptake and metabolism in mouse kidney cells. *Frontiers in Physiology* 4: 136.
48. R. M. Harris; H. A. Hofmann. 2013. Brain transcriptomes vary with reproductive tactic in the ocellated wrasse. *Society for Behavioral Neuroscience Conference.*
49. R. M. Harris; H. A. Hofmann. 2013. Development of an integrative neuromolecular and neurophysiological curriculum for the Neural Systems & Behavior course at MBL. *Gordon Research Conference on Neuroethology: Behavior, Evolution & Neurobiology.*
50. R. M. Harris; H. A. Hofmann. 2013. Arginine vasotocin and androgen pathways are associated with mating system variation in North American cichlid fishes. *Hormones and Behavior* 64: 44-52.
51. R. M. Harris; H. A. Hofmann. 2013. Complex structural and regulatory evolution of the pro-opiomelanocortin gene family. *General and Comparative Endocrinology.* (In Press)

52. R. D. Hayes; C. M. Scott; M. Kjelvik. 2013. *Engaging Students with Evolution in Action.* (In Preparation)
53. T. A. Hether; P. Hohenlohe. 2013. Genetic regulatory network motifs constrain adaptation through curvature in the landscape of mutational (co)variance. *Evolution.* (In Press)
54. A. Hintze; C. Adami. 2013. Punishment catalyzes the evolution of cooperation. *Journal of the Royal Society Interface.* (Submitted)
55. A. Hintze; R. S. Olson; C. Adami; R. S. Hertwig. 2013. Risk aversion as an evolutionary adaptation. *PNAS.* (Submitted)
56. W. J. Johnson. 2013. Disentangling Science and Ideology. *The American Biology Teacher* 75(8): 516. (In Press)
57. J. E. Krol; A. J. Wojtowicz; L. M. Rogers; H. Heuer; K. Smalla; S. Krone; E. Top. 2013. Invasion of *E. coli* biofilms by multidrug resistance plasmids. *Plasmid.*70:110-119.
58. A. G. Lackey; J. Boughman. 2013. Divergent sexual selection via male competition: ecology is key.*Journal of Evolutionary Biology* 26(8): 1611-1624.
59. A. G. Lackey; J. Boughman. 2013. Loss of sexual isolation in a hybridizing stickleback species pair. *Current Zoology.* (In Press)
60. A. M. Lark; G. Richmond; R. T. Pennock. 2013. Modeling evolution in the classroom: The case of Fukushima's mutant butterflies. *Journal of College Science Teaching.* (Submitted)
61. M. D. Ledbetter; T. Hwang; G. M. Stovall; A. D. Ellington. 2013. Continuous *in vitro* evolution of a ribozyme ligase: a model experiment for the evolution of a biomolecule. *Biochemistry and Molecular Biology Education.* (Submitted)
62. J. M. Lehman; R. Miikkulainen. 2013. Effective diversity maintenance in deceptive domains. *GECCO 2013.*
63. J. M. Lehman; R. Miikkulainen. 2013. Leveraging human computation markets for interactive evolution. *ICML workshop: Machine Learning Meets Crowdsourcing.*
64. J. M. Lehman; R. Miikkulainen. 2013. Neuroevolution. *Scholarpedia.*8(6).
65. K. D. Lehmann; B. Goldman; I. Dworkin; D. M. Bryson; A. Wagner. 2013. From cues to signals: evolution of interspecific communication via aposematism and mimicry in a predator-prey system. *Proceedings of the Royal Society B.* (Submitted)
66. P. G. Lemons; C. Herreid; L. S. Mead; K. Perez; M. Terry; A. Thanukos; T. McElhinnny; R. Price; T. Andrews. 2013. Biology Undergraduates' Misconceptions about Genetic Drift.*CBE-Life Sciences.* 11: 248-259.
67. D. J. Lessin; D. Fussell; R. Miikkulainen. 2013. Open-Ended Behavioral Complexity for Evolved Virtual Creatures. *GECCO.*
68. D. Li; L. Xu; E. D. Goodman. 2013. Illumination-robust foreground detection in a video surveillance system. *IEEE Transactions on Circuits and Systems for Video Technology* 28(10): 1637-1650.
69. H. Lindsey; J. M. Gallie; B. Kerr. 2013. Evolutionary rescue from extinction is contingent on a lower rate of environmental change. *Nature.* 494: 463-466.
70. L. L. Marstaller; A. Hintze; C. Adami. 2013. The evolution of representation in simple cognitive networks. *Neural Computation* 25(8): 2079-2107
71. E. J. McTavish; J. E. Decker; R. D. Schnabel; J. F. Taylor; D. Hillis. 2013. New World cattle show ancestry from multiple independent domestication events. *PNAS* 110: E1398-E1406.
72. R. J. Miikkulainen; J. Lehman. 2013. Boosting Interactive Evolution using Human Computation Markets. *Theory and Practice of Natural Computing.*

73. J. J. Moore; A. K. Gutmann; C. McGowan; P. McKinley. 2013. Exploring the role of the tail in bipedal hopping through computational evolution. *Proceedings of the 12th European Conference on Artificial Life.*
74. J. Moore; P. McKinley. 2013. Evolution of an amphibious robot with passive joints. *Proceedings of the 2013 IEEE Congress on Evolutionary Computation.*
75. J. Moore; T. J. Clark; P. McKinley. 2013. Evolution of station keeping as a response to flows in an aquatic robot. *Proceedings of the 2013 ACM Genetic and Evolutionary Computing Conference.*
76. S. S. Narum; C. A. Buerkle; J. Davey; M. R. Miller; P. Hohenlohe. 2013. Genotyping-by-sequencing in ecological and conservation genomics. *Molecular Ecology* 22: 2841-2847.
77. E. S. O'Dea; C. Wilke. 2013. Joint estimation of transmission rate and initial growth rate with data aggregated from multiple norovirus outbreaks. *Epidemics.* (Submitted)
78. C. Ofria; A. Wagner; L. Zaman; M. Fortuna. 2013. Evolving digital ecological networks. *PLoS Computational Biology.*
79. R. S. Olson; M. Mirmomeni; T. Brom; E. Bruger; A. Hintze; D. Knoester; C. Adami. 2013. Evolved digital ecosystems: Dynamic steady state, not optimal fixed point. *European Conference for Artificial Life (ECAL 2013).*
80. D. Opoku; A. M. Homaifar; E. W. Tunstel. 2013. The A-r-Star (Ar) Pathfinder. *International Journal of Computer Applications* 67(8): 32-44.
81. D. Opoku; A. Homaifar; E. Tunstel. 2013. Towards Incremental A-r-Star. (In Press)
82. H. D. Radha; J. R. Deller, Jr; J. J. McCormick. 2013. Exploiting identifiability and inter-gene correlation for improved detection of differential expression. *ISRN Bioinformatics.* Article ID 404717
83. M. J. Rose; T. Clark; J. Moore; P. McKinley. 2013. Just keep swimming: accounting for uncertainty in self-modeling aquatic robots. *Proceedings of the 6th International Workshop on Evolutionary and Reinforcement Learning for Autonomous Robot Systems.*
84. S. G. Sleight; H. Sauro. 2013. Randomized BioBrick assembly: a novel DNA assembly method for randomizing and optimizing genetic circuits and metabolic pathways. *ACS Synthetic Biology.*
85. S. G. Sleight; H. Sauro. 2013. The visualization of evolutionary stability dynamics and competitive fitness of *Escherichia coli* engineered with randomized multi-gene circuits. *ACS Synthetic Biology.* (Submitted)
86. H. A. Soini; D. J. Whittaker; D. J. Wiesler; E. D. Ketterson; M. V. Novotny. 2013. Chemosignaling diversity in songbirds: chromatographic profiling of preen oil volatiles in different species. *Journal of Chromatography A.* (In Press)
87. G. M. Stovall; R. Bedenbaugh; S. Singh; A. D. Ellington. 2013. In vitro selection using modified or unnatural nucleotides. *Current Protocols in Nucleic Acid Chemistry.* Unit 9.6 (In Preparation)
88. C. J. Sun; G. Wyngaard; D. Walton; H. Wichman; R. Mueller. 2013. Billions of basepairs of recently expanded, repetitive sequences are eliminated from the somatic genome during copepod development. (Submitted)
89. E. L. Swanson; T. McElhinny; I. Dworkin; M. Weldele; S. Glickman; K. E. Holekamp. 2013. Ontogeny of sexual size dimorphism in the spotted hyena (*Crocuta crocuta*). *Journal of Mammalogy.* (In Press)

