BEACON

An NSF Center for the Study of Evolution in Action

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.

Richard Lenski's (MSU) Long-Term Evolution Experiment continues to provide important insights about evolution and the process of natural selection. Advances in modern biology have allowed the measurement evolutionary fitness and estimate the rate of fixation of beneficial mutations. Studying the evolution of *Escherichia coli* in a constant environment, Michael Wiser, Noah Ribeck, and Lenski demonstrate that even after 50,000 generations over 20 years, gains in fitness show no evidence of leveling off. Instead, fitness is following a power-law relationship that is dependent on epistasis and clonal interference. This work was published in *Science* after last year's annual report was submitted, and received a great deal of media attention from outlets

like NPR, *New Scientist*, and Carl Zimmer in his blog *The Loom*. In a news item about this study, *Science* famously referred to Lenski as "The Man Who Bottled Evolution."

BEACONites have made significant progress in understanding one of the **major transitions in evolution**: the transition from single-celled to multicellular life. Questions surrounding this transition include how reproductive division of labor evolved (what evolutionary pressures gave rise to delineated germ and somatic cells), and how cooperating groups of cells handle cheaters in their populations. Heather Goldsby (MSU), Ben Kerr (UW), and Charles Ofria (MSU) used digital evolution to propose and test a hypothesis, the "Dirty Work Hypothesis," that the mutagenic consequences associated with performing metabolic work favor such differentiation. In this study, published in *PLoS Biology*, the digital organisms began as undifferentiated multicellular individuals that could evolve computational functions that improved their rate of reproduction. When such functions are associated with moderate mutagenic effects, reproductive division of labor evolves - specifically, a fraction of the cells remove themselves from consideration as propagules for multicellular offspring, while simultaneously performing a disproportionately large amount of mutagenic work, and are thus classified as soma. As a consequence, other cells are able to take on the role of germ, remaining quiescent and thus protecting their genetic information. In a separate collaboration with researchers at Massey University in Auckland, New Zealand and Max Planck Institute for Evolutionary Biology in Plön, Germany, Ben Kerr (UW) studied how populations of the bacteria *Pseudomonas fluorescens* selected against cheating cell types when collective-level persistence was rewarded. Collectives reproduced via life cycles that either embraced, or purged, cheating types. When embraced, the life cycle alternated between phenotypic states. Selection fostered inception of a developmental switch that underpinned the emergence of collectives whose fitness, during the course of evolution, became decoupled from the fitness of constituent cells. Such development and decoupling did not occur when groups reproduced via a cheat-purging regime. These findings, published in *Nature*, capture key events in the evolution of Darwinian individuality during the transition from single cells to multicellularity. Goldsby, Kerr, and Ofria are continuing to work on this problem, currently focusing on the question of why single-cell transitions are ubiquitous. Preliminary data from digital evolution experiments suggest that a single-cell provides a more stable configuration for developmental patterns.

BEACON offers cross-disciplinary graduate courses in evolutionary biology and computational biology, culminating in a project-based course where students work together on interdisciplinary research projects. These projects are ultimately written up and submitted for publication. One such publication in *PLoS ONE* received quite a bit of attention: Kenna Lehmann, Brian Goldman, Ian Dworkin, David Bryson, and Aaron Wagner (MSU) used digital evolution to understand how **aposematism** (warning coloration of toxic animals) evolves – and especially how **mimicry** of warning coloration in non-toxic animals can evolve. Such warning coloration has long been thought to be impossible to evolve through gradual steps, but the team's work shows that such signals can evolve gradually from pre-existing cues via predator cue recognition and prey signal manipulation.

One of BEACON's largest educational products, **Data Nuggets**, has seen significant growth over the past year. Data nuggets are worksheets designed to help students practice interpreting quantitative data and make claims based on evidence, and are designed by scientists using real data. They were originally designed to accommodate and supplement instruction at the K-12 level, but the team repeatedly received feedback and excitement from undergraduate educators

suggesting that these concepts should be extended to post-secondary instruction. Louise Mead, with graduate students Elizabeth Schultheis and Melissa Kjelvik (MSU), received a grant from NIMBioS to hold a working group in January 2014 to bring together science education researchers, teachers, professors, mathematicians, and biologists to develop an assessment of Data Nuggets. The team has held several professional development workshops for graduate students, postdocs, and faculty within and outside BEACON, and has helped scientists create Data Nuggets based on their own evolutionary research. They have also held several workshops for teachers around the country.

With an NSF supplement from the NSF Office of Cyberinfrastructure, Titus Brown and Tracy Teal (MSU) have led the development of **Data Carpentry workshops** in collaboration with NESCent, SESYNC, iDigBio, and iPlant. These workshops are designed to teach researchers to retrieve, view, manipulate, analyze and store their and others' data in an open and reproducible way. Four workshops have been run so far, with seven more scheduled; they are wildly popular and fill up within hours of being announced.

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	68 projects currently underway, 647 publications to date (136 in the current reporting period)
New paradigms for research in organic and digital domains	Number of new sessions at scientific meetings or scientific meetings hosted at BEACON	3
	Number of new journals and societies	None to report yet
	New or increased funding for biocomputational research	BEACON researchers submitted 68 proposals for >$60M 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 >68 media pieces since previous annual report, including high profile pieces in *ABC News, The Scientist, The Economist, Scientific American, NOVA, Wired,* and on NPR.
Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	Number of requests for information	Since last report: 20,457 downloads of Avida-ED, over 3,500 downloads of Avida. Over 3,400 visits to BEACON website monthly
Ethical Research Goals		
Center participants will understand shared and discipline-specific practices of Responsible Conduct of	Percent completion of online training courses and face-to-face mentoring by participants.	Over 75% reported completion by Oct 20, 2014; on track for 100% of participants to fulfill their

Research (RCR).	Percent completion of online training courses and face-to-face mentoring by participants.	requirements by Dec 2014.
	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 2014
Respect for views and ideas "horizontally" and "vertically."	Number of Toolbox seminars and trials	New Scientific Virtues workshops piloted in 2014; 2 offered at Friday seminars and 4 at BEACON Congress
	Number of BEACON participants who get cross-disciplinary training	New Scientific Virtues workshops piloted in 2014
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	136 publications submitted, 115 conference or other presentations, 68 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 four thrust groups, three of which are based on natural levels of organization: genomes, behavior among individuals, and community-level dynamics. In 2014, BEACON leadership decided to elevate "Evolutionary Applications" to a fourth thrust group. These thrust groups are united by two cross-cutting themes: biological evolution and digital evolution.

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, Genetic Architectures, 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. Foci include (1) understanding the dynamics of genome evolution; (2) the form of gene interactions (epistasis) and the structure of fitness landscapes; (3) evolvability and robustness; and (4) the effects of these genomic processes on phenotypic variation. A total of 16 projects are currently supported in this thrust group. 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. This group investigates the evolutionary emergence, maintenance, and nature of intelligence and other behavioral phenomena. The organisms studied tend to be self-directed and capable of adaptive responses to ecological and social stimuli. Behaviors of interest include navigation, foraging, risk avoidance, cognition, communication, coordination, and social dominance. 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. Data from these studies of digital evolution are integrated with studies of living systems from single-celled organisms all the way up to mammals. Broadly, the 15 projects in this thrust group are studying (1) the evolution of complex behaviors, (2) the evolution of intelligence, and (3) the evolution of mechanisms mediating complex behaviors.

Thrust Group 3: Evolution of Communities and Collective Dynamics. Research in this group focuses on systems of interacting individuals and the emergence and organization of higher-level assemblages including communities, social groups and multicellular organisms. Broadly speaking, this research includes (1) evolutionary processes that generate biological diversity; (2) coevolutionary dynamics of interacting species; and (3) evolution of communication, cooperation, and group problem solving. Thirteen funded projects currently fall into this thrust group.

Thrust Group 4: Evolutionary Applications. Technological applications of evolution have become more prominent in BEACON, as has knowledge transfer, leading us to create a new Thrust Group as an umbrella for work that uses evolution as a powerful tool. Evolution is a generative process that has created diverse and complex biological systems, but fully harnessing that creative power has remained elusive. BEACON researchers are making advances in areas including (1) evolutionary algorithms; (2) artificial evolution of neural networks and Markov

brains; (3) evolution-based software engineering; and (4) using evolution to create novel biomolecules. Sixteen projects are currently funded in 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	This year, 21 BEACON students reported receiving degrees (13 PhD's, 6 Master's, 2 Bachelor's). Of the PhD graduates, 54% are currently in postdoc positions, 15% are in faculty positions, and 15% are working in industry. Information on former postdocs has been harder to gather, but of 5 MSU postdocs who left BEACON this year, 3 took faculty positions, 1 took a postdoc at a different institution, and 1 is working in industry.
Increased public literacy in evolution and the nature of science	Development of educational materials.	Testing, presentation, and 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 Drs. Titus Brown and Arend Hintze; 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, with students at partner universities participating via videoconference and online technology. The Center for Engineering Education Research at MSU evaluates the course sequence given the BEACON 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 currently funds a number of educational activities and programs, all of which help to meet our EHRD goals and optimal outcomes. Student-centered activities during the past year included the annual BEACON High School Summer Institute at MSU and Kellogg Biological Station and the BEACON REU Field Experience at Kellogg Biological Station (MSU). BEACON is developing teacher training and educational materials including evolutionary games for elementary students and software that engages undergraduate students in testing evolutionary hypotheses. BEACON continues to participate/organize community outreach efforts, including the US Science and Engineering Festival held in Washington DC and the Evolution Symposium held at the annual professional development conference of the National Association of Biology Teachers. We also have a number of educational activities that target the general public, including an evolution podcast and museum exhibits at MSU and UT.

Knowledge Transfer

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

Knowledge Transfer Goals		
GOAL	**METRICS**	**PROGRESS**
New collaborative research with industry partners	The number of external industry/government laboratory collaborations with BEACON through its member	In addition to working with existing industrial collaborators, this past year, BEACON has added 6

	universities	additional industrial collaborators with a seventh one under NDA negotiation as of October 2014.
	Number of joint grant proposals submitted with industrial partners	One proposal has been submitted, and another is 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 10 companies are providing challenge problems and feedback.
Spinoffs formed	Number of spinoffs formed	Existing spinoff with Risto Miikkulainen, Digital Certainty, is continuing to do well. No new spinoffs to report in the current period, but foundations are being laid for one to be rolled out in 2015 involving bio-inspired aquatic robots.

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 Metron, Ford Motor Company, Northrop Grumman, Continental Automotive, Chrysler, BAE Systems, General Motors, and Living PlanIT.

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.

Titus Brown and Tracy Teal have partnered with SESYNC, NESCent, iDigBio, and iPlant Collaborative to develop and run workshops offering computer science training to biologists, within and beyond BEACON.

Education Director Louise Mead is working with a number of institutions on BEACON educational initiatives, including NIMBios, BSCS (Biological Science Curriculum Study), CREATE for STEM Institute at MSU, University of Michigan, and the Concord Consortium.

Our BEACON Faculty Affiliates program now has members at University of California at Irvine, Yale University, and University of Texas Pan American.

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. One of our biggest goals for this year was increasing the participation of women at all levels. Overall, participation of women in BEACON is now above the National Norms: 35.2% of BEACON members are women, compared to 32.8% of scientists in the represented fields. While we have surpassed the national norms for women undergraduates and graduate students in past years, postdocs and faculty were still areas that needed improvement. This year, the percentage of BEACON female postdocs increased from 26.9% to 32% (compared to the National Norm of 35%), and female faculty increased from 22.1% to 29.4% (compared to the National Norm of 31.0%). We expect to surpass the National Norms in the next year by continuing our current efforts. BEACON's underrepresented minorities (URMs) are well above the National Norms overall (33.2%, compared to 25.4%), as are individuals with disabilities (2.7% compared to 1.1%). We will continue our efforts to increase ethnic and racial diversity at the postdoc level, and hope to increase self-reporting of disabilities, as we know that this category is underreported.

Diversity is very well represented across all of the Center's activities, as can be seen by analyzing the personnel on BEACON-supported research and education projects. Of 93 projects analyzed, 99 participants on those projects were URMs (including 49 undergraduates, 28 graduate students, 13 faculty, and 9 postdocs), and 210 were women (including 76 undergraduates, 78 graduate students, 46 faculty, and 10 postdocs).

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 continues to increase; in this period, 57% of all reported publications (see graph below) and 47% of presentations

	Number of new courses	After consideration, we have determined that adding new university courses every year is not a reasonable goal, and we have removed this metric from our plan.
	Number of students enrolled in cross-disciplinary courses	~30 in semester-long courses, plus hundreds in workshops on computational science for biologists
	Number of funding proposals submitted	43 of 68 grant proposals submitted (63%) reported as interdisciplinary; 30 of 68 (44%) inter-institutional
Increase in cross-institutional research and education	Number of paper/conference submissions	Reported cross-institutional publications continues to increase; in this period, 45% of all reported publications (see graph below) and 30% of presentations
	Number of new courses and workshops	New Data Carpentry, EDAMAME workshops
	Number of students in cross-institutional courses	~30 in semester-long courses, plus hundreds in workshops on computational science for biologists
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	BEACON researchers submitted 68 proposals for >$60M of external funding, and >$12M in external funding has been granted
	Award dollars	BEACONites have been awarded over $12M in this funding period (~$9M 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 2010) by October 2015]	These targets were exceeded in 2012. We are now focusing on increasing the interdisciplinarity, diversity, and academic distinction of our participants.
Effective support of Center operations by Management	Survey for participants about management team	Year 4 evaluation was very positive but revealed some

team	Survey for participants about management team	areas for improvement, which we are addressing
	Feedback from External Advisory Committee	Feedback has been positive and encouraging (Appendix C)
Center is perceived by NSF as exemplary	Renewal of NSF funding	Renewal was approved for our fifth funding increment, and we have received positive feedback from NSF. Our renewal proposal for phase 2 has been submitted.
	Number of public mentions made by NSF about BEACON	At least three BEACON studies were featured on the front page of nsf.gov in 2014

Projects at BEACON are chosen through an annual selection process, in which BEACON members submit "budget requests" in January under one of seven categories: Thrust Group 1, 2, 3, or 4; 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. For 2014, Farrell-Cole and Amey conducted a qualitative impact study focusing on in-depth interviews to capture input from an individual and organizational perspective. The questions centered on (1) expectations when joining and if the expectations have been met and changed over time, (2) ways in which the organization is meeting its mission, (3) how the Center is having impact, (4) expectations and recommendations for the next five years, and (5) BEACON's legacy. Many BEACONites expressed that their work would not have been possible without the Center, and that BEACON has created important new ways to study evolution in action. Through their participation in BEACON, members have increased their networks outside their discipline, a fact that is reflected in their work. Many members also commented favorably – without being asked – on BEACON's efforts to increase diversity. Interviews highlighted a desire for more opportunities for students, increasing potential impact of BEACON research on the field, and for BEACON leadership to increase their impact beyond BEACON, especially in advocating for evolution in action research and interdisciplinary research.

External Donor Support Highlights BEACON's Pre-eminence in Evolutionary Computation. BEACON received its second Endowed Chair in 2014. The donor, Dr. John R. Koza, is a pioneer in genetic programming, a form of evolutionary computation. In September, 2014, he made a gift to BEACON Center at Michigan State University to establish the John R. Koza Endowed Chair

in Genetic Programming. The search to fill this chair is commencing in November, 2014. This position will help to assure BEACON's legacy, while greatly contributing to its research in its second five years of STC support. Because Dr. Koza is not an alumnus of MSU, this is an unusual gift that, according to the donor, results from BEACON's leadership in the field.

Center-Wide Outputs

Publications submitted: 136 reported

Conference presentations and other dissemination activities (including lectures, seminars): 115 reported

Awards and Honors: 46 awards and honors reported

Students that graduated (reported): 13 PhD's, 6 Master's, 2 Bachelor's

General outputs of knowledge transfer activities: 1 start-up company, 1 provisional patent

Participants: 335 participants, plus another 304 affiliates (under 160 hours/year in Center activities), for a total of 639 BEACONites

Media publicity: Since the previous annual report, we have put out 12 press releases so far. Over 68 features on BEACON activities appeared in the mainstream and online media in the last reporting period.

Indirect/Other Impacts

International activities: BEACON hosted visiting faculty members from China (Professor Lihong Xu, Tongji University and Meng Yao, East China Normal University), New Zealand (Dr. Oliver Chikumbo, then of Scion, a crown research laboratory in New Zealand), and Austria (Prof. Stephan Winkler, of the HEAL [Heuristic and Evolutionary Algorithms] Laboratory of the Upper Austria University of Applied Sciences). These research and knowledge transfer collaborations have been extremely productive. In fact, Dr. Chikumbo was hired as a Research Associate Professor at Michigan State University. This project is described under the Knowledge Transfer section as it is aimed at collaboration with Living PlanIT, a "smart cities" company headquartered in the U.K.

To facilitate continuation of the extensive collaboration going on between Dr. Goodman and Prof. Zhun Fan and his colleagues in the newly established Guangdong Provincial Key Laboratory of Digital Signal and Image Processing of Shantou University, BEACON signed a five-year agreement establishing the International Joint Research Center for Evolutionary Intelligence and Engineering Applications, dated July 25, 2014. Both in-person visits and videoconferences will be employed to further the collaboration.

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. 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 68 research projects were supported by BEACON, including 44 projects that just began in summer/fall 2014. 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	68 projects currently underway, 647 publications to date (136 in the current reporting period)
New paradigms for research in organic and digital domains	Number of new sessions at scientific meetings or scientific meetings hosted at BEACON	3
	Number of new journals and societies	None to report yet
	New or increased funding for biocomputational research	BEACON researchers submitted 68 proposals for >$60M 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	Using Google Scholar as a tracking tool, we are seeing a steady annual increase in

	citations of their work.	BEACON publications and in citations. (See figure below.)
	High visibility science journalism about BEACON research	12 press releases and >68 media pieces since previous annual report, including high profile pieces in *ABC News, The Scientist, The Economist, Scientific American, NOVA, Wired,* and on NPR.
Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	Number of requests for information	Since last report: 20,457 downloads of Avida-ED, over 3,500 downloads of Avida. Over 3,400 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 75% reported completion by Oct 20, 2014; on track for 100% of participants to fulfill their requirements by Dec 2014.
	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 2014
Respect for views and ideas "horizontally" and "vertically."	Number of Toolbox seminars and trials	New Scientific Virtues workshops piloted in 2014; 2 offered at Friday seminars and 4 at BEACON Congress
	Number of BEACON participants who get cross-disciplinary training	New Scientific Virtues workshops piloted in 2014
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	136 publications submitted, 115 conference or other presentations, 68 grant proposals submitted during this reporting period
BEACON research output	Feedback from the External	Positive feedback. See

will be perceived as making an important contribution to the literature.	Advisory Committee	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 fifth annual BEACON Congress in August 2014. The Congress is now a full 4 days, including one student/postdoc "retreat" day, and features numerous networking events.
- **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. While some progress was made in 2014, we experienced a transition with our new Information Technologist, Tim Schmidt. We anticipate full completion by early 2015.
- **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 originally defined three thrust groups, based on natural levels of organization: genomes, behavior among individuals, and community-level dynamics. These thrust groups were united by three cross-cutting themes: biological evolution, digital evolution, and evolutionary applications. We recently re-assessed the usefulness of these thrust group definitions and determined that researchers focusing on evolutionary applications were not served well by this organization, especially as these technical applications and knowledge transfer have grown within BEACON. We have now redefined "Evolutionary Applications" as a fourth thrust group, and now have two cross-cutting themes (biological evolution and digital evolution). We describe each of these thrust groups below. Many projects can be assigned to two or more research groups, but for convenience we only report each project as belonging to a single thrust group below. Below, we describe progress on research projects, divided into general research themes, that are currently under way within each thrust group and their goals and activities.

Thrust Group 1: Genomes, Genetic Architectures, 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. Foci include (1) understanding the dynamics of genome evolution; (2) the form of gene interactions (epistasis) and the structure of fitness landscapes; (3) evolvability and robustness; and (4) the effects of these genomic processes on phenotypic variation. A total of 16 projects are currently supported in this thrust group. 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 current research in each theme.

Dynamics of genome evolution

Julius Jackson (MSU) and Erik Goodman (MSU) are **modeling metabolic gene clustering in bacterial chromosomes using a custom-crafted computational evolution platform**. Discovering the forces that shape the distribution and organization of the bacterial chromosome is an open question that biologists have been addressing for decades. Particularly, scientists have presented models attempting to explain the gene clustering phenomenon, the observation that genes of related function tend to cluster together on chromosomes of some well-studied bacteria. Although hypotheses to explain the gene clustering phenomenon have generated many models, only the Limited Protein Mobility model (proposed by the Jackson lab in 2004) considers the effect of gene clustering on the metabolic efficiency of the organism. This project for this report used the Primal Chromosome hypothesis as a focal point to simulate gene clustering on primal plasmids as precursors of modern chromosomes in bacteria. This simulation aims to approximate events that likely occurred during the first hundred million years of life on Earth, i.e., 4 - 3.9 billion years ago. The simulation environment built for this study is the Gene Distribution Lab (GDL). All GDL simulation runs produced heterologous gene clusters on the target primal plasmid size. GDL is a simulation environment that seeks to test models of the gene clustering phenomenon. It will test how metabolic benefits of gene clustering can preserve clusters once they form by random processes. In future versions, GDL will explore the effects of the metabolic benefits of gene clustering as stated by the Limited Protein mobility model, and test other models that attempt to explain gene clustering.

Jeff Barrick (UT), Shin-han Shiu (MSU), and Chris Waters (MSU) are testing the hypothesis that bacteria contain previously undiscovered populations of **self-encoded RNAs** (seRNAs). The rationale for this hypothesis is the fact that a significant proportion of sequenced RNA from bacteria does not map to the parent genome. This team identified 14 persistent transcripts isolated from the parent (REL606) and a 20,000 generation evolved isolate from the LTEE. Identification of large sets of seRNAs in bacteria would be an exciting, significant finding as it would suggest significant hereditary information that potentially drives evolution and biological function had gone unnoticed. Moreover, these seRNAs could be relics of the RNA world. The team has found compelling evidence of seRNAs in multiple bacterial species, including *Salmonella enterica* and *Xenorhabdus nematophila*. Although none of these extra-genomic transcripts are similar to each other or to the transcripts previously identified from the LTEE *E. coli* samples, they suggest that the presence of these extra-genomic RNAs can be wide spread

and warrant further analyses, particularly experimental studies to verify their authenticity and roles.

Gene interactions and fitness landscapes

MSU postdoc Noah Ribeck, with Rich Lenski, is **incorporating frequency-dependent selection into Fisher's Fundamental Theorem of Natural Selection**, which states that the rate of mean fitness increase in a population is equal to the variance in fitness among individuals within that population. It has been hypothesized that Fisher's Theorem is likely to fail in most real-life situations, due to many possible complications. Fisher's Theorem has been tested twice during the course of Lenski's LTEE; it was found to hold during early generations and fail in later generations, thought to be due to evolved frequency-dependent selection. Using known examples from the LTEE as well as Avida digital organisms, Ribeck is testing a version of the theorem that is modified to account for frequency-dependent selection.