90. K. R. Theis; A. Venkataraman; J. A. Dycus; K. D. Koonter; E. N. Schmitt-Matzen; A. Wagner; T. Schmidt; K. E. Holekamp. 2013. Symbiotic bacteria underlie hyena social odors. *PNAS.* (In press)
91. K. R. Theis; T. R. Schmidt; K. E. Holekamp. 2013. Evidence for a bacterial mechanism for group-specific social odors among hyenas. *Nature Scientific Reports* 2:615.
92. R. H. Tinghitella; E. G. Weigel; M. Head; J. Boughman. 2013. Flexible mate choice when mates are rare and time is short. *Ecology and Evolution* 3(9): 2820-2831.
93. V. K. Valsalam; R. Miikkulainen. 2013. Using symmetry and learning to minimize sorting networks. *Journal of Machine Learning Research.*14: 303-331.
94. L. E. Vandepas; B. J. Swalla. 2013. The biogeography of *Phallusia nigra*: Is it really black and white? *Diversity and Distributions.* (Submitted)
95. A. M. Wagner; L. Zaman; I. Dworkin; C. Ofria. 2013. Arms races and strategy chases promote the evolution of prey intelligence. *Nature Communications.* (Submitted)
96. J. D. Wang; X. Tan. 2013. A dynamic model for tail-actuated robotic fish with drag coefficient adaptation. *Mechatronics* 23(6): 659-668.
97. J. D. Wang; P. McKinley; X. Tan. 2013. Dynamic modeling of robotic fish with a base-actuated flexible tail. *Journal of Dynamic Systems, Measurement, and Control.* (Submitted)
98. P. Wanko; P. Stanfield. 2013. Assessing the applicability of schooling genetic algorithms to product design. *Industrial and Systems Engineering Research Conference.*
99. P. Wanko; P. Stanfield. 2013. Adaptive metaheuristics with genetic social network. *Industrial and Systems Engineering Research Conference.*
100. C. Waters. 2013. Occurence of cyclic di-GMP-modulating output domains in cyanobacteria: an illuminating perspective. *mBio.* (In Press)
101. C. M. Waters. 2013. Extracellular polysaccharide inhibits flagellar rotation. *Journal of Bacteriology.* 195(3): 409-410.
102. C. M. Waters; A. C. Edmunds; L. F. Castiblanco; G. W. Sundin. 2013. Cyclic di-GMP modulates disease progression in *Erwinia amylovora*. *Journal of Bacteriology.* 195(10): 2155-2165.
103. C. M. Waters. 2013. Exploring environmental control of cyclic di-GMP signaling in *Vibrio cholerae* using TELCA. *Applied and Environmental Microbiology.* (In Press)
104. C. M. Waters. 2013. Genetic Analysis of *Agrobacterium tumefaciens* unipolar polysaccharide production reveals complex integrated control of the motile-to-sessile switch. *Molecular Microbiology.* (In Press)
105. D. J. Whittaker; N. M. Gerlach; H. A. Soini; M. V. Novotny; E. D. Ketterson. 2013. Bird odour predicts reproductive success. *Animal Behaviour.* 86(4): 697-703.
106. H. B. Wichman; C. Brown; C. Williams; J. Millstein. 2013. Selection affects genes involved in replication during long-term evolution in experimental populations of the bacteriophage phiX174. *PLOS ONE* 8(3): e60401-e60410.
107. S. A. Wielgoss; J. E. Barrick; O. Tenaillon; M. Wiser; W. J. Dittmar; S. Cruveiller; B. Chane-Woon-Ming; C. Medigue; R. Lenski; D. Schneider. 2013. Mutation rate dynamics in a bacterial population balance evolvability and genetic load. *Proceedings of the National Academy of Sciences, USA* 110: 222-227.
108. J. Yan; J. R. Deller, Jr; B. Fleet; E. D. Goodman; M. Yao. 2013. Evolutionary identification of nonlinear parametric models with a set-theoretic fitness criterion. *IEEE China Summit & International Conference on Signal and Information Processing* 44-48.

109. A. Yano; L. M. Rogers; M. Knox; H. Heuer; K. Smalla; C. J. Brown; E. Top. 2013. Host range diversification within the IncP-1 plasmid group. *Microbiology.* (In Press)
110. L. Zaman; J. Meyer; S. Devangam; D. M. Bryson; R. Lenski; C. Ofria. 2013. Coevolution drives the emergence of complex traits and promotes evolvability. *PLoS Biology.* (Submitted)
111. I. A. Zhbannikov; S. Hunter; M. Settles; J. A. Foster. 2013. SlopMap: a software application tool for quick and flexible identification of similar sequences using exact k-mer matching. *Journal of Data Mining in Genomics and Proteomics.* (In Press)
112. C. J. Zhu; P. Unachak; J. R. Llera; D. B. Knoester; E. B. Runkle; L. B. Xu; E. D. Goodman. 2013. Robust multi-objective evolutionary optimization to allow greenhouse production/energy use tradeoffs. *Greensys 2013.*

Book Chapters

1. C. Adami; B. S. Østman. 2013. Predicting evolution and visualizing high-dimensional fitness landscapes. *Recent Advances in the Theory and Application of Fitness Landscapes.*
2. J. L. Graves, Jr. 2013. US Civil War Politics. *Encyclopedia of Race and Racism 2nd Ed.*
3. J. L. Graves, Jr. 2013. The Bell Curve. *Encyclopedia of Race and Racism 2nd Ed.*
4. J. L. Graves, Jr. 2013. Racial Violence. *Encyclopedia of Race and Racism 2nd Ed.*
5. J. L. Graves, Jr. 2013. Genocide: The Japanese Occupation. *Encyclopedia of Race and Racism 2nd Ed.*
6. J. L. Graves, Jr. 2013. Naturalizing Supernatural. *Supernatural and Philosophy: Metaphysics and Morals for Idjits.*
7. J. L. Graves, Jr. 2013. Race, Genomics, and IQ. *Intelligence Quotient: Testing, Role of Genetics and the Environment and Social Outcomes.*
8. J. L. Graves, Jr. 2013. 21. The Safety of nanomaterials: what we know and what we need to know. *Advances in Nanoscience and Nanoengineering.*
9. B. L. Østman. 2013. Effects of epistasis and pleiotropy on fitness landscapes. *Origin of Life and Evolutionary Mechanisms.*
10. D. J. Whittaker. 2013. Pagai macaque, *Macaca pagensis*. *Handbook of the Mammals of the World Vol. 3, Primates,* pp. 634-635.
11. D. J. Whittaker. 2013. Siberut macaque, *Macaca siberu*. *Handbook of the Mammals of the World Vol. 3, Primates,* p. 635.
12. D. J. Whittaker. 2013. Mentawai sureli, *Presbytis potenziani*. *Handbook of the Mammals of the World Vol. 3, Primates,* p. 721.
13. D. J. Whittaker. 2013. Siberut sureli, *Presbytis siberu*. *Handbook of the Mammals of the World Vol. 3, Primates,* p. 721.
14. D. J. Whittaker. 2013. Pig-tailed langur, *Simias concolor*. *Handbook of the Mammals of the World Vol. 3, Primates,* p. 729-730.
15. D. J. Whittaker. 2013. Kloss's gibbon, *Hylobates klossii*. *Handbook of the Mammals of the World Vol. 3, Primates,* p. 781

1b. Conference presentations

Talks

1. Chris Adami; Arend Hintze; Masoud Mirmomeni; Eric Bruger; David B. Knoester; Randal S. Olson; Timothy Brom. 2013. Evolved digital ecosystems: Dynamic steady state, not optimal fixed point. European Conference on Artificial Life 2013. Taormina, Italy.
2. Chris Adami; Bjørn Østman. 2013. Resource specialization in a model of sympatric asexuals: The importance of tradeoffs. Evolution 2013. Snowbird, Utah.
3. Chris Adami; David B. Knoester; Randal S. Olson. 2013. Critical Interplay Between Density-dependent Predation and Evolution of the Selfish Herd. Genetic and Evolutionary Computation Conference (GECCO 2013). Amsterdam, The Netherlands.
4. Chris Adami; Fred Dyer; Arend Hintze; David B. Knoester; Randal S Olson. 2013. Using digital models of evolution to study how animal behavior evolves: a case study with the predator confusion effect. Behaviour 2013. Newcastle upon Tyne, United Kingdom.
5. Chris Adami; Fred Dyer; Arend Hintze; David B. Knoester; Randal S Olson. 2013. Studying the Evolution of Swarm Behavior in Action. Workshop on Collective Behaviours and Social Dynamics. Taormina, Italy.
6. Ahmed Ali; Etilet Maipi; Emma Timmins-Schiffman; Karen Matsumoto; Billie J. Swalla. 2013. Molecular Assays of Local Invertebrates to Monitor Beach Health. Citizen Science Symposium. UW School of Fisheries Auditorium.
7. Zachary David Blount. 2013. The evolution of aerobic citrate utilization in an experimental population of *E. coli*: A case study in evolutionary contingency. Contingency and Order in History and the Sciences. Oxford, England, UK.
8. Zachary David Blount; Richard Lenski. 2013. Adaptation of Experimental *E. coli* Populations to a Citrate-only Medium. American Society for Microbiology 2013 General Meeting. Denver, Colorado.
9. Zachary David Blount; Richard Lenski. 2013. Adaptation of Experimental *E. coli* Populations to a Citrate-only Medium. Evolution 2013. Snowbird, Utah.
10. Zachary David Blount; Richard Lenski. 2013. Incipient Speciation in an Experimental Population of *E. coli*. Microbial Population Biology Gordon Research Seminar. Andover, NH.
11. Jenny Boughman; Emily Grace Weigel. 2013. The effects of a density shift on nesting and mating behavior in a species of stickleback fish. Mid-Michigan Symposium for Undergraduate Research Experiences (Mid-SURE). East Lansing, MI.
12. Jenny Boughman; Emily Grace Weigel; Anna Reh-Gingerich. 2013. Male stickleback (*Gasterosteus* spp.) courtship activity fluctuates across the season. UURAF. MSU Union.
13. Eric Bruger; Chris Waters. 2013. Quorum sensing in *Vibrio harveyi*: Links to cooperative behavior. Microbial Population Biology Gordon Research Seminar. Proctor Academy, Andover, New Hampshire.
14. Alita Burmeister; Justin R Meyer; Richard Lenski. 2013. Evolution of a Novel Function in a Changing Environment. Evolution 2013. Snowbird, Utah.
15. Jessica Caton; Jennifer Owen. 2013. Migratory Behavior of Captive Blue-winged Teals (*Anas discors*). Animal Behavior Society. Boulder, CO.

16. Betty HC Cheng. 2013. Keynote address: Harnessing Evolutionary Computation to Enable Dynamically Adaptive Systems to Manage Uncertainty. First International Workshop on Combining Modeling and Search- Based Software Engineering. San Francisco, CA.
17. Jeffrey Conner; Idelle Cooper; Raffica La Rosa; Sam Perez; Anne Royer. 2013. Patterns of phenotypic correlations and integration in animals and plants. Society for the Study of Evolution Annual Meeting. Snowbird, Utah.
18. Matthieu Delcourt; Paul Hohenlohe. 2013. Quantifying the neutral expectations of genomic patterns of divergence. Evolution 2013. Snowbird, UT.
19. Matthieu Delcourt; Paul Hohenlohe. 2013. Quantifying the neutral expectations of genomic patterns of divergence. European Society for Evolutionary Biology annual meeting 2013. Lisbon, Portugal.
20. Larry Forney. 2013. Community ecology and the human vaginal microbiome. . Forum on Microbial Threats: Microbial Ecology in States of Health and Disease. Institute of Medicine, National Academy of Sciences.
21. Erik David Goodman. 2013. Introduction to Genetic Algorithms. Genetic & Evolutionary Computation Conference (GECCO) 2013. Amsterdam, NL.
22. Erik David Goodman. 2013. Evolutionary Optimization in Industry. Genetic & Evolutionary Computation Conference (GECCO) 2013. Amsterdam, NL.
23. Erik David Goodman. 2013. Using Evolutionary Multi-Objective Optimization in Land Use Management by Stakeholders. Internat. Conf. on Intelligent Data Engineering and Automated Learning. Hefei, Anhui, China.
24. Erik David Goodman. 2013. Introduction to Genetic Algorithms. Internat. Conf. on Intelligent Data Engineering and Automated Learning. Hefei, Anhui, China.
25. Anne K. Gutmann; Craig McGowan. 2013. Built to hop: functional specialization of the hindlimb of the desert kangaroo rat (*Dipodomys deserti*). Society for Integrative and Comparative Biology Annual Conference. Austin, TX.
26. Anne K. Gutmann; Nathan W. Cope; Craig McGowan. 2013. Functional anatomy and scaling of the kangaroo rat hindlimb. Northwest Biomechanics Symposium. Moscow, ID.
27. Rebecca Harris; Adam Leache. 2013. Evolution of nesting behavior in megapodes. Evolution. Snowbird, Utah.
28. Tyler Hether; Paul Hohenlohe. 2013. Genetic regulatory network motifs constrain adaptation through curvature in the landscape of mutational variation. Evolution 2013. Snowbird, UT.
29. David Hillis; April Wright. 2013. Utilizing likelihood models for phylogenetic reconstruction from discrete phenotypic characters. Evolution 2013. Snowbird, UT.
30. Paul Hohenlohe. 2013. Genomic patterns of differentiation between populations: what do the data actually mean? Gordon Research Conference: Ecological and Evolutionary Genomics. University of New England.
31. Kay E. Holekamp. 2013. Anthropogenic influences on the behavior & physiology of African carnivores. Student Conference on Conservation Science. Bangalore, India.
32. Kay E. Holekamp. 2013. The evolution of intelligence in response to social complexity. Society for the Study of Evolution. Snowbird, UT.
33. Wendy Johnson. 2013. Evolution in Action in the Classroom with Avida-ED Digital Evolution Software. Michigan Science Teachers Association Conference. Eastern Michigan University.
34. Jason Keagy; Liliana Lettieri; Jenny Boughman. 2013. Male competition is not a diversifying force in sticklebacks. Evolution 2013. Snowbird, UT.

35. Jason Keagy; Neeltje Boogert. 2013. Beautiful minds, brawny brains, and calculating choosers: Towards a better understanding of the interactions between cognition and sexual selection. Behaviour 2013. Newcastle, UK.
36. Jason Keagy; Neeltje Boogert. 2013. Cognition and sexual selection: how does one influenced the other? Behaviour 2013. Newcastle, UK.
37. Melissa Kjelvik. 2013. The effects of boldness on shoaling tendency in bluegill sunfish. Kellogg Biological Station Undergraduate Symposium. Hickory Corners, MI.
38. Melissa Kjelvik; Elizabeth Schultheis. 2013. Data Nuggets: unearthing inquiry skills. Ecological Society of America Life Discovery Conference - Doing Science. St. Paul, MN.
39. Alycia Lackey; Jenny Boughman. 2013. Comparing contributions to reproductive isolation for intact and collapsed stickleback species pairs. Evolution 2013. Snowbird, Utah.
40. Alycia Lackey; Jenny Boughman. 2013. Divergent sexual selection via male competition: ecology is key. Animal Behavior. Boulder, Colorado.
41. Amy Lark; Wendy Johnson; Louise Souther Mead; Jim Smith; Gail Richmond; Robert T. Pennock. 2013. Learning with digital evolution software: Improving student understanding and acceptance of evolution. Evolution 2013. Snowbird, UT.
42. Amy Lark; Wendy Johnson; Louise Souther Mead; Jim Smith; Gail Richmond; Robert T. Pennock. 2013. Teaching with digital evolution software: Assessing student understanding of fundamental concepts. Mid-west Ecology and Evolution Conference (MEEC). South Bend, IN.
43. Richard Lenski. 2013. Time Travel in Experimental Evolution: A 25-Year Journey. Evolution in the laboratory, on the occasion of awarding an honorary degree to Prof. Richard E. Lenski by Wageningen University. Wageningen, The Netherlands.
44. Richard Lenski. 2013. The Dechronization of *E. coli*: A 25-Year Love Story. Society for the Study of Evolution, Presidential Address. Snowbird, Utah.
45. Richard Lenski; Noah Ribeck. 2013. Frequency-Dependent Selection in Evolution Experiments. Evolution 2013. Snowbird, UT
46. Elijah Kariem Lowe; C. Titus Brown; Billie J. Swalla. 2013. In search of tails: Efficient transcriptome assembly of closely related non-model species. Spring AGEP Alliance Conference 2012 Research Symposium. University of Michigan, Ann Arbor.
47. Louise Souther Mead; Kathryn Perez. 2013. Using Concept Inventories in the Classroom. Evolution 2013. Snowbird, UT.
48. Risto Miikkulainen. 2013. Evolving Neural Networks. Genetic and Evolutionary Computation Conference. Amsterdam, the Netherlands.
49. Risto Miikkulainen. 2013. Evolving Neural Networks. International Joint Conference on Neural Networks. Dallas, TX.
50. James Jeffrey Morris. 2013. Coexistence of competing bacterial strains stabilized by a shared Black Queen "function." Evolution 2013. Snowbird, UT.
51. James Jeffrey Morris; Richard Lenski. 2013. Coexistence of competing bacterial strains stabilized by a shared Black Queen "function." Molecular Genetics of Bacteria and Phage. Madison, Wisconsin.
52. James Jeffrey Morris; Richard Lenski; Michael Follows. 2013. Algal Evolution in a Changing Ocean. Mathematical Biosciences Institute Workshop 2: Rapid Evolution and Sustainability. Columbus, Ohio.
53. Charles Ofria. 2013. The Evolution of Biological Complexity in Digital Organisms. American Physical Society. Baltimore, MD.