MSU postdocs Aditi Gupta, Bjørn Østman, and Tao Zhou are working together with MSU faculty member Yong-Hui Zheng to **model the fitness landscape of HIV-1 protease** and test whether **valley-crossing is a biological phenomenon**. Although fitness landscapes have been shown to be rugged in empirical settings, they have not been investigated in viral populations. The team hypothesizes that the fitness landscape of HIV-1 protease is rugged and crossing valleys in this landscape can evolve proteins that are fitter, which is possible because HIV has a high mutation supply rate and thus deleterious mutations can be quickly followed by a fitness-restoring mutation allowing experimental evidence of valley crossing in biological systems. The team is serially introducing mutations in the protease by site-directed mutagenesis starting with the mutations that are known to decrease fitness of the wild-type protease (drug resistance mutations). Subsequent mutations will be those that are known to compensate the deleterious effect of the resistance mutation. To test whether valley crossing occurs in evolving virus populations, mutated (low fitness) proteases will be reintroduced into the virus to test whether fitness is restored by subsequent cycles of replication that introduce new mutations.

Andrew Ellington (UT) and Eric Klavins (UW) are researching the **fitness landscape of a synthetic genetic circuit** that combines a positive feedback loop (a polymerase that activates its own transcription) and a negative feedback loop (a repressor driven by the polymerase that represses its transcription). They seek to determine to what extent experimental evolution can be predicted by computational modeling. In so doing, they hope to provide a basis for developing algorithms for predictive evolution. They anticipate that such algorithms may prove robust to the organism in which a given circuit is located, providing key insights for the burgeoning field of synthetic biology. For example, it may prove possible to develop generalized models for transferring expression constructs from *E. coli* to other organisms.

Evolvability and robustness

Ben Kerr (UW) and Charles Ofria (MSU), with graduate students Michael Wiser and Rosangela Canino-Koning (MSU), are **investigating the impact of horizontal gene transfer with digital organisms**. Horizontal Gene Transfer (HGT) is a widespread phenomenon in microbial life whereby organisms can acquire DNA from individuals other than their direct parent(s). The origins and consequences of HGT have been discussed frequently in the literature but empirical tests of these hypotheses remain rare primarily due to methodological difficulties

in performing these experiments with microbes. Digital evolution offers a way to test hypotheses regarding the origin and effects of HGT on evolving populations. This team will use the Avida platform to test whether the ability to use foreign genome fragments as growth resources is sufficient to promote HGT, whether physically compact tasks (a digital analog to pathways) are more likely to spread through HGT than are dispersed tasks, and whether environments which allow HGT result in increased genomic modularity than environments that do not.

James Bull (UT) and Scott Nuismer (UI) are investigating the **evolutionary robustness of a synthetic ecosystem** with three replicating entities: a host bacterium, a phage lethal to the host, and a transmissible vector that confers resistance to the phage. The heart of the method is the release of an engineered, viral genome designed to alter the interaction between its host and a predator of that host. The engineered genome itself "engineers" the genome of its bacterial host to block infection by a different virus, one that is lethal to the bacterium. This model system has real-world relevance for transmissible genetic elements that are engineered to modify disease-transmitting insects, deliver genes to stem-cell populations, and produce infectious vaccines. The system is amenable to mathematical modeling, and the experimental dynamics of each element is easily obtained for comparison to the predicted dynamics.

Aditi Gupta and Chris Adami (MSU) are examining 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 understanding how the virus maintains all the required drug-resistance mutations with an error-prone replication system. They hypothesize that drug-resistance 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 a 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.

Joseph Graves, Jr. (NCAT), Jeff Barrick (UT), and Rich Lenski (MSU) are using experimental evolution, whole-genome resequencing, and phenotypic evaluation via advanced microscopic techniques to understand the **evolvability of metallic/metallic oxide nanoparticle resistance in bacteria**. Metallic/metallic oxide nanoparticles (NPs) are increasingly being used in consumer products as antimicrobials. The content, shapes, sizes, and coatings of these NPs are factors known to influence their effectiveness at killing bacteria. Due to their multiple modes of action it is still widely thought that bacteria will not readily evolve resistance to these new biocides. However, the Graves laboratory has already produced a silver nanoparticle (AgNP) resistant strain of *E. coli* K12-MG1655. This strain had no known silver resistance elements. The team is characterizing these AgNP resistant strains to investigate a series of questions concerning the evolvability of metallic/metallic oxide resistance, including: what are the limits to m/mo NP resistance; is metallic resistance general to all metals (Ag, Cu, Zn); does resistance to metallic NPs confer resistance to metallic oxide NPs; does resistance to m/mo NPs come at a cost to

fitness in non-metal environments; is there a trade-off between m/mo NP resistance and resistance to traditional antibiotics?

Jeff Barrick (UT), Scott Harrison (NCAT), and Rob Newman (NCAT) are **illuminating evolution in action with expanded genetic codes.** Though the genetic code for the translation of DNA-encoded information into proteins is one of the most important and universal properties of biology, its early evolution and current potential for change remain mysterious. This team is using state-of-the-art genetic engineering strategies to synthetically alter the genetic code of *Escherichia coli* to incorporate a 21st noncanonical amino acid (ncAA) into proteins. They are also performing analogous experiments in the Avida artificial life system in which the coding of computational instruction sets changes during evolution. In both of these systems, they are testing the ability of genetic code expansion to spur evolutionary innovation, which ncAAs (or instructions) will have the most impact in promoting the acquisition of new phenotypes, and what parameters of expanded genetic code systems are critical for their evolutionary utility.

Coupling genomic processes to phenotypic variation

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.

Peter Fuerst (UI), Deborah Stenkamp (UI), Jenny Boughman (MSU), and Barrie Robison (UI) are studying **genome duplication as a source of variability in evolution of the fish visual system.** Neural circuitry is specified by a combination of molecular cues and experience. The developmental and evolutionary origin of novel neural circuitry is not well understood. This team set out to test the role of genome duplication as a source of evolutionary novelty that gave and gives rise to novel circuitry in the retina of the teleost fishes. The genome of the teleost fishes was duplicated approximately four hundred million years ago. Duplicated genes not required in a dose dependent manner in the teleost lineages were susceptible to loss but also able to adopt new expression patterns and functions. While much of the fish central nervous system is less specialized than the mammalian nervous system the retina of teleost fishes is remarkable in several fashions. In addition to being able to regenerate and continually produce neurons, teleost fishes contain a larger repertoire of primary photoreceptor types and a corresponding increase in the downstream cells composing visual circuitry. The mechanism underlying this increased complexity of visual circuitry in the teleost fishes is largely unexplored, and the team is testing the hypothesis that genome duplication has increased the opportunity for teleost fish to develop novel retinal circuitry over long evolutionary periods as well as in response to more recent environmental changes and niche invasions.

Jeff Barrick (UT), Christopher Marx (UI), and Zachary Blount (MSU) are examining the **mechanistic basis of mutations potentiating the evolution of citrate utilization in the long-term evolution experiment** (LTEE). After 31,500 generations of propagation in the laboratory (>15 years), *Escherichia coli* evolved in the Lenski long-term evolution experiment (LTEE) that were able to utilize abundant citrate present in the growth medium (Cit+ phenotype). Cit+ is highly beneficial in the LTEE because it grants access to a previously untapped resource. Yet, this evolutionary breakthrough is rarely observed: it has occurred in only 1/12 LTEE populations after >25 years. Previous work has established that evolution of Cit+ was contingent on at least

one, and possibly more, potentiating mutations that arose before citrate utilization evolved. The goals of this research project are to understand this transition in terms of bacterial metabolism and to determine the genetic and/or ecological factors that potentiated Cit+ evolution. This project will employ genome sequencing, isogenic strain reconstruction, metabolic flux analysis, and competition assays to determine what mutations and nutrients define Cit+ potentiation and to explore whether other LTEE populations are likely to evolve citrate utilization in the future.

Graduate students Caroline Turner and Emily Dolson are working with Rich Lenski (all MSU) to understand the **evolution of stoichiometry in digital and biological organisms.** Biological organisms vary in the proportions of different elements that make up their biomass, also known as their stoichiometry. These differences in stoichiometry are known to have important ecological consequences, with effects ranging from the growth rate of organisms to predator-prey interactions and the identity of limiting nutrients in an ecosystem. However, the evolutionary origins of variation in stoichiometry are less well understood, and in many cases, hypotheses cannot feasibly be tested in biological organisms. These students are implementing stoichiometry in the digital evolution system of AVIDA in order to test several of these hypotheses.

Dukka KC (NCAT), Chris Adami (MSU), and Claus Wilke (UT) are taking an **evolutionary computation approach to protein contact map prediction**. The prediction of amino acid contacts is a difficult problem, affected by many factors such as the kinds of amino acids, length of a protein, etc. It is part of a larger problem that seeks to describe the three-dimensional structure of proteins. Improving contact map prediction is difficult, but also has great potential rewards, such as a) the ability to predict a much larger protein space much more quickly; b) guidance of wet-lab experimental work via the above capability; c) insights into evolutionary relationships by structural (and, through this, functional) comparisons; and d) the ability to design new proteins with desired structural and functional characteristics. The team is using Markov networks, a computational framework for connecting variables to one another, to analyze protein features. In this implementation, the networks are essentially logic circuits that take input (the features) and produce output (whether or not the amino acids in the pair are in contact). The Markov networks are capable of evolving to produce contact map prediction accuracy that is much better than random chance. The team has also found that certain features seem to be better at predicting the contacts of amino acids, and is making progress toward a fuller list of useful features.

Maitreya Dunham (UW), Charles Ofria (MSU), Ben Kerr (UW), and postdoc Heather Goldsby (UW) are investigating the **evolutionary origins of phenotypic plasticity**. Theory predicts that phenotypic plasticity will be favored when organisms live in heterogeneous environments and when a single phenotype is not optimal across all environments experienced. In order for plasticity to be adaptive, the organism must match the optimal phenotype to a given environment at the appropriate time (it must be able to accurately predict future selective conditions). This suggests an additional criterion for the evolution of phenotypic plasticity – the environmental variation experienced must provide reliable information about future selective conditions. This team is testing theoretical predictions about the role of cue reliability in the evolution of phenotypic plasticity using experimentally tractable microbial (multicellular yeast) and digital systems in which plasticity must evolve *de novo*. Analysis of evolved isolates will not only shed light on the conditions that favor the evolution of phenotypic plasticity but may also reveal mechanisms for achieving plasticity.

Claus Wilke (UT), Patrick McPhail Martin (NCAT), and Checo Rorie (NCAT) are investigating the **evolution of resistance to treatment in brain cancer**. Glioblastoma multiforme (GBM) is the most common and deadly primary brain tumor, accounting for over 13,000 new cases in the United States annually and with a two-year survival rate of less than 5%. Typical treatment for GBM includes surgical resection with adjuvant radiation and chemotherapy. Despite this aggressive treatment, GBM almost always recurs within six months to a year of surgery. One primary reason for the high rate of recurrence is that surgical resection is always, necessarily, incomplete, and those cancer cells remaining after resection evolve to resist radiation and chemotherapeutic treatment. How these cells evolve to resist treatment, what genetic and epigenetic changes are involved, how many changes, and of what types, has not been systematically studied. This group has begun a long-term evolution experiment to study GBM adaptation to chemotherapeutics by exposing GBM cell lines to typical chemotherapy treatments, and measuring their global changes in protein-expression and genetic sequence at regular time points. Improving understanding of GBM adaptation to therapies may help in designing more durable treatments for patients with GBM.

Thrust Group 2: Evolution of Behavior and Intelligence.

This group investigates the evolutionary emergence, maintenance, and nature of intelligence and other behavioral phenomena. The organisms studied tend to be self-directed and capable of adaptive responses to ecological and social stimuli. Behaviors of interest include navigation, foraging, risk avoidance, cognition, communication, coordination, and social dominance. 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. Data from these studies of digital evolution are integrated with studies of living systems from single-celled organisms all the way up to mammals. Broadly, the 15 projects listed below are studying (1) the evolution of complex behaviors, (2) the evolution of intelligence, and (3) the evolution of mechanisms mediating complex behaviors.

Evolution of complex behaviors

Knowledge of how living organisms evolve complex behavioral strategies to promote survival and reproduction can be used to refine evolutionary design techniques. Even simple living organisms perform many complex behavioral tasks that remain intractable for machines. By targeting the evolution of animal behavior, research in this area is merging computer science with biology so each can learn from the other. This rich exchange is expanding the field from biologically-inspired computation to include innovative experiments that contribute to biological knowledge.

Several BEACON projects focus on mate choice behavior. Postdoc Jason Keagy (MSU), with MSU faculty members Jenny Boughman and Charles Ofria, and UT faculty members Hans Hofmann, Daniel Bolnick, and Molly Cummings is studying the **evolution of reproductive isolation through mate discrimination in sticklebacks and Avida**. Mate choice decisions are important for determining future fitness, and discrimination against members of other species is a

critical part of this process. A full understanding of the evolution of mate discrimination cannot be achieved without gaining insight into its heritable (i.e., genetic) basis. This team is examining gene expression patterns in female sticklebacks (*Gasterosteus* species complex) making mate choice decisions, specifically by comparing females who reject a heterospecific male to females who accept a conspecific male. To parallel this work they are using digital organisms in Avida, with the recently added capability to evolve male display and female mate choice. With these modifications, the group is studying populations adapting to two different environments to test hypotheses about the evolution of reproductive isolation during ecological speciation.

Thomas Getty (MSU) and Ben Kerr (UW) are studying the **coevolutionary dynamics of mate choice and parental care**. This is a theoretical study of the coevolution of male and female mating strategies and parental investment patterns. Evolutionary theory predicts that individuals should prefer mates of higher "quality" who are in good physical condition and possess superior genotypes. However, in species where males vary not only in their intrinsic quality but also in their willingness to care for offspring, female preferences for male quality may be more nuanced. Research questions include: 1) Should females sometimes prefer males with lower intrinsic quality? 2) What happens when there is also important variation in female quality - how do preferences differ between low-quality and high-quality females? Getty and Kerr are developing and analyzing mathematical models to investigate these questions.

Postdoc Eben Gering (MSU) and Tom Getty (MSU) are also looking at mate choice, specifically **sexual selection for mito-nuclear compatibility in a feral chicken model**. A new theory of sexual selection posits that female mate choice helps ensure complementarity of offspring's nuclear and mitochondrial (mt) genomes. They have discovered a large-scale natural experiment that is currently underway in the Pacific, and poised to provide the first empirical test of this potentially transformative theory. Specifically, they are conducting field sampling, mate choice trials, and genetic analyses of feral chickens on Kauai island (Hawaii) to 1) ascertain whether mt genotypes predict mate preferences and/or mating success 2) determine how mito-nuclear compatibility influences offspring number and performance. Their results will shed new light on the evolutionary interplay between the complex behaviors of animals, and the interacting genomes within (nearly) every animal cell.

Craig McGowan (UI) and Phil McKinley (MSU) are **exploring the evolution of robust joint-level control**. In this project, they integrate biomechanics, computation, and physics-based simulations to understand how selection shapes the evolution of leg design and gaits in animals, with the ultimate goal of improving robot locomotion. So far they have developed the Digital Muscle Model, a joint-level control method that operates in a manner analogous to biological muscles, yet is abstract enough to apply to conventional robotic joints. They are also using kangaroo rats as a model to examine how these animals modulate hopping gate in response to changes in speed and incline, and how they adapt to changes in substrate stiffness. They are also using direct in-vivo measurements of muscle activity and length change to examine the contributions of individual muscles to powering accelerations and hopping up an incline.

In another biomechanics project, postdoc Travis Hagey (UI) is working with Matt Riley (UI) and Parviz Soroushian (MSU) to understand the **optimization of the gecko adhesive system.** Geckos have the striking ability to cling to surfaces using hair-like setal structures on the underside of their toes. Although there have been many previous studies of gecko adhesion, we still do not understand how setal morphology and perch texture interact dictating how geckos use their adhesive pads in the wild. This team is using genetic algorithms (GA), computed

tomography (CT), and dynamic finite element analyses (FEA) to study the gecko adhesive system and to predict the best morphological configuration for producing friction on different surfaces. With this approach they are investigating the complex relationship between form and function of gecko toe pads establishing how different species may be adapted to their environments. This work will also have implications for the development of synthetic adhesives. This study is ground-breaking in its use of evolutionary computing to investigate biomechanics and ecology to better understand adaption.

Gerry Dozier (NCAT) and Ian Dworkin (MSU) are using **tools developed for facial recognition** (Genetic and Evolutionary Feature Extraction, GEFE) **to characterize variation in fruit fly wings**, which will enable work to examine how very subtle morphological differences evolve and impact flight performance. They are now seeking to enhance GEFE in an effort to improve its performance on the fly wing classification problem (including fly wing mutations). Additionally, Dozier and Dworkin will investigate reconstruction techniques for visualizing potential fly wings from hypothetical feature vectors, and experimentally and computationally examine the relative contributions of biological (i.e. shape and size) vs. technical (image quality, orientation, etc..) variation in generating feature vectors. It is believed that by improving the performance of GEFE in the area of fly wing biometrics will lead to an overall improved feature extraction technique for biometric recognition as a whole.

Evolution of intelligence

Intelligence is one of the most complex biological capacities; understanding its origins is of fundamental interest from both computational and biological perspectives. Here we adopt Kamil's broad definition of intelligence as “those processes by which organisms obtain and retain information about their environments, and use that information to make behavioral decisions.” The creation of intelligent machines has proven extremely difficult, probably because most efforts have attempted ‘top-down’ design of such overwhelmingly complex entities as the human brain. Mammalian brains evolved from simpler forms, so BEACONites use digital organisms, artificial neural networks, and Markov Network Brains to examine intelligence from the ‘bottom-up’ perspective of evolution, integrating computational and analytical approaches to investigate information acquisition, storage, processing, and use in adaptive behavior.

Hans Hofmann (UT), Chris Adami (MSU), and postdoc Alex Jordan (UT) combine social behavior of fish with digital evolution experiments to study **information flow through hierarchical social systems**. To understand how information flows through systems, we must first understand how individual agents interact to pass information between them. In biological systems, including human societies, the nature of these interactions may vary dramatically based on the social relationship of the information transfer agents. Thus, the efficacy of information flow in groups and larger social organizations depends on the hierarchical social structure within these groups. This team has trained fish, *Astatotilapia burtoni*, to associate an LED stimulus with a food reward. They then place these informed individuals into groups of uninformed individuals and measure how social information transfer allows uninformed members to learn this association. Using automated tracking, they are quantifying the social interactions between all members, and measuring whether dominant or subordinate social members are more effective agents of information transfer. Seeding information at the most behaviorally dominant network node (the dominant male) does not produce the fastest acquisition of group information. Rather,

subordinate males in the network, traditionally thought to occupy unimportant network positions, are the most effective agents of information transfer within their social groups. Based on these empirical results, the team is developing *in silico* visual models of information flow and construct optimal network designs for information flow, testing these in turn in biological systems.

BEACON studies also explore selective processes and nonselective constraints that have shaped brains and cognitive abilities. Competing hypotheses disagree about whether brain and cognitive evolution were driven primarily by complexity in social or physical environments. Charles Ofria, Ian Dworkin, Aaron Wagner, Louise Mead, David Bryson, Dave Knoester, and Abhinja Parigi (all MSU) are examining **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 corresponded 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. This team is testing the generality of the variability selection (VS) hypothesis via digital evolution experiments investigating the tempo and modes of biotic and abiotic environmental change that promote the evolution of adaptive complexity. 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.

Debates also surround the question of whether selection favors only domain-specific intelligence, and if so, what evolutionary forces resulted in the unique generality of human intelligence. Kay Holekamp (MSU) and Risto Miikkulainen (UT) are using comparative studies of living animals and experiments *in silico* to explore **convergence in the evolution of domain-general intelligence** from ancestors with nervous systems comprised of domain-specific modules. It has been hypothesized that general intelligence may originally have evolved as an expansion of a domain-specific ability to deal with a particular type of environmental complexity, and primatologists argue that this specific domain was social cognition. Primates are well known for their remarkable behavioral flexibility, defined as the ability to switch readily among alternative strategies to solve a problem. The 'social brain hypothesis' suggests that the key selection pressures shaping the evolution of these cognitive abilities in primates have been imposed by complexity associated with the labile social behavior of conspecifics. If so, then primate-like cognitive abilities should have evolved convergently in non-primate mammals living in large, complex societies. Alternatively, it is possible that domain-specific intellectual abilities have converged, whereas domain-general ones have not. That is, carnivores may respond to social selection pressures in the same ways that primates do with respect to domain-specific intelligence, but their domain-general cognitive abilities might remain far more limited than those in primates. Holekamp and Miikkulainen are using behavioral flexibility as a strong, and relatively tractable, measure of general intelligence; it can be studied by measuring probability and latency of subjects changing tactics as necessary to solve a problem. Using simple tests of behavioral flexibility in the field, the team is determining whether, and how readily, hyenas and baboons are able to switch strategies as demanded by simple food-acquisition problems with solutions contingent on reversal learning. This field work is in

combination with computational modeling of neural network evolution to test competing hypotheses suggesting how domain-general intelligence might have evolved, and to identify other factors in brain evolution aside from social complexity that might facilitate the evolution of domain-general intelligence.

Evolution of mechanisms mediating complex behaviors

BEACON now includes evolutionary neurobiologists working with diverse systems on the evolution of the neuroendocrine, genomic and microbial mechanisms that mediate behavior.

Barbara Lundrigan, Laura Smale and postdoc Arend Hintze (all MSU) are concurrently using phylogenetic, neurobiological, and computational approaches to investigate **evolutionary dynamics of transitions between nocturnality and diurnality**. These transitions require enormous change in the neural systems that coordinate the timing of myriad behavioral, neural, and physiological functions that support activity in a cold/dark night vs. a warm/bright day. The team is exploring the nature of those complex changes in one focal taxonomic group (Order Rodentia) via three interrelated projects: (1) analysis of the pattern of temporal niche evolution, (2) assessment of constraints and tradeoffs associated with the evolution of sensory regions of the brain that have contributed to that pattern, and (3) development of computational models to test hypotheses concerning the factors that (likely) influence the process of temporal niche transitions.

Fred Dyer, Ian Dworkin and Charles Ofria are studying **the applicability of hidden Markov models (HMMs) to decipher motivational states underlying complex behaviors**. The target of natural selection for behavior evolution is not just isolated actions, but extended sequences of behaviors driven by shifts in underlying motivational states. HMMs use any kind of sequence data (or transition matrices derived from sequence data) to estimate latent (hidden) variables, with transitions between hidden states influencing observed behavioral states. Despite the applicability of HMMs, the meaning of the hidden (latent) states is rarely obvious. Currently it is unclear how the hidden factors can be interpreted as motivational or neurophysiological states. In particular, evaluation of hidden factors in the context of behavior is less straightforward. Thus, there is a critical need to both extend and evaluate HMMs in systems where motivational states can be directly evaluated, and thereby to correlate latent variables in HMMs to validated control mechanisms. The team is exploring motivational states in both digital (Avida) and biological (*Drosophila* and bees) systems.

In a related project, Fred Dyer and Arend Hintze (MSU) are studying the **evolution of incentive contrast effects**. This project focuses on "negative incentive contrast effects," a behavioral phenomenon exhibited when animals need to adjust their behavior in response to shifting or uncertain rewards. These effects are seen when an animal responds with less enthusiasm to a given mediocre reward if it has recently experienced something better. From an evolutionary perspective, negative contrast effects are puzzling because the animal may, after a downshift from a higher reward, temporarily pass up a mediocre reward even if it is the only currently known option. Dyer and Hintze are using behavioral studies of nectar-feeding bees and digital evolution to explore hypotheses about the evolutionary pressures that shape the tendency to lag in resuming exploitation of a mediocre food source.