54. Robert T. Pennock. 2013. Going Live: The Origin of (Artificial) Life. International Society for History, Philosophy and Social Studies of Biology. Montpelier, France.
55. Robert T. Pennock. 2013. Going Live: The Origin of (Artificial) Life. International Society for the History, Philosophy & Social Studies of Biology. Montpelier, France.
56. Sarah Bodbyl Roels. 2013. Plant mating system evolutionary responses to anthropogenic pollinator decline. III World Summit on Evolution. San Cristobal, Galapagos Islands, Ecuador.
57. Anne Royer; Jeffrey Conner; Samuel Slowinski. 2013. Don't put all your sperm in one basket: are dimorphic stamens adaptive in wild radish? Society for the Study of Evolution Annual Meeting. Snowbird, Utah.
58. Tierra Schanbeck; Robert Hicks; Bryan Bartley; Karen Matsumoto; Billie J. Swalla. 2013. Molecular Identification of Phytoplankton Communities. Citizen Science Symposium. UW School of Fisheries Auditorium.
59. Imani N. Sharpe; Quincy Cunningham; Joseph L Graves, Jr.; Scott H. Harrison. 2013. Whole-Genome Association Study of Silver Resistance Pathways. ABRCMS 2013. Nashville, TN.
60. Shruti Singh. 2013. Development of a Classroom Evolution Demonstration. Rice Regional Undergraduate Symposium. Houston, Texas.
61. Terence Soule; Robert Heckendorn. 2013. Designing and Building Powerful, Inexpensive Robots for Evolutionary Research. Genetic and Evolutionary Computation Conference (GECCO). Amsterdam.
62. Kevin R Theis; A. Venkataraman; J. A. Dycus; K. D. Koonter; E. N. Schmitt-Matzen; Aaron Wagner; Kay E. Holekamp; Tom Schmidt. 2013. Symbiotic bacteria mediate hyena social odors. Animal Behavior Society. Boulder, CO.
63. Robin Tinghitella; Emily Grace Weigel; M Head; Jenny Boughman. 2013. Flexible mate choice when mates are rare and time is short. 50th Annual Conference of the Animal Behavior Society. Boulder, CO.
64. Eva Top; Wesley Loftie-Eaton. 2013. Evolution of plasmid persistence. Evolution 2013. Snowbird, Utah.
65. Caroline Turner; Brian Wade; Justin Meyer; Richard Lenski. 2013. Changes in elemental composition of *E. coli* during 50,000 generations of experimental evolution under carbon limitation. Evolution 2013. Snowbird, UT.
66. Brian Wade; Richard Lenski. 2013. Experimentally evolved desiccation and UV-C-radiation tolerance in Escherichia coli, stresses present on the early Earth and current Mars. NASA Astrobiology Science Conference. Atlanta, Georgia, USA.
67. Chris Waters. 2013. The Vc2 Cyclic di-GMP Binding Riboswitch in Vibrio cholerae Controls the Stability of a small RNA. American Society of Microbiology Annual Meeting. Denver, CO.
68. Chris Waters. 2013. Elucidating and targeting cyclic di-GMP signaling. Center for Biofilm Engineering Annual Meeting, Montana State University. Bozeman, MT.
69. Chris Waters. 2013. Cyclic di-GMP: A Regulatory Maestro that Orchestrates Gene Expression. Federation of European Microbial Societies International Meeting. Leipzig, Germany.
70. Emily Grace Weigel. 2013. Temporal Impacts of Sexual Selection in Threespine Stickleback. Ecology, Evolutionary Biology, and Behavior (EEBB) Program Colloquium. East Lansing, MI.

71. Emily Grace Weigel. 2013. Fishing for a Mate: Threespine Stickleback Mating Across the Season. Alliances for Graduate Education and the Professoriate (AGEP) Meeting. East Lansing, MI.
72. Emily Grace Weigel; Louise Souther Mead; Teresa L. McElhinny. 2013. How and why can knowledge of concepts in genetics improve student understanding of concepts in evolution? Future Academic Scholars in Teaching (FAST) Symposium. East Lansing.
73. Emily Grace Weigel; Louise Souther Mead; Teresa L. McElhinny. 2013. How and why can knowledge of concepts in genetics improve student understanding of evolution? Symposium on Teaching, Learning and Graduate Education. MSU.
74. Emily Grace Weigel; Robin Tinghitella; Jenny Boughman. 2013. Play the odds: Mate availability, not timing, impacts female reproductive investment. Midwest Ecology and Evolution Conference (MEEC). University of Notre Dame, South Bend, Indiana.
75. Danielle J. Whittaker; Kevin R Theis. 2013. Symbiotic Microbes May Mediate Songbird Chemical Signals. Animal Behavior Society. Boulder, CO.
76. Claus Wilke. 2013. The role of population structure in adaptive evolution. Gordon Research Conference on Microbial Population Biology. Andover, NH.
77. Michael Wiser; Noah Ribeck; Richard Lenski. 2013. Analysis of Fitness Trajectories in a Long Term Evolution Experiment. Evolution 2013. Snowbird, Utah.
78. Michael Wiser; Noah Ribeck; Richard Lenski. 2013. Analysis of Fitness Trajectories in a Long Term Evolution Experiment. Gordon Research Conference Microbial Population Biology. Andover, NH.
79. Ilya Zhbannikov; Sam Hunter; Helena Mendes-Soares; James Arthur Foster; Matthew Settles. 2013. BALMNet: Biologically Associated Text Miner and Network builder. Idaho Academy of Science. Pocatello, ID.

Posters

1. Zachary David Blount; Richard Lenski. 2013. Incipient Speciation in an Experimental Population of *E. coli*. Microbial Population Biology Gordon Research Conference. Andover, NH.
2. Adriana Briscoe; Aide Macias Muños. 2013. Visual transcriptomics of seasonal forms of the butterfly *Bicyclus anynana*. Society for Integrative and Comparative Biology Meeting. San Francisco.
3. Eric Bruger; Chris Waters. 2013. Quorum Sensing provides resistance to cheaters in *Vibrio harveyi*. Microbial Population Biology Gordon Research Seminar. Proctor Academy, Andover, New Hampshire.
4. Eric Bruger; Chris Waters. 2013. Quorum Sensing provides resistance to cheaters in Vibrio harveyi. Microbial Population Biology Gordon Research Conference. Proctor Academy, Andover, New Hampshire
5. Alita Burmeister; Justin R Meyer; Richard Lenski. 2013. Coevolution Facilitates the Evolution of a Novel Function in Phage Lambda. Gordon Conference -- Microbial Population Biology. Andover, NH.
6. Alita Burmeister; Mark Kauth; Richard Lenski; Michael Bagdasarian. 2013. Evolution in Action: From Classroom to Career. MSU CREATE for STEM Mini-Conference. Michigan State University.
7. Anahí Espíndola; Matt Settles; John Jones; Jack Sullivan. 2013. High throughput sequencing as a tool for pollen identification. Evolution 2013. Snowbird, UT.