BEACONites have identified multiple systems in which the genetic and neural underpinnings of coevolutionary processes can be studied empirically, as changes in both signals and their detection mechanisms involve well-understood sensory systems and small numbers of genes.

For example, Kevin Theis and Danielle Whittaker (MSU) are studying the evolution of symbiotic relationships between microbes and their vertebrate hosts that function importantly in animal communication. Specifically, they are **testing the hologenome model of evolution** using behavioral and bacterial symbiont data on the chemical signaling system of a wild songbird, the dark-eyed junco (*Junco hyemalis*). No animal population has evolved independently of symbiotic microbes. Instead, each has been densely populated by, and has coevolved with, suites of microbes whose genomes have profoundly affected its biology. An effective communication system is a critical component of each animal's behavioral repertoire, and most animals communicate, at least in part, via chemical signals. One way that symbiotic microbes might contribute to their hosts' behavioral phenotypes is by increasing the diversity and efficacy of chemical signals available to them. This research expands on previous work in social mammals by incorporating field studies of songbirds—a group historically neglected in the study of chemical communication—and experimental evolution with digital organisms, an extremely tractable system.

Graduate student Patric Vaelli (MSU), with Heather Eisthen (MSU), James Foster (UI), and Kevin Theis (MSU), is investigating **the role of symbiotic bacteria in a predator-prey coevolutionary arms race**. In this predator-prey coevolutionary system, prey (rough-skinned newt, *Taricha granulosa*) possess tetrodotoxin (TTX) and are highly toxic, and predators (common garter snake, *Thamnophis sirtalis*) have evolved toxin resistance. Asymmetrical selection for increasing toxicity and toxin resistance has 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 but not limited to 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. Vaelli is working to characterize the bacterial communities associated with newt tissues using next-generation sequencing technologies and develop ecologically-guided cultivation media to effectively isolate putative TTX-producing bacteria.

In a related project, Vaelli and Eisthen are also working to understand **voltage-gated sodium channel evolution in this neurotoxic amphibian**, as it is not currently known how these rough-skinned newts avoid self toxicity of their own voltage-gated sodium channels (Nav channels), which are primarily responsible for initiating electrical signals in nervous tissue and are blocked by TTX. In the absence of snake predators some populations of newts possess little or no TTX, suggesting that TTX toxicity is costly and that Nav channel function may be compromised by TTX resistance. They are sequencing the TTX binding regions of all six newt Nav channel paralogs and characterizing novel mutations, to test the prediction that all six paralogs will possess TTX resistance mutations. They are also using electrophysiological methods to

characterize the effects of TTX resistance mutations on the biophysical properties of resistant channels.

Thrust Group 3: Evolution of Communities and Collective Dynamics.

Research in this group focuses on systems of interacting individuals and the emergence and organization of higher-level assemblages including communities, social groups and multicellular organisms. Broadly speaking, this research includes (1) evolutionary processes that generate biological diversity; (2) coevolutionary dynamics of interacting species; and (3) evolution of communication, cooperation, and group problem solving. Thirteen funded projects currently fall into this thrust group.

Evolutionary processes that generate biological diversity

Elena Litchman, Tracy Teal, and graduate student Paul Wilburn (all MSU) are **sequencing evolutionary adaptations in microorganisms endemic to the planet's oldest lake**. The goal of this project is to reveal functional information on endemic and cosmopolitan microorganisms in Lake Baikal, Siberia, Russia. Baikal is the planet's oldest, deepest and most voluminous lake that holds about 20% of the world's unfrozen freshwater. It is an island of biodiversity, marked by high endemism in the cold open waters and cosmopolitan flora in warmer shallows. Historically cold year-round, Baikal is experiencing rapid warming. Sequencing samples with contrasting community composition will reveal metabolic capabilities of communities dominated by endemic and cosmopolitan species. In addition to gene-centric information on the different communities, deep sequencing of samples with simple endemic assemblages can give genomic insights into the highly specialized metabolisms of endemic microorganisms. Baikal endemics are likely to exhibit adaptations to cold, oligotrophic conditions. Because these adaptations may be absent in their cosmopolitan competitors, metabolic constraints in the endemics may be important driving forces for the spatial heterogeneity of endemic and cosmopolitan microorganisms in the lake. The contrasting metabolic repertoires may also play a crucial role in the restructuring of Baikal's microbiome in the scenario of rising water temperatures in the wake of climate change.

Doug Schemske (MSU) and Ben Kerr (UW) are **comparing biotic and abiotic selection to determine whether coevolution is "special."** The latitudinal biodiversity gradient is a striking biological pattern lacking an accepted explanation. One evolutionary hypothesis is that biotic interactions are relatively more important drivers of adaptation than abiotic factors in the benign stable climate of the tropics. Therefore, more coevolution at lower latitudes could lead to faster rates of divergence and thus faster speciation rates. The team is testing the latter component of this hypothesis using experimental evolution in bacteria to compare evolution driven by biotic (phage) vs. abiotic (antibiotic concentration) selective agents. A technological innovation (the morbidostat) allows them to dynamically administer antibiotics in a chemostat and recapitulate selective death imposed by phage, allowing a controlled comparison of selective agents. Four treatments are being tested for their effect on replicate bacterial population divergence from the ancestor and each other: phage, fluctuating antibiotic, reciprocally changing antibiotic, and a control. The antibiotic treatments mimic components of coevolution—namely temporal change in selection and reciprocal selection, respectively. Divergence is expected to be highest for the

phage treatment because its structure evolves, while antibiotic can only change in concentration. Because allopatric divergence is a key component of speciation, these experiments may provide evidence linking biotic interaction strength to diversification rates, filling a gap in our understanding of global biodiversity patterns.

Coevolutionary dynamics of interacting species

Ben Kerr (UW) and Charles Ofria (MSU) are examining **the role of spatial structure in shaping coevolutionary patterns and processes**. Natural communities are made up of fragmented subpopulations distributed across space. Migration between these fragments determines the topology of the 'metacommunity,' which can be thought of a network where edges connect subpopulation nodes when migration occurs between them. The structures of metacommunities affect many aspects of eco-evolutionary dynamics. Thus understanding how topology influences coevolutionary dynamics between hosts and parasites is particularly important for conservation agriculture and medicine. However, limitations in both the scale of experiments and the detail of analysis have made manipulative experiments difficult. This team is conducting experiments exploring the relationship between metacommunity structure and coevolutionary patterns and processes using digital hosts and parasites in Avida, and a swimming bacterial host and phage parasite in the wet lab. This project will measure how metacommunity topology affects the evolution of ecological interaction networks that play a key role in organizing biodiversity in nature across space and time. They will also measure how global topologies as well as individual building blocks or motifs of metacommunities affect the evolution of local adaptation, the evolution of virulence, rates of evolution, and the evolution of sexual recombination. Doing so will allow a test of theoretical predictions about the role of migration rates, heterogeneous selection, and rates of evolution.

Maitreya Dunham (UW) and Ian Dworkin (MSU) are **examining the stability and lability of an interspecific mutualism using experimental co-evolution**. Much of the adaptive change observed within a given species is the result of interactions with other co-evolving species. Many such interactions are harmful to one of the focal species (e.g. predation & parasitism), while in other instances, both partners greatly benefit (e.g. mutualism & symbiosis). However, in some species interactions, the nature of the interaction varies considerable within and between populations. How such variation is maintained, and the degree to which it is evolutionarily stable, is generally unclear. Yet there is clear evidence for variation in such interactions, and this variation appears to be maintained over long evolutionary time spans. To address the evolutionary stability and lability of such systems, the team is using co-evolution between *Drosophila* and *Saccharomyces* yeast as their study system. *Drosophila* utilizes yeast cells as a nutritional source, yet yeast spores can survive passage through the *Drosophila* gut. Furthermore, yeast appear to use *Drosophila* as a method for dispersal, and potentially to increase outcrossing rates. The group is experimentally co-evolving both *Drosophila* and yeast, as well as evolving each species individually while constraining evolution on its partner to investigate how the pattern of variation between mutualism and exploitation evolves. They are also conducting digital evolution experiments in Avida to address these questions to determine under what conditions variation in this cross-species interaction can be maintained.

Kristina Hillesland (UW) and Tracy Teal (MSU) are investigating **how dependence of one species upon another evolves.** There are many examples of beneficial associations between

species, where at least one of the partners has lost the ability to live on its own. How do such associations evolve? The team is studying the repeated loss of a key function in populations of the bacteria *Desulfovibrio vulgaris* after evolution in conditions requiring cooperation with the methanogen *Methanococcus maripaludis*. *D. vulgaris* normally thrives independently of methanogens by coupling oxidation of lactate with the reduction of sulfate to sulfide. Previously, *D. vulgaris* was put in an environment lacking sulfate and other electron acceptors, forcing it to survive by transferring electrons to *M. maripaludis*. Within 1000 generations of evolution in these conditions, at least 12 of 22 evolved populations substituted loss-of-function mutations in genes essential for sulfate reduction. Molecular phylogenies of species specialized for interactions with methanogens suggest similar evolutionary events have occurred repeatedly in nature. To understand these phenomena, the team is testing whether simply deleting these genes provides a fitness benefit in direct competition with an unmodified strain. To assess the possibility of observing the loss of the sulfate reduction ability in a natural environment, they are also searching anaerobic digesters for loss-of-function mutations in genes for sulfate reduction.

Graduate student Octavio Campos (UW), under the supervision of Ben Kerr (UW), is **integrating rapid prototyping, machine vision, and experimental evolution to explore floral phenotype diversification.** Campos seeks to investigate the relationship between flower shape and pollinator foraging performance, and also how pollinator visitation influences the evolution of floral shape. This is being accomplished by using 3D-printed flowers whose shapes are mathematically specified by an equation with four shape parameters. The complexity of floral shape has been distilled into a few quantifiable characteristics: flower length, petal width, nectary width, and petal curvature. More parameters can be added to the equation to produce floral phenotypes of increasing complexity and sophistication (e.g. petal dissection, tilt, asymmetry and bilateral symmetry, etc.). With these techniques and technologies, Campos can construct populations of artificial flowers whose shapes are precisely known and that can be repeatedly made with great precision, and with great speed. These artificial flowers are then filled with artificial nectar (sucrose solution) and exposed to visitation and foraging by actual pollinators in the lab (hawkmoths). Careful observations of pollinator foraging behavior are made via video recordings and sensors that are triggered when an animal exploits the nectar source of a flower. These observations are then used to infer the strength and direction of selection by the pollinator for floral shape, and the effects of different flower shapes on pollinator foraging effectiveness/ability can be determined.

Heather Goldsby (MSU), Ben Kerr (UW), and Charles Ofria (MSU) are **studying major transitions in evolution using digital organisms**. Major transitions in evolution occur when formerly distinct individuals form a higher-level unit that functions as a single reproductive entity. These transitions can be fraternal, where genetically similar individuals (i.e., close kin) differentiate to perform various tasks, or egalitarian in which formerly distinct organisms create a super-organism that replicates all of its genetic material. A fundamental aspect of major transitions in evolution is the role of division of labor, where lower-level individuals specialize and cooperate as part of a higher-level unit to survive. These transitions raise evolutionary questions regarding the conditions under which formerly distinct individuals would cooperate with others, and once they did, how this arrangement persisted. An open biological question central to group formation is why are single-cell transitions ubiquitous? One potential advantage is that single-cell bottlenecks limit genetic variation and thus the number of potential cheaters within a multicell. Another potential explanation is that a single-cell provides a more stable

configuration for developmental patterns. Preliminary data obtained using digital evolution supports this second hypothesis.

Evolution of communication, cooperation, and group problem solving

Chris Adami (MSU) and Claus Wilke (UT) are using physics and mathematics modeling principles to investigate the **thermodynamics of evolutionary games**, such as the famous "Prisoner's Dilemma" game. In particular, they are interested in understanding the answer to the question, "**Why do we cooperate**?" The question appears to have an obvious answer: "Because it benefits everybody to do so!" While this response is true, it does not take into account a dilemma: if everybody cooperates, then it is beneficial for each individual to switch to noncooperation (defection). Thus, while cooperation is beneficial as long as everybody cooperates, it is also an unstable state. And indeed, the mathematics of game theory has shown that the rational behavior in this case is for everyone in the population to defect, as shown by Nash. If this is the case, then why do we observe cooperation in the biosphere, and more importantly, how can it even evolve? Evolution, after all, is only rewarding short-term benefits (such as those conferred by defection), and cannot act on long-term benefits. Recently, Adami's group has made progress by re-casting standard games so that they can be analyzed using tools from the statistical physics of non-equilibrium phase transitions. In this work, they considered games in which agents can choose between two different strategies ("cooperate" or "defect"), and this choice is represented as a "spin" vector that can interact with other spins. Then, whether or not the population evolves to cooperate or defect is recast in terms of the overall "magnetization" of the "crystal" of players (for example, "all spins up" means positive magnetization and therefore cooperation, while "all spins down" means defection, and negative magnetization). This team has thus recast the problem of figuring out when cooperation evolves as a problem to determine what affects the critical point in a ferromagnetic phase transition.

Chris Waters (MSU), Ben Kerr (UW), Ajai Dandekar (UW), and John Mittler (UW) are examining the **evolution of communication and cooperation in social systems**. Natural selection offers little room for cooperative behaviors, which necessarily involve a trade-off of individual fitness for the benefit of a group. Nevertheless, cooperative behaviors are common throughout nature. This team seeks to understand how communication and physical structure within populations might promote and stabilize cooperation. Inspired by bacterial chemical communication systems (i.e., quorum sensing) and structure formation (i.e., biofilm formation), the team is developing differential equation and agent-based models to investigate how these properties stabilize cooperative tasks, specifically: 1) to determine if communication stabilizes cooperation in a well-mixed environment and 2) to investigate the effects of spatial structure on cooperation. The results of these models will then be tested experimentally with microbial systems developed for this purpose, a marine bacterium, *Vibrio harveyi*, and a human pathogen, *Pseudomonas aeruginosa*. By using experimentally tractable mathematical and agent-based models and microbial systems, the results of this project will uncover fundamental principles underlying the evolution of cooperation.

In a related collaboration, Josephine Chandler (UW), Chris Waters (MSU), Ben Kerr (UW), Ajai Dandekar (UW), John Mittler (UW), and Marvin Whiteley (UW) are **exploring Hamilton's rule in quorum sensing systems**. Many bacteria use a population density-dependent communication system called "quorum sensing" to regulate cooperative behaviors. 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). Here Hamilton's Rule is used as a centering theme to address how quorum sensing promotes cooperation by altering cost, benefits and relatedness of the microbes in a community. The team is investigating each of these using a combination of mathematical modeling and molecular and evolution approaches in experimental model systems (*Pseudomonas aeruginosa*, *E. coli*, *Burkholderia thailandensis*, *Vibrio cholerae* and *Vibrio harveyi*).

MSU postdoc Jeff Morris, with Rich Lenski (MSU) and Ben Kerr (UW), is **investigating the Black Queen Hypothesis with mathematical and experimental approaches**. 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. Morris is testing 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.

Eric Klavins (UW), Ben Kerr (UW), and Charles Ofria (MSU) are studying **the evolution of suicidal altruism**. There are few traits that pose greater evolutionary difficulty than killing oneself for the benefit of others. However, altruism, even in forms that result in the benefactor's death, is frequently observed in nature. Many studies explore how altruistic traits can be maintained against defectors, which reap the benefits provided by altruists without paying costs. But much less has been done to explain how a tendency towards altruism increases over time. This team is exploring the conditions under which suicidal altruists evolve to become more altruistic using 1) the digital evolution platform Avida, 2) mathematical modeling in "gro", and 3) a biological (*Escherichia coli*) system. For 1), they are implementing an instruction in Avida that makes organisms produce a valuable resource but also kills them with some probability, and examining when and how this instruction is used under different resource distribution schemes. For 2), "gro" is used to systematically evaluate how stochasticity, parameter variation, cell density and nutrient concentration affect cell growth and proportion of altruists. For 3), they are using a strain of *E. coli* that has been engineered to switch between non-altruistic and altruistic states, where altruism results in suicidal production of a public good. The team is testing the hypothesis that structured populations, where benefits from altruists remain localized and there is positive assortment of altruists and defectors, lead to the evolution of higher levels of suicidal altruism. Because altruism in the engineered *E. coli* results in cellulose degradation, an increase in altruistic suicide could have profound applied significance for biofuel production.

Wenying Shou (UW), Ben Kerr (UW), and Charles Ofria (MSU) are exploring a **new hypothesis for the evolution of cooperation: "genetic niche hiking."** Genetic niche hiking begins with an exogenous stress completely unrelated to cooperation. This stress thins the population, allowing the clustering of like types. In structured populations, cooperators experience more mutational opportunities to adapt simply because cooperator, but not defector, populations can grow. This allows cooperators to competitively displace defectors. The team is testing this hypothesis both through computer simulation and through experiments with the bacterium *Pseudomonas aeruginosa*. In *P. aeruginosa*, the cooperating strain produces a public good, a protease exoenzyme that digests proteins, and a defecting strain that does not produce the

protease. On the computational side of the project, two students and a postdoc have developed a computational model that allows the genetic niche hiking process to be observed, and allows the examination of how robust the process is to changes in the cost of public good production, mutation rate, the number of possible stress tolerance mutations, carrying capacities of cooperator- and defector-only populations, migration rate, and metapopulation topology. Computational results show how stress can set the stage for the niche hiking process where a deleterious allele (public good production) is able to increase due to an association with the niche it creates.

Thrust Group 4: Evolutionary Applications.

Technological applications of evolution have become more prominent in BEACON, as has knowledge transfer, leading us to create a new Thrust Group as an umbrella for work that uses evolution as a powerful tool. Evolution is a generative process that has created diverse and complex biological systems, but fully harnessing that creative power has remained elusive. BEACON researchers are making advances in areas including (1) evolutionary algorithms; (2) artificial evolution of neural networks and Markov brains; (3) evolution-based software engineering; and (4) using evolution to create novel biomolecules. Below we describe 16 projects currently funded in this thrust group.

Evolutionary algorithms

MSU graduate student Brian Goldman is working with Bill Punch (MSU) to develop **real world applications of the Parameter-less Population Pyramid (P3)**. Real world applications of evolutionary optimization are often hindered by the need to determine problem-specific parameter settings. Parameters can have a significant impact on search efficiency and finding good settings can be very time consuming. While some previous methods have reduced or removed the need for parameter tuning, many do so by trading efficiency for general applicability. The Parameter-less Population Pyramid (P3) is an evolutionary technique that requires no parameters and is still broadly effective. P3 strikes a balance between continuous integration of diversity and exploitative elitist operators, allowing it to solve easy problems quickly and hard problems eventually. Goldman and Punch compared P3 with three optimally tuned state-of-the-art algorithms (thierens:2013:ltgahiff, doerr:2013:lambdalambda). Across seven problem classes, P3 always found the optimum at least a constant factor faster than the comparison algorithms. More importantly, on the three most challenging problem classes, P3 had a lower order of computational complexity as measured by evaluations. Based on over one trillion evaluations, these results suggest P3 has wide applicability to a broad class of problems. Next, the team plans to (1) integrate P3 into X-TOOLSS so it may be applied to new, practical problems, (2) use feedback from P3 X-TOOLSS applications to improve P3 and (3) expand P3's representation to Genetic Programming and explore its applicability to different kinds of problems.

Bill Punch and graduate student Armand Burks (both MSU) are developing **techniques for improving genetic programming by utilizing lineage diversity**. As availability of computing power grows, it becomes possible to analyze larger amounts of data in ways that were once intractable. One of the major advantages of Evolutionary Computation is that it allows the study

of evolutionary processes at a speed and scale that is not possible in nature. Tracking the history of genetic lineages in genetic programming enables a deeper analysis of evolutionary processes, which will ultimately lead to improved algorithms. The team is focusing on the following areas: (1) evolutionary history as an analysis and visualization tool for understanding and explaining evolutionary processes and phenomena, (2) designing novel evolutionary algorithms such as genetic diversity preservation techniques, and (3) improved and more informed evolutionary search.

Kalyanmoy Deb, Erik Goodman, and Ron Averill (all MSU) are working on **generative variable length genetic algorithms**. Optimization algorithms typically operate in a design space of a fixed-dimensional size, implying that each design is represented by a fixed number of variables. However, many engineering design problems call for a variable number of analogous components, such as wind turbines in a wind farm or layers in a composite laminate. The optimal number of components is usually not known *a priori* for such problems. 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. This team is investigating the use of genetic algorithms, and possibly other evolutionary algorithms, in solving variable-dimensional problems. In collaboration with the Composite Vehicle Research Center at Michigan State University, they are using variable-length algorithm findings to optimize the placement of graphene throughout composite plates in order to improve the impact resistance of the plates. Rather than developing an algorithm for this particular problem, they are developing a framework that will be useful on a wide class of variable-dimensional problems. To date, they have developed a variable-length genetic algorithm that successfully solves several testbed problems, and are working to improve it for wider applications.

Kalyanmoy Deb and Sandeep Kulkarni (MSU) are studying **multi-scenario optimization using evolutionary multi-criterion optimization for engineering problem solving**. Practical design tasks must aim to find a solution that is safe and optimized for not one, but multiple scenarios that arise from different operating conditions during its lifetime. For example, a solution of a bridge-structure design task must withstand: (i) different static vertical loads simulating different traffic conditions on the bridge, (ii) different dynamic wind loads simulating different hurricane or tornado situations, (iii) different dynamic loads due to earthquake or other possible natural disasters, and (iv) certain combinations of the above. Due to wear and tear, a successful design must also be considered for their functionalities both 'as-new' and 'as-old' conditions. Despite the practicalities involving multiple different scenarios affecting a design, their treatment in design optimization has not received much attention. To avoid complexities in the optimization process, objectives and constraints arising only from the worst scenario are usually considered, presuming that the design will then also be safe for any other scenario. Although this is true in general, such a design is not always desired due to a number of reasons; most importantly, it may be an overdesign for most other scenarios. To better use limited available resources, better optimized and more agile designs can be obtained using today's advancement in optimization methodologies. Deb and Kulkarni are treating multiple scenarios in single and multi-objective design optimization problems and developing systematic, efficient, yet pragmatic computational methodologies using evolutionary algorithms.

Kaushik Roy and Arun Ross (NCAT) are developing a **nonideal iris recognition method using evolutionary game theory and genetic algorithms**. Automated person identification systems based on iris biometrics have gained immense popularity due to their applicability to

many areas, including national border control, forensics and secure financial transactions. A large number of iris recognition algorithms mainly depend on the ideal iris images that are captured in a controlled situation to ensure high performance. However, in many cases, the iris image acquisition process may be affected by nonideal factors such as illumination variations, noncooperation of persons, head rotations, gaze directions, and camera angles, resulting in motion blurs, reflections, eyelash and eyelid occlusions, and pupil center deviation, and can hamper the segmentation performance. Iris recognition using such noisy iris images still remains a challenging issue. Roy and Ross are focusing on iris localization and feature extraction/selection using evolutionary approaches, including game theory-based curves and Genetic and Evolutionary Feature Extraction (GEFE) in an effort to improve the overall performance of iris recognition in an unconstrained situation.

James Foster (UI) and Gerry Dozier (NCAT) 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. Foster and Dozier are 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 have analyzed 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). They 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.