8. Thomas Getty; Idelle A Cooper; Jonathan M Brown. 2013. Evolution of sexual dimorphism and species variation in Hawaiian damselflies. Evolution. Snowbird, UT.
9. Travis Hagey; Matthew Riley. 2013. Using FEA Simulations to Investigate the Gecko Adhesive System. Annual IBEST Science Expo. University of Idaho.
10. Michael Hammerling; Jared Ellefson; Andrew Ellington; Jeffrey E Barrick. 2013. Whole-genome evolution of bacteriophage T7 with an expanded genetic code. Synthetic Biology 6.0. London.
11. Randall Hayes; Suad Alghamdi; Fallou Diouf. 2013. Using an online writing tutor in science classes. Lilly Conference on College Teaching. Greensboro, NC.
12. Anya Elaine Johnson; Heather Goldsby; Charles Ofria. 2013. Evolving Distributed Computer Algorithms Using Division of Labor. Evolution 2013. Snowbird, UT.
13. Jason Keagy; Ashley Baird; Whitley Lehto; Sarah LoPresto; Ross Minter; victoria braithwaite; Thomas Neuberger; Jenny Boughman. 2013. Using Speciose Sticklebacks to Study Cognitive Evolution. Evolution 2013. Snowbird, UT.
14. Cory Brandon Kohn; Barry L Williams. 2013. Artificial Life for Validation in Molecular Evolution. Evolution. Snowbird, UT.
15. Cara Krieg; Thomas Getty. 2013. Female House Wrens in Michigan sing-- to each other. Animal Behavior Society. Boulder, CO.
16. Alycia Lackey; Jenny Boughman. 2013. Comparing contributions to reproductive isolation in intact and collapsed stickleback fish species pairs. American Genetic Association: Speciation Continuum. Ithaca, New York.
17. Amy Lark; Gail Richmond; Robert T. Pennock. 2013. Modeling evolution in the classroom: The case of Fukushima's mutant butterflies. CREATE-ing Collaborations in STEM Education Research Mini-Conference. East Lansing MI.
18. Amy Lark; Wendy Johnson; Louise Souther Mead; Jim Smith; Gail Richmond; Robert T. Pennock. 2013. Learning with digital evolution software: Improving student understanding and acceptance of evolution. Society for the Advancement of Biology Education Research (SABER). Minneapolis, MN.
19. Elijah Kariem Lowe; C. Titus Brown; Billie J. Swalla. 2013. In search of tails: Transcriptome assembly and analysis of tailed and tailless molgulids. 7th International Tunicate Meeting. Naples, Italy.
20. Elijah Kariem Lowe; C. Titus Brown; Billie J. Swalla. 2013. I have my notochord cells but where is my tail: a comparative study of tail loss in molgulid ascidians. Society for Molecular Biology and Evolution Annual Conference. Chicago, IL
21. Louise Souther Mead. 2013. Bringing Action to Evolution Education. III World Congress on Evolution. Galapagos Islands.
22. Noah Ribeck; Richard Lenski. 2013. Frequency-Dependent Selection in Evolution Experiments. Gordon Research Conference on Microbial Population Biology. Andover, NH.
23. Silvia Smith; Ilya Zhbannikov; Brice Andrew James Sarver; Celeste Brown; Eva Top. 2013. Detection of selection in bacterial plasmid backbone genes: an example from the IncP family. Evolution. Snowbird/Salt Lake City.
24. Terence Soule; Robert Heckendorn; Patrick Abbot; Travis DeVault; Juan Felipe Marulanda. 2013. On-Board Evolution of Robotic Trail Following. IBEST Science Expo. University of Idaho.

25. Caroline Turner; Brian Wade; Justin R Meyer; Richard Lenski. 2013. Evolution of elemental composition in a 50,000 generation experiment with *E. coli*. Gordon Conference on Microbial Population Biology. Andover, NH.
26. Lauren Elizabeth Vandepas; Billie J. Swalla. 2013. The native range of *Phallusia nigra*: is it really black and white? Society for Integrative and Comparative Biology. San Francisco, CA.
27. Brian Wade; Jeffrey E Barrick; Richard Lenski. 2013. Genomic changes in E. coli during experimental evolution under stress from desiccation and ultraviolet-C radiation. American Society for Microbiology 113th General Meeting. Denver, Colorado.
28. Ceri Weber. 2013. Early Activation of Metamorphosis in Tailless Ascidians: Heterochrony Affecting Body Plan. 7th International Tunicate Meeting. Naples, Italy.
29. Ilya Zhbannikov; Sam Hunter; Matthew Settles; James Arthur Foster. 2013. SlopMap: a software application tool for quick and flexible identification of similar sequences using exact k-mer matching. Inland Northwest Genomics Syposium. Moscow, ID.

1c. Other dissemination activities

Talks

1. Jesse Bloom. Constraints on the evolution of an influenza protein. Gordon Conference on Microbial Population Biology. Andover, New Hampshire.
2. Maighread Clark; Maddy Schneider; Lauren Elizabeth Vandepas; Karen Matsumoto; Billie J. Swalla. Biodiversity and Ecological Succession in Intertidal Invertebrate Communities in Puget Sound. Citizen Science Symposium. UW School of Fisheries Auditorium.
3. Jeffrey Conner. Mechanisms of rapid adaptive evolution in flowers and weeds. Lanzhou University, Lanzhou, China.
4. Jeffrey Conner. Mechanisms of rapid adaptive evolution in flowers and weeds. University of Akron.
5. John (Jack) R Deller, Jr. Evolutionary Identification of Nonlinear Parametric Models. Invited seminar. Zhejiang Gongsheng University, Hangzhou, China.
6. Heather Eisthen. Evolution and tinkering in olfactory systems. Barcelona Cognition, Brain, and Technology Summer School. Barcelona, Spain.
7. Larry Forney. Community ecology of the human vaginal microbiome. Grand Rounds. Cornell University.
8. Larry Forney. The human vaginal microbiome: rethinking health and disease. President's Dream Course: The Human Micriobiome. University of Oklahoma.
9. Larry Forney. Community ecology of the human vaginal microbiome. University of Arizona.
10. Erik David Goodman. Multi-Criterion Decision Making Using Multi-Objective Optimization for a Land Use Problem. Departmental Seminar, Automation and Control Engineering, Tongji University. Shanghai, China.
11. Erik David Goodman. Multi-Criterion Optimization with Decision by Shopping for a Land Use Problem. Lecture, College of Engineering Science and Technology. Shanghai Ocean University, Shanghai, China.
12. Travis Hagey; Matthew Riley. Using FEA Simulations to Investigate the Gecko Adhesive System. Mechanical Engineering 501 graduate student seminar class.
13. Scott H. Harrison; Imani N. Sharpe; Alshae R. Logan; Corey D. Young. Case Studies in Genomic Data and Host-Pathogen Coevolution. NC A&T Biology Department Seminar.

14. Randall Hayes; Chad Rohrbacher. Panel on Science Communication. North Carolina College Media Association. Greensboro, NC.
15. Robert Heckendorn. Nonclassical Mathematical Tools for Conceptualizing Epistasis. Brown University.
16. Paul Hohenlohe. Population genomics for evolutionary and conservation biology in non-model organisms. Invited seminar. University of Arizona.
17. Kay E. Holekamp. The evolution of intelligence in mammalian carnivores. Departments of Biology & Anthropology. Arizona State University.
18. Kay E. Holekamp. Evolution & mediation of sex-role reversed traits. Dept. of Integrative Biology. U. C. Berkeley.
19. Kay E. Holekamp. Social complexity and the evolution of intelligence. Department of Behavioral Science, University of Michigan, Dearborn.
20. Kay E. Holekamp. Evolution & mediation of sex-role reversed traits. University lecture, Biology Dept. University of Illinois at Urbana-Champaign.
21. Sam Hunter; James Arthur Foster. How many viruses are there in a pig? Site Visit to NH INBRE. Great Bend Community College.
22. Jason Keagy. Using Speciose Sticklebacks to Study Cognitive Evolution. Centre for Biodiversity Seminar Series. St. Andrews, UK.
23. Benjamin Kerr; Brian Connelly; Joshua Richard Nahum. Computational Tools for Experimental Evolution. CompCamp. UW.
24. Amy Lark. Teaching and learning with digital evolution software: Using technology to bring authentic science practice into the classroom. Center for Inquiry - MSU Chapter. East Lansing MI.
25. Amy Lark; Robert T. Pennock. Observing evolution in action in the lab and in the classroom. North Carolina A&T University, Greensboro NC.
26. Richard Lenski. Evolutionary Applications in Disease and Technology: Some Musings of a Basic Scientist. Wageningen University, The Netherlands
27. Richard Lenski. Time Travel in Experimental Evolution. University of Chicago.
28. Richard Lenski. Time Travel in Experimental Evolution. California Institute of Technology.
29. Richard Lenski. Time Travel in Experimental Evolution. Fred Hutchinson Cancer Center.
30. Richard Lenski. Time Travel in Experimental Evolution. Lausanne, Switzerland.
31. Richard Lenski. Time Travel in Experimental Evolution. University of Edinburgh.
32. Richard Lenski. Dynamics of Phenotypic and Genomic Evolution during a 50,000 Generation Experiment with *E. coli*. University of North Carolina, Chapel Hill.
33. Craig McGowan. Why hop? Non-steady hopping mechanics provides insight into the evolution of musculoskeletal design in bipedal hoppers. Departmental Seminar. University of Nevada, Las Vegas.
34. Louise Souther Mead. Introduction to BEACON. Overview of graduate programs at MSU for potential graduate students. MSU, East Lansing, MI.
35. Louise Souther Mead; Melissa Kjelvik; Anne Royer; Michael Wiser; Robert Mobley. Day Long Hands-On Evolution in Action. MSU Science and Engineering Festival. MSU, East Lansing, MI.
36. Bjørn Østman. The Fitness Landscape: How evolution shapes population dynamics. Center for Inquiry. Grand Rapids.
37. Bjørn Østman. Fitness Landscapes, epistasis, and predicting evolution. Toledo University.

38. Chad Rohrbacher. Science and Writing. North Carolina College Media Association. Greensboro, NC.
39. Terence Soule. Computer Programming and Scratch. Gear Up STEM Expo. Coeur d'Alene.
40. Terence Soule. Artificial Intelligence. Logos High School.
41. Eva Top. Shifts in the Host Range of Promiscuous Drug Resistance Plasmids. Biology Department, University of Montana. Missoula, Montana.
42. Chris Waters. To stick or swim: The role of chemical signaling in bacterial biofilm formation. Grand Valley State departmental seminar. Grand Rapids, MI.
43. Chris Waters. To stick or swim: Cyclic di-GMP control of gene expression in Vibrio cholerae. Wadsworth Center department seminar. Albany, NY.
44. Chris Waters. Elucidating and Targeting Cyclic di-GMP Signaling. Western Michigan University. Kalamazoo, MI.
45. Chris Waters. To stick or swim: The role of chemical signaling in bacterial biofilm formation. Grand Valley State University.
46. Chris Waters. To stick or swim: Cyclic di-GMP control of gene expression in *Vibrio cholerae*. Wadsworth Public Health Center, The University of Albany.
47. Chris Waters. Elucidating and Targeting Cyclic di-GMP Signaling. Western Michigan.
48. Emily Grace Weigel; Louise Souther Mead; Teresa L. McElhinny. Genetically Hard-wired: How and why can knowledge of concepts in genetics improve student understanding of evolution? Teaching-as-Research Final Presentation Capstone Series. CIRTL Blackboard Collaborate virtual room.
49. Danielle J. Whittaker. Making Scents: How Songbirds Use Odors to Communicate. University of Chicago.
50. Danielle J. Whittaker. Making Scents: How Songbirds Use Odors to Communicate. Grand Valley State University.
51. Holly Wichman. Crystal Structures: Viruses in Glass. University of Kansas.
52. Holly Wichman; Martina Ederer; Katelyn Slavens. Synthetic biology and vaccine design meets experimental evolution of phage. University of Kansas.
53. Ilya Zhbannikov. decisivatoR: an R package that addresses the problem of phylogenetic decisiveness. IBEST Science Update Series. Moscow, ID.

2. Awards and Honors

	Recipient	Reason for Award	Award Name and Sponsor	Date	Award Type
1	Chris Adami; David B Knoester; Randal S Olson	Voted by peers as best paper in conference track	Best Paper Award in Artificial Life track, GECCO 2013	July 2013	Scientific
2	Alita Burmeister	Education	NSF Graduate Research Fellowship, NSF	April 2013	Scientific
3	Alita Burmeister	Education-Related	MSU FAST Fellowship, MSU FAST Program	May 2013	Education-Related

4	Jeff Clune; Robert T. Pennock; Charles Ofria; Richard Lenski	Research Award	Runner-up for the Student Paper of the Year in American Naturalist, American Society of Naturalists	April 2013	Scientific
5	Peter Conlin	Research Award	NSF Graduate Research Fellowship, NSF	2013	Fellowship
6	Brian Connelly	Research Award	NSF Postdoctoral Research Fellowship in Biology, NSF	June 2013	Fellowship
7	Jeffrey Conner		Distinguished Sabbatical Scholar, NESCent	2013-2014	Fellowship
8	Kalyanmoy Deb	Research Award	World Academy of Sciences Prize in Engineering Sciences, World Academy of Sciences	October 2013	Scientific
9	Kalyanmoy Deb	Honorary doctorate	Honorary Doctoral Degree, Faculty of Information Technology at the University of Jyvaskyla in Finland	August 2013	Scientific
10	Larry Forney	Research	Distinguished Professor Award, University of Idaho	May 2013	Education-Related
11	Erik David Goodman; Kalyanmoy Deb; Oliver Chikumbo	Biennial competition of Multi-Criteria Decision Making Society	Wiley Practice Prize, MCDM Society, John Wiley & Sons, Inc. publishers	June 2013	Scientific
12	Rayna M Harris	to attend the 2013 Gordon Conference in Neuroethology	Heiligenberg Student Travel Award, International Society for Neuroethology	June 2013	Scientific
13	Kay E. Holekamp	Outstanding alumnus	Smith Medal, Smith College	February 2013	Other
14	Kay E. Holekamp	Significant contributions to science	Elected AAAS Fellow, AAAS	February 2013	Scientific
15	Alycia Lackey	Research Award	Dissertation Completion Fellowship, College of Natural Science,	2013	Fellowship

			Michigan State University		
16	Kenna Deyette Smith Lehmann	Research Award	Research Enhancement Funds, MSU	2013	Scientific
17	Richard Lenski	Honorary doctorate	Doctor Honoris Causa, Wageningen University (The Netherlands)	March 2013	Scientific
18	Nora Lewin	Research Award	John R. Shaver Graduate Research Award, Zoology	Spring 2013	Scientific
19	Shawn M. Luttrell	Research Award	NSF Graduate Research Fellowship Program, NSF	2013	Fellowship
20	Aide Macias-Muñoz	Graduate training	National Science Foundation Graduate Research Fellowship, NSF	2014-2017	Fellowship
21	Aide Macias-Muñoz	Graduate training	Ford Foundation Predoctoral Fellowship, Ford Foundation	2013-2016	Fellowship
22	Elizabeth Schultheis	Teaching experience	Fields Teaching Award, Department of Plant Biology, Michigan State University	2012-2013	Education-Related
23	Imani N. Sharpe	Scholarship	NIH/MARC program, NIH	August 2013	Education-Related
24	Katelyn Slavens	Outstanding graduating senior	John B. George Award, College of Science	May 2013	
25	Eva Top	Research	College of Science Distinguished Faculty Award, College of Science, University of Idaho	May 2013	Scientific
26	Lauren Elizabeth Vandepas; Billie J. Swalla	Research Award	Charlotte Magnum Student Support, Society for Integrative and Comparative Biology	January 2013	Other
27	Chris Waters	Research Award	Young Investigator Award, Center for Biofilm Engineering,	August 2013	Scientific