John Deller and Erik Goodman (both MSU) are working on **evolutionary algorithms for enhanced ultra-wideband microwave imaging of breast cancer tumors**. In collaboration with Meng Yao, BEACON Visiting Scientist and Professor of Engineering at East China Normal U. (ECNU) in Shanghai, they are engaged in a project that could revolutionize screening technology for breast cancer. The research is predicated upon the development at ECNU of an ultrawideband microwave transceiver system with impedance-matching characteristics that permit unprecedented penetration of microwave energy into the breast tissue. Many experts consider microwave screening infeasible, but the potential benefits of this diagnostic modality are so great that research persists after three decades of inconclusive results. BEACON work has resulted in the only published account of *in situ* breast scanning. The fundamental technical challenge of this project is the development of new evolutionary signal processing strategies for the detection of disease signatures in very low signal-to-noise breast scan data. A four-faceted research strategy is being pursued with the following component areas: 1) Innovative data conditioning and classical evolutionary computational approaches. 2) Set-theoretic-based evolutionary identification, detection, and filtering. 3) Application of BEACON-based work on Markov networks to breast cancer detection. 4) Refinement of the ultrawideband microwave

instrumentation. The ultimate goal is new technology for a safe, painless, and cost-effective test for breast disease. Success in the development of microwave breast scanning would significantly improve the experience of patients, and simplify and improve the accuracy of screening. This would almost certainly result in higher rates of screening as tests would be quick, comfortable, and virtually radiation-free. Early detection is the most significant factor in surviving breast cancer.

Artificial evolution of neural networks and Markov brains

Chris Adami, Wolfgang Bauer, Bill Punch, and graduate student Masoud Mirmomeni (all MSU) are developing **evolutionary computation for nuclear physics**. Recently, the U.S. Department of Energy has funded the construction of the Facility for Rare Isotope Beams (FRIB) on the MSU campus. In fact, construction of the $700 million project is taking place at the foot of the Biomedical and Physical Sciences Building, where BEACON is housed. FRIB will provide access to completely uncharted territory at the limits of nuclear stability, revolutionizing our understanding of the structure of nuclei as well as the origin of the elements and related astrophysical processes. This team recently developed an alternative to ANNs called Markov networks (or sometimes, "Markov brains") that can be evolved, instead of trained, and have shown that MNs can evolve to make fine-tuned decisions when navigating mazes or recognizing and catching objects of different sizes. In both cases, somewhat different input distributions can be associated with drastically different behavior, and they show readily that MNs outperform ANNs significantly in such a task. They also used MNs successfully on a much different classification problem: the recognition of handwritten digits encoded in a gray-scale image of 28 x 28 pixels. Because the prediction of nuclides has been shown to be similar to image reconstruction techniques, there are reasons to believe that MNs can make significant progress in predicting nuclear masses far from stability, thus paving the way for more efficient operation of FRIB, a flagship project in the physical sciences at MSU. They are currently testing the performance of Markov brains to predict nuclear properties far from stability, and plan to use the technique to predict "hard-to-predict" masses that are on the edge of closed shells in nuclei, where properties can change drastically.

Abdollah Homaifar, Dukka KC, and Gerry Dozier (all NCAT) are developing **biologically inspired solutions to computational problems**. This project is centered on modeling and identifying the dynamics of complex nonlinear systems using an evolutionary approach. The goal of system identification is to understand the relation between observed input-output data without having access to the dynamics of the system. The team is using a novel partially connected artificial neural network with evolvable structure (PANNET) to examine the exploration and exploitation capabilities of a new variable-length genetic algorithm. PANNET is a new paradigm for prediction of complex time series without any assumptions about the underlying dynamics of the systems. In contrast to traditional neural networks, the evolvable topology of PANNET provides flexibility in recognition of complex systems. The method is innovative, since in addition to observation at current time, the network has a set of hidden nodes which play the role of memory or internal states. The relationship between observation node and the hidden nodes are guided through the evolutionary process of variable-length genetic algorithm. During the training process, topology of the network including number of processing units, their corresponding connections, and connection weights are evolved to generate a network with efficient number of connections. Preliminary results for three of the most famous

benchmarks problems, including Wolf's sunspot number, the Canadian lynx, and the British pound/US dollar exchange rate, show the efficiency and relevance of this approach for prediction of real-life time series.

Gary Lebby and his graduate students (NCAT) are **using neural networks for controlling electric energy systems**. This research group is working on several developments of biologically inspired methods, involving the design of an energy manager, for coordinating the operation of a hybrid renewable residential micro-grid and energy storage control for a multi-fuel plug-in hybrid electric vehicle (PHEV). Flexible optimization procedures that minimize the cost of renewable distribution generators based upon the climate and location of the load profile have been developed and modeled in simulation. A novel design of a dual channel converter system and its control system forms the distributed energy storage (DES) system that features the capability of balancing the power flow in the micro-grid (even in the grid-off mode). The proposed energy management system utilizes a back propagation neural network in order to predict the state of charge (SOC) of the DES, yielding the reference value of control variables, which allows the micro-grid to respond to the desired operation conditions rapidly with acceptable controller error. Preliminary results indicate that the DES system allows for the implementation of energy management strategies in a technically viable manner and energy management in FPG-driven PHEVs remains strongly dependent upon the electric energy storage capacity.

Evolution-based software & robotics engineering

Gerry Dozier (NCAT) and collaborators are developing a **Malware Cyber Attack Advisement Tool**. Malware is an ever-present threat online. Many attempts have been made to create tools to classify web pages by their malicious content and many of these tools are commercially available. In collaboration with the Center for Advanced Studies in Identity Sciences (CASIS), the Cyber Crime Technology program at Guilford Technical Community College, the Information Systems Security Association (Triad of North Carolina Chapter), and Secure Designs, Inc. Dozier and his students are developing a Malware Cyber Attack Advisement Tool (MalwareCAAT) that will allow users to detect a malicious website before it can affect their system.

Erik Goodman (MSU), Erik Runkle (MSU), and Lihong Xu (Tongji University, Shanghai, China) are working on **greenhouse optimization using evolutionary computation**. The goal of this project is to develop greenhouse climatic control strategies that balance between maximizing yield and minimizing resource consumption. The team is using NSGA-II, a multi-objective evolutionary algorithm that performs Pareto optimization, which does not have a bias for one objective over another, thus allowing the exploration of a wider part of the solution space. Models of greenhouse environment and crop, which are used to drive and to validate the control strategies, have been developed and are being used to improve greenhouse controller design.

Terence Soule (UI), Robert Heckendorn (UI), Philip McKinley (MSU), Justin Zhan (NCAT), and Scott Harrison (NCAT) are developing **distributed, onboard evolution in a robotic cloud**. Distributed smart systems are networks of smart components – components that make autonomous decisions based on available data in a predictive or adaptive manner, thereby performing "smart" actions. Such systems include smart traffic systems, smart power grids, smart buildings, and, most notably, networked autonomous robots. Because distributed smart

systems must address situations not anticipated during development and must adapt to changing conditions in real-time, adaptability, resiliency, and safety are critical requirements. The goal of this project is to 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. 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.

Terence Soule (UI), Robert Heckendorn (UI), Gerry Dozier (NCAT), Peter Fuerst (UI), and Deborah Stenkamp (UI) are working to apply **genetic and evolutionary feature extraction for evolutionary robotics**. The Genetic and Evolutionary Feature Extraction (GEFE) techniques developed in Dozier's lab are being applied to the problem of robot navigation using evolutionary robots developed by Soule and Heckendorn. The project is also informed and motivated by open questions regarding adaptive explanations for the structure of the retina, through collaboration with Stenkamp and Fuerst. The computational time required to process images to detect roads, obstacles, signs, etc. remains a bottleneck for vision-based robotics. GEFE reduces image processing load by using evolution to find the significant regions of an image for a given task. The team is testing GEFE's ability to improve performance and reduce image processing load, thereby freeing resources for the evolutionary algorithms. Data from the robots have been sent to NCAT as experimental data, from a novel problem domain, for refining the GEFE algorithm. It is widely assumed that in biological organisms variations in retinal structure (e.g. cone densities) are evolutionary adaptations to environmental or behavior need, but in many cases there is no clear adaptive explanation for a particular organism's retina structure. By presenting the evolving robots with different tasks and/or environments and then evolving both the regions of interest and the neural network control structure `behind' those regions the group will be able to study relationship between the task, environment, robot morphology and the evolution of retinal structure.

Xiaobo Tan and Kalyanmoy Deb (both MSU) are working on **robust multi-objective evolutionary design of artificial lateral line systems in robotic fish**. The lateral system is an important hydrodynamic sensory system for fish. There is growing interest in engineering artificial lateral lines, consisting of arrays of flow or pressure sensors, as a new noiseless sensing modality for underwater robots and vehicles. Optimal design of artificial lateral lines is faced with significant challenges due to the sophisticated flow-structure interaction dynamics and the vast design space. This project aims to address these challenges by exploring evolutionary design methods for artificial lateral lines. The long-term goal of this effort is to establish a novel, robust, multi-objective evolutionary design framework for bio-inspired artificial lateral line systems. Specific goals of the current project include: (1) exploring design mechanisms that ensure the robustness of the resulting design in the presence of noises and system uncertainties, (2) developing design methods that accommodate multiple, potentially conflicting objectives, and (3) experimentally validating the approaches with ionic polymer-metal composite (IPMC)-based lateral line systems.

Using evolution to create novel biomolecules

Several synthetic biology projects previously described in other research thrust groups could also be categorized here; we currently list one project that doesn't fit in other groups. Jeff

Barrick (UT) and postdoc Colin Brown (UT) are studying the **evolutionary origins and engineering applications of bacterial DNA secretion machinery**. The controlled secretion of DNA into the extracellular milieu by bacteria in a way that does not involve cell death by lysis is a newly discovered function known from only one example. The evolution of DNA secretion systems is puzzling from an evolutionary standpoint, as conjugative transfer directly to recipient cells seems to be a more efficient way for genes to spread through a population. It has been proposed that the existence of such systems may be explained by a "selfish gene" mechanism in microbes that are competent for DNA uptake, but this model is difficult to test with only one example. In addition, DNA secretion systems have a wide range of potential bioengineering applications, including signaling systems for multicellular biocomputing, dynamic control of bacterial community structure, and cell-mediated construction of DNA nanostructures. Barrick and Brown are addressing both the evolutionary and engineering aspects of DNA secretion by (a) constructing an assay system to select DNA-secreting mutants from conjugative plasmids, in order to explore the mutational pathways from conjugation to secretion while also yielding a set of generalized DNA secretion plasmids for use in engineering applications and (b) exploring the natural diversity of DNA secretion systems by using comparative genomics to identify systems similar to the known case from sequenced bacterial genomes, and by using environmental sampling in combination with our assay to identify novel bacterial species capable of DNA secretion by other molecular mechanisms.

2b. Progress towards metrics listed above.

Integrative Research Goals

1. New research collaborations and proposals

- Of the 60 projects currently underway, 35 are new projects and include new collaborations.
- 136 publications submitted this reporting period, of which about 57% are categorized as multidisciplinary and 45% can be categorized as multi-institutional
- Many projects include funding for students/postdocs/faculty to travel between partner institutions.