			Montana State University		
28	Emily Grace Weigel	Research Award	EEBB Program Summer Fellowship, EEBB Program	Spring 2013	Fellowship
29	Emily Grace Weigel	Teaching Award	Preparing Future Faculty for the Assessment of Student Learning (PFF-ASL) Fellow, PFF-ASL	Spring 2013	Fellowship
30	Emily Grace Weigel	Teaching Award	Gates Foundation-MSU Massively Open Online Course (MOOC) Fellowship, Gates Foundation	Spring 2013	Fellowship
31	Emily Grace Weigel	Research Award	John R. Shaver Graduate Research Award, Zoology Department, MSU	Spring 2013	Fellowship
32	Emily Grace Weigel	Research Award	Summer Continuation Fellowship, College of Natural Science, MSU	2013	Fellowship
33	Emily Grace Weigel; Anna Reh-Gingerich	Research Award	Best Undergraduate Poster Winner at Midwest Ecology and Evolution Conference (MEEC) 2013, Midwest Ecology and Evolution Conference	March 2013	Scientific

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

	Student Name	**Degree**	**Years to Degree**	**Placement**
1	Carlos Anderson	PhD	6	Post-doc under Dr. Dan Rabosky at the University of Michigan
2	Andrew Flies	PhD	6	Post doc at Univ of South Australia
3	Max Maliska	PhD	6	Illumina
4	Gowon Patterson	Masters	2	Norfolk & Southern Railway
5	Andres Ramirez	PhD		Industry
6	Katelyn Slavens	Bachelors	4	Grad school, U of Washington

4a. General outputs of knowledge transfer activities

No patents were filed in this reporting period. However, three patents were filed during our previous reporting period that were not reported to NSF:

	Patent Name and Inventors/Authors	Number	Application Date
1	Bactobolin analog and synthesis method thereof, Josephine Chandler	Provisional Patent Application, 13/530,020	June 21, 2012
2	Benzimidazole Inhibition of Biofilm Formation, Chris Waters, M B Neiditch, M F Semmelhack, K Sambanthamoorthy	US Utility Patent 3000.038PRV	April 2012
3	A Fitness Proportionate Reward Sharing: A Variable Default Hierarchy Formation Strategy in LCS, Abrham Workineh, Abdollah Homaifar	Provisional Patent Application, EN0075 0312	March 9, 2012

4b. Other outputs of knowledge transfer activities

One invention disclosure: Gliding robotic fish; Xiaobo Tan, Feitian Zhang, Jianxun Wang, John Thon (MSU); February 2013

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
16	Seattle Aquarium	Other	1483 Alaskan Way, Pier 59, Seattle, WA 98101	Karen Matsumoto	Education	Y

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)	14
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	$1,140,368
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)	300

8. Media publicity

VIDEO: What is BEACON? http://www.youtube.com/watch?v=9dgCJ9wetqI

Press Releases

9/4: Kalyanmoy Deb named Koenig Endowed Chair.
http://msutoday.msu.edu/news/2013/kalyanmoy-deb-named-koenig-endowed-chair/
9/3: Birds choose sweet-smelling mates. http://msutoday.msu.edu/news/2013/birds-choose-sweet-smelling-mates/
8/1: Evolution will punish you if you're selfish and mean.
http://msutoday.msu.edu/news/2013/evolution-will-punish-you-if-youre-selfish-and-mean/
6/5: Swarming offers clues on how intelligence evolved.
http://msutoday.msu.edu/news/2013/swarming-offers-clues-on-how-intelligence-evolved/
3/25: Decoding the Longhorn genome. http://web5.cns.utexas.edu/news/2013/03/decoding-the-longhorn-genome/
3/21: Robotics-themed program takes aim at science teaching.
http://msutoday.msu.edu/news/2013/robotics-themed-program-takes-aim-at-science-teaching/
3/20: Carnivores, livestock, people share same space in relative peace.
http://msutoday.msu.edu/news/2013/carnivores-livestock-people-share-same-space-in-relative-peace/
2/24: Ancient lamprey DNA decoded. http://msutoday.msu.edu/news/2013/ancient-lamprey-dna-decoded/
2/19: Mutant champions save imperiled species from almost-certain extinction.
http://www.washington.edu/news/2013/02/19/mutant-champions-save-imperiled-species-from-almost-certain-extinction/
1/14: Robofish Grace glides with the greatest of ease.
http://msutoday.msu.edu/news/2013/robofish-grace-glides-with-the-greatest-of-ease/
1/14: New Evolution in Action gallery opens at MSU museum.
http://ns.msu.edu/index.php/2013/01/new-evolution-in-action-gallery-opens-at-msu-museum/
1/7: Captive hyenas outfox wild relatives. http://msutoday.msu.edu/news/2013/captive-hyenas-outfox-wild-relatives/

Media Coverage

10/10: Al Jazeera: Scientists threatened by demands to share data
http://america.aljazeera.com/articles/2013/10/10/scientiststhreatenedbydemandstosharedata.html
10/6: Danielle Whittaker on Ray's Brown's Talkin' Birds radio show. Show #443 The scent of birds — And why it's a big deal—really big. http://www.talkinbirds.com/
9/24: Nature: Mozilla plan seeks to debug scientific code
http://www.nature.com/news/mozilla-plan-seeks-to-debug-scientific-code-1.13812
9/18: Nature: Fertility smells like preen spirit
http://www.nature.com/nature/journal/v501/n7467/full/501285a.html

9/11: Nature: Next-generation sequencing: the genome jigsaw
http://www.nature.com/nature/journal/v501/n7466/full/501261a.html
9/6: Discover magazine blogs: Birds can whiff a winner of a mate
http://blogs.discovermagazine.com/d-brief/2013/09/06/birds-can-whiff-a-winner-of-a-mate/
9/6: Into the Air (birding blog): Birds that smell better produce more offspring
http://www.backyardchirper.com/blog/birds-that-smell-better-produce-more-offspring/
9/4: Audubonmagazine.org: Better-smelling birds produce more offspring
http://magblog.audubon.org/better-smelling-birds-produce-more-offspring
9/4: Michigan Sun: Birds find sweet-smelling mates
http://www.michigansun.com/index.php/sid/216829577/scat/9e75b1ce4082dd57/pp/1
9/4: Grist: Birds like their boyfriends to smell good
http://grist.org/list/birds-like-their-boyfriends-to-smell-good/
9/4: CBS News: For birds, looks just ain't enough
http://www.cbsnews.com/8301-205_162-57601279/for-birds-looks-just-aint-enough/
9/4: Science360: Breaking story: Birds choose sweet-smelling mates
http://news.science360.gov/obj/story/15098bc6-7685-49ca-b8b8-f58a0c681ae3/birds-choose-sweet-smelling-mates
9/4: Futurity: Smell can sweeten birds' chances of mating
http://www.futurity.org/preening-sweetens-birds-chances-mating/
9/4: Wild Birds Unlimited: Michigan State University reveals birds communicate via scent
http://lansingwbu.blogspot.com/2013/09/michigan-state-university-reveals-birds.html
9/4: RedOrbit: Birds communicate through scents
http://www.redorbit.com/news/science/1112938618/birds-communicate-through-scents-090413/
9/3: NSF News from the Field: Birds choose sweet-smelling mates
http://www.nsf.gov/news/news_summ.jsp?cntn_id=128994
9/3: Fox47 News: MSU research finds birds choose sweet-smelling mates
http://www.jrn.com/fox47news/galleries/MSU-Research-Finds--222193011.html
9/3: PhysOrg: Birds choose sweet-smelling mates
http://phys.org/news/2013-09-birds-sweet-smelling.html
9/3: ScienceDaily: Birds choose sweet-smelling mates
http://www.sciencedaily.com/releases/2013/09/130903123600.htm
9/2: Mlive: For KAMSC students, a summer of learning -- and, literally, climbing to new heights
http://www.mlive.com/news/kalamazoo/index.ssf/2013/09/for_kamsc_students_a_summer_of.html
9/1: Kay E. Holekamp, FL CONCEPTS &CO, Hour-long film on MSU Mara Hyena Project
8/27: MSU Undergraduate Research: Lazarius Miller '17
http://urca.msu.edu/people/mill2321
8/16: Science: ScienceShot - Forget plumage, birds sniff out good mates
http://news.sciencemag.org/plants-animals/2013/08/scienceshot-forget-plumage-birds-sniff-out-good-mates
8/13: Hometownlife.com: Heil's trail project earns Eagle Scout status
http://www.hometownlife.com/apps/pbcs.dll/article?AID=/201308130950/NEWS13/308130016
8/5: You.beauty: Mean girls are headed for extinction
http://www.youbeauty.com/relationships/selfishness-and-evolution

8/5: Bionity.com: Nice organisms finish first: Why cooperators always win in the long run http://www.bionity.com/en/news/144302/nice-organisms-finish-first-why-cooperators-always-win-in-the-long-run.html

8/5: The Scientist: A twist in evolutionary game theory http://www.the-scientist.com/?articles.view/articleNo/36880/title/A-Twist-in-Evolutionary-Game-Theory/

8/4: Guardian Express: New study shows that selfish traits are not favored by evolution http://guardianlv.com/2013/08/new-study-shows-that-selfish-traits-are-not-favored-by-evolution/

8/3: Why Evolution is True: To all chowderheads, including Andrew Brown: the selfish gene is just a *metaphor*! http://whyevolutionistrue.wordpress.com/2013/08/03/to-all-chowderheads-including-andrew-brown-the-selfish-gene-is-just-a-metaphor/

8/2: Daily Kos: Science finally proves Republicans doomed to extinction http://www.dailykos.com/story/2013/08/02/1228537/-Science-Finally-Proves-Republicans-Doomed-to-Extinction

8/2: Arkansas News: A little evolution from my friends http://arkansasnews.com/sections/columns/news/matthew-pate/little-evolution-my-friends.html

8/2: NTD Television: Selfishness may not be evolutionarily viable http://www.ntd.tv/en/programs/news-politics/runlist-news/20130802/81995-selfishness-may-not-be-evolutionarily-viable.html

8/2: Psychology Today: Evolution does not reward selfish and mean people http://www.psychologytoday.com/blog/the-athletes-way/201308/evolution-does-not-reward-selfish-and-mean-people

8/2: Futurity: Evolution will punish selfish meanies http://www.futurity.org/top-stories/evolution-will-punish-selfish-meanies/comment-page-1/

8/2: Wired.co.uk: Study: queen-less honeybees remain altruistic to the bitter end http://www.wired.co.uk/news/archive/2013-08/02/bees-stick-together-to-the-bitter-end

8/2: Digital Journal: Evolution favors cooperation http://www.digitaljournal.com/article/355734

8/2: The Independent: Be nice. Evolution will punish you if you're selfish and mean, says study http://www.independent.co.uk/news/science/be-nice-evolution-will-punish-you-if-youre-mean-and-selfish-says-study-8744009.html

8/2: Los Angeles Times: Selfishness doomed while cooperation evolves, study says http://www.latimes.com/news/science/sciencenow/la-sci-sn-game-theory-selfish-20130802,0,7909138.story

8/2: MLive: Michigan State study: 'Evolution will punish you if you're selfish and mean' http://www.mlive.com/lansing-news/index.ssf/2013/08/michigan_state_study_evolution.html

8/2: MSN Now: Nice guys might not finish last after all, according to study http://now.msn.com/christoph-adami-arend-hintze-say-study-shows-nice-guys-dont-finish-last

8/2: BBC News: Selfish traits not favoured by evolution, study shows http://www.bbc.co.uk/news/science-environment-23529849

8/2: National Geographic: Meet the Animats http://phenomena.nationalgeographic.com/2013/08/02/meet-the-animats/

8/1: Ethiopian Review: Tribalists will be extinct, says study http://www.ethiopianreview.com/forum/viewtopic.php?f=2&t=58311

8/1: CBC: Don't be that guy: "Evolution will punish you if you're selfish and mean" http://www.cbc.ca/strombo/alt-news/dont-be-that-guy-evolution-will-punish-you-if-youre-selfish-and-mean.html

8/1: Medical Daily: Evolution punishes the selfish: how the mean and self-centered could one day become extinct http://www.medicaldaily.com/evolution-punishes-selfish-how-mean-and-self-centered-could-one-day-become-extinct-249093

8/1: The State News: MSU researchers debunk game theory http://statenews.com/article/2013/08/msu-researchers-debunk-game-theory

8/1: Nature World News: Selfishness is unsustainable and may eventually disappear as an evolutionary trait http://www.natureworldnews.com/articles/3284/20130801/selfishness-unsustainable-eventually-disappear-evolutionary-trait.htm

8/1: Daily Mail: Why you SHOULD give away your last chocolate: Selfish people 'will eventually die out' because evolution favours cooperation http://www.dailymail.co.uk/sciencetech/article-2382017/Selfish-people-eventually-die-evolution-favours-cooperation.html

8/1: Popular Science: Evolution punishes selfish people, game theory study says http://www.popsci.com/science/article/2013-08/game-theory-study-says-evolution-punishes-selfish

8/1: Discovery: Does evolution punish or favor the selfish? http://news.discovery.com/human/psychology/does-evolution-punish-or-favor-the-selfish-130801.htm

7/31: GenomeWeb Feature: Many Options, Formal and Informal, for Those Seeking Bioinformatics Education http://www.genomeweb.com/print/1260471

7/26: Faculty Voice: Xiaobo Tan: Robofish Grace takes a road trip http://msutoday.msu.edu/360/2013/faculty-voice-xiaobo-tan-robofish-grace-takes-a-road-trip-1/

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7/11: Fox 47 News: MSU undergraduates present summer research http://www.fox47news.com/news/wearespartans/215058131.html

6/7: Science: Video: When predators attack http://news.sciencemag.org/math/2013/06/video-when-predators-attack

6/5: RedOrbit: Discovering why and how swarming evolved http://www.redorbit.com/news/science/1112866070/why-how-swarming-evolved-060513/

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6/5: PhysOrg: Discovering one reason why swarming evolved offers tantalizing clues on how intelligence developed http://phys.org/news/2013-06-swarming-evolved-tantalizing-clues-intelligence.html

4/13: Kay E. Holekamp, BBC video on hyena communication

4/6: Decaffeinating waste: Brewing a solution http://www.economist.com/news/science-and-technology/21575743-genetic-engineering-may-clean-up-processing-coffee-brewing-solution

3/25: Benzinga.com: These Amazing Charts Detail Reddit's Evolution Over Time http://www.benzinga.com/tech/13/03/3444220/these-amazing-charts-detail-reddits-evolution-over-time

3/25: ScienceNews: Longhorn cattle ancestors came from Pakistan http://www.sciencenews.org/view/generic/id/349210/description/News_in_Brief_Longhorn_cattle_ancestors_came_from_Pakistan

3/25: LiveScience: Longhorn Legacy: Surprising origins of Columbus' cattle found http://www.livescience.com/28154-new-world-cattle-origins.html

3/20: The Daily Dot: Reddit is becoming an imageboard - here's proof http://www.dailydot.com/news/reddit-imageboard-pics-study/

3/15: Blog: The Mermaid's Tale. Functional illiteracy and genetic background http://ecodevoevo.blogspot.com/2013/03/functional-illiteracy-and-genetic.html

3/14: RedOrbit: Study finds people, livestock and carnivores share same space http://www.redorbit.com/news/science/1112803329/people-livestock-carnivores-coexist-kenya-031413/

2/19: Science Daily: Mutant champions save imperiled species from almost-certain extinction http://www.sciencedaily.com/releases/2013/02/130219161301.htm

2/1 to present: Kay E. Holekamp hyena research blog http://msuhyenas.blogspot.in/2013/09/a-scary-reminder.html

1/17: IEEE Spectrum: Submersible robotic fishoplane can swim for hundreds of kilometers http://spectrum.ieee.org/automaton/robotics/industrial-robots/ submersible-robotic-fishoplane-can-swim-for-hundreds-of-kilometers

1/16: NBC News: Robo fish can glide (almost) forever http://www.nbcnews.com/technology/futureoftech/robo-fish-can-glide-almost-forever-1B7987620

1/8: RedOrbit: Captive animals may be better problem solvers than their wild counterparts http://www.redorbit.com/news/science/1112759950/captive-animals-better-problem-solvers-010813/

1/8: PopSci: Captive hyena figures out a meat puzzle faster than its wild cousin http://www.popsci.com/science/article/2013-01/watch-captive-hyena-eagerly-figure-out-meat-puzzle-faster-its-wild-cousin

1/8: Futurity: Captive hyenas think 'outside the box.' http://www.futurity.org/science-technology/captive-hyenas-think-outside-the-box/print/

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.

Two faculty members from China (Professor Lihong Xu, Tongji University and Meng Yao, East China Normal University) visited in BEACON in 2013, each funded primarily by the visitor's host institution or a grant from their government; they brought 3 students with them. Dr. Oliver Chikumbo also visted from New Zealand. All of these researchers engaged in collaborative research with Director Erik Goodman and other BEACON participants on three projects described under Research. 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)