2. New paradigms for research in organic and digital domains

- Number of new sessions at scientific meetings or scientific meetings hosted at BEACON: 3
  - Rob Pennock and Louise Mead organized the Education Symposium at the Evolution 2014 conference. The title was "Assessing Undergraduate Student Understanding."
  - Louise Mead organized the 2014 NESCent/BEACON Evolution Symposium at the National Association of Biology Teachers (NABT) meeting that will be held Nov. 14 in Cleveland. The title is ""Evolution in Action!" BEACON speakers scheduled at this symposium are Rob Pennock, Danielle Whittaker, Zachary Blount and Terrence Soule.
  - Rob Pennock was on the organizing committee for the 2014 Life Discovery - Doing Science Education conference which was held Oct 2 - 5 in San Jose (http://www.esa.org/ldc/), sponsored by Ecological Society of America, Botanical Society of America, Society for Economic Botany and Society for the Study of

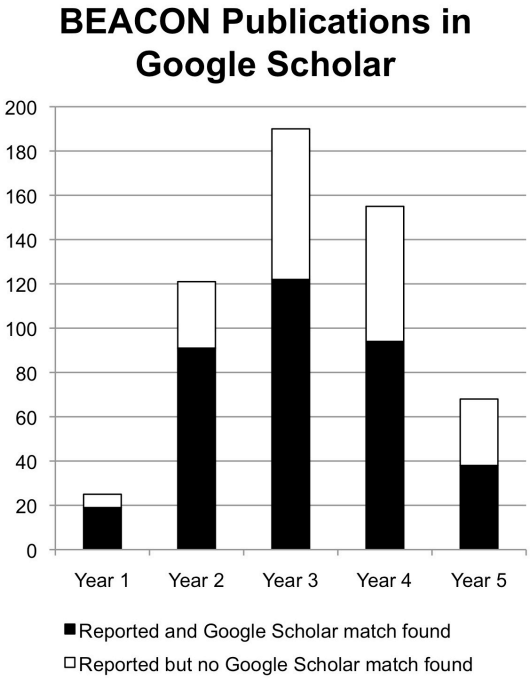
Evolution. The theme of the conference this year was "Realizing Vision and Change, Preparing for Next Generation Biology" and included "Evolution in Action" as one of the three major topics.

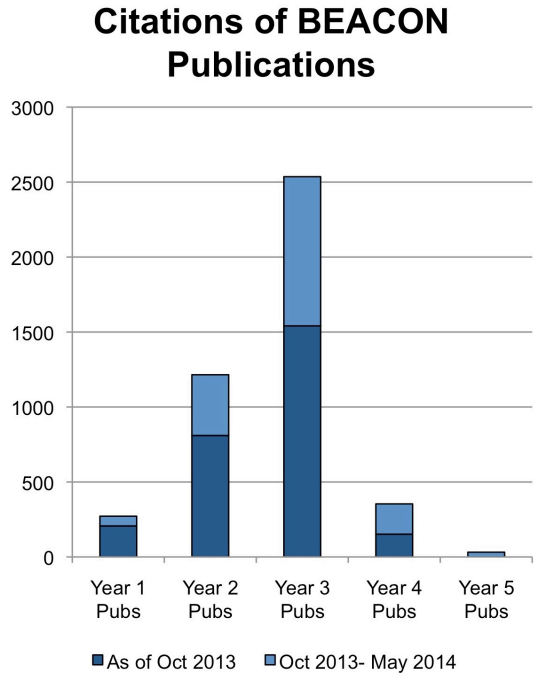
- Additionally, in the past year BEACONites have had a very visible presence at several international scientific meetings. BEACON had a booth at 4 conferences. Evolution 2014 featured dozens of BEACON talks. Over a dozen BEACONites reported giving plenary addresses at a broad range of conferences, including Chris Adami, Jenny Boughman, Titus Brown, Erik Goodman, Christopher Marx, Danielle Whittaker, and Claus Wilke.
- In the previous reporting period, there was one additional symposium that was not included in the 2013 annual report. At the 2013 SSE meeting, co-PI Richard Lenski organized a well attended symposium titled "Everything You Always Wanted to Know About Evolution But Never Thought to Ask." It had a strong BEACON flavor with a focus on new ways of studying evolution and new questions about evolution. The six speakers included BEACON co-PI Kay Holekamp (on the evolution of intelligence) and two BEACON external advisory board members Joan Strassmann (on social evolution) and Josh Bongard (on evolutionary robotics); the other talks were on the origin of life, resurrecting ancient proteins, and evolutionary medicine.

- 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 68 proposals for over $60M of external funding, and >$12M in external funding has been granted.

3. Increase in publications related to evolution in action

- Number of publications: 136 publications submitted by BEACONites to date in the current reporting period
- *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 below summarizes the results as of May 2014, when these statistics were compiled for our renewal proposal. 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. Moving forward, we have revised the goal for number of publications, and will now aim for an increase of 10% over the previous year each year.





- High visibility science journalism about BEACON research: Since our previous annual report (November 1, 2013) we put out 12 press releases. Over 68 features on BEACON research appeared in the mainstream and online media since then, including ABC News, NPR, NOVA, *Wired*, *The Economist*, *The Scientist*, and *Scientific American*.

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

- 20,457 downloads of Avida-ED since the previous report
- over 3,500 downloads of Avida since the previous report
- over 3,400 visits to BEACON website monthly, where all resources are linked
- C. Titus Brown and Tracy Teal are 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 20, 2014, over 75% of participant trainees have reported completing the required training. We anticipate that our goal of 100% will be reached by December 2014.
- 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. Several workshops have been run at BEACON since summer 2013, especially at the BEACON Congresses. New modules are being designed and refined.
- 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

- Scientific Virtues sessions have been offered multiple times (in 2014, 2 at Friday seminars and 4 at Congress) and will continue to be offered.

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

- Toolbox/Scientific Virtues sessions have been offered multiple times (in 2014, 2 at Friday seminars and 4 at Congress) and will continue to be offered.

Research Output Goals

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

- Number of publications submitted: 136 reported to BEACON February-October (goal is 150 per reporting period, February-January)
- Conference presentations: 115 reported (goal is 150)
- Grant proposals submitted: 68 submitted (goal is 40)
- Our ongoing goal is 150 publications, 150 conference presentations, and 40 grant proposals submitted per year in the first two years. These goals were not met in 2011 – likely due to underreporting by BEACON members – but have been met annually since then. Our original goal was to increase these numbers by 50% by October 2015, which has been achieved already for conference presentations and grant proposals. Our new goal for phase 2 of BEACON funding is to double the original numbers: 300 publications, 300 conference presentations, and 80 grant proposals submitted per year, by October 2020.

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

- Fourth External Advisory Committee meeting was held August 2014
- 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 2015. We will hold our project selection process for Year 6 (see explanation in VII. Management) in February 2015 in order to choose projects that will begin in August 2015, after the grant renewal. We do not anticipate any further 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	This year, 21 BEACON students reported receiving degrees (13 PhD's, 6 Master's, 2 Bachelor's). Of the PhD graduates, 54% are currently in postdoc positions, 15% are in faculty positions, and 15% are working in industry. Information on former postdocs has been harder to gather, but of 5 MSU postdocs who left BEACON this year, 3 took faculty positions, 1 took a

		postdoc at a different institution, and 1 is working in industry.
Increased public literacy in evolution and the nature of science	Development of educational materials.	Testing, presentation, and 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. Dr. Hintze has been continuing to offer this course in this fashion, and we are waiting to receive the final evaluation. We also did not offer the *Evolutionary Biology for Non-life Scientists* during the Fall 2014 semester because of low student enrollment. We suspect this reflects two issues: (1) a number of computer science students have already received training in evolutionary biology; (2) few graduate students admitted to computer science and engineering programs and identified to work with BEACON faculty this year. We do not anticipate this will continue to be an issue in future years, but we will identify possible mechanisms for recruiting engineering and computer science students specifically if this issue persists.

External education activities: The greatest challenge comes in assessing our effectiveness at meeting our goals related to increasing public understanding of evolution and the nature of science. Many of our external outreach activities are designed to be short and highly interactive. It is difficult to assess what learning occurs. We do, however, use these opportunities to test the operations of the activities we develop, and from that perspective, these can be viewed as successful as they give us an opportunity to work out the bugs.

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 (MSU's 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 the course sequence, relative to our training objectives. Results of the evaluation appear at the end of the course descriptions below.

Activity Name	**Interdisciplinary Graduate Education**
Led by	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: The class is taught simultaneously at three different BEACON locations (MSU, UT Austin, UW) using the teleconferencing system. Due to the short overlap of the schedules, the class is a 10-week course, with a 2-day ramp up workshop, which is broadcast as well. Based on the feedback and discussions from 2013 the class was further adjusted to match the demand of students to be more self-sufficient with programming and doing the research associated with the interdisciplinary BEACON class. This class emphasizes programming in the first 5 weeks and teaches students Python and iPython-notebook. The second half of the class is about computational modeling and data analysis, and deepens the students' programming skills further. The 2014 class has 22 students, of which two are from UW and one is from UT Austin.

Evolutionary Biology for Non-Life Scientists: ZOL 890-601 is being taught during fall semesters at Michigan State University. Four students from Michigan State University and one student from University of Idaho completed the course in Fall 13. We are not offering the course during the Fall 14 semester due to low student enrollment. 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 to construct and test evolutionary hypotheses; (3) be excited about evolutionary biology; (4) be able to explain evolutionary biology to non-scientists; (5) recognize what they do not know about evolutionary biology and develop strategies to complete their knowledge. Students generally report that the instructor exceeds all evaluation criteria. During the Fall 2013 course offering, we provided professional development for two graduate students at BEACON (Caroline Turner and Emily Weigel) who co-instructed the course with Dr. Louise Mead. The instructional team received the AT&T Faculty-Staff Instructional Technology Award for Best Enhanced Course.

Multidisciplinary Approaches to the Study of Evolution: In Spring 2014, 15 students enrolled in the course, and 3 additional research staff members audited and participated in all class activities. The course provides an introduction to engaging in multidisciplinary 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 multidisciplinary 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 (as decided by both students and faculty) are then selected as group projects. The class selected and tackled 6 projects in teams of 3 students: (1) Early Evolution of Associative Memory; (2) Signal Attenuation: The Role of Pheromone Evaporation in Cooperative Foraging Strategies; (3) What Causes the Difference between "Fit" and "Flat" Populations?; (4) Conspicuous Computation: The Handicap Principle and Sexual Selection; (5) Does Spatial Resource Heterogeneity Increase Evolvability?; and (6) Adaptive Radiation in a Fluctuating Environment. All 6 final project reports were turned in formatted as a submission to a PLoS journal. Four of the 6 manuscripts are still in active preparation for submission. Three of the 4 papers from the previous years's class have now been published.

Dr. Claudia Vergara of the Center for Engineering Education Research (CEER) at MSU leads the external evaluation of the BEACON graduate course sequence. Her report for the 2013-2014 year is in preparation. As we proceed with the fourth year of evaluation, we will be interviewing the instructors for these courses, as well as following up with all students who have completed the spring course, requesting details on whether and how their BEACON training has influenced their research plans.

Activity Name	**Materials and Workshops for Cyberinfrastructure Education in Biology**
Led by	C. Titus Brown and Tracy Teal (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.

Training in data analysis and management was identified as a strong need at a meeting of informatics staff from the NSF BIO Centers (CollabIT) in 2013. While Software Carpentry workshops exist to teach software development best practices, there were no workshops teaching data best practices, and in particular none aimed at people with little or no prior computational experience, and none that were biology-focused. As this was a shared need, people from SESYNC, NESCent, iDigBio, iPlant and BEACON worked together to establish course objectives and develop materials for a Data Carpentry workshop. Based on surveys conducted across the NSF BIO-funded centers, we defined the following overall learning objective for the workshop: researchers should be able to (1) retrieve, (2) view, (3) manipulate, (4) analyze and (5) store their and others' data in an open and reproducible way.

To attain this objective, Brown and Teal developed the following training modules.

- How to use spreadsheet programs (such as Excel) more effectively, and the limitations of

such programs.

- Getting data out of spreadsheets and into more powerful tools --- using R or Python.
- Using databases, including managing and querying data in SQL.
- Workflows and automating repetitive tasks, in particular using the command line shell and shell scripts.

Funding from the supplement supported the first Data Carpentry workshop at NESCent, May 8-9, 2014 (http://software-carpentry.org/blog/2014/05/our-first-data-carpentry-workshop.html). Instructors who developed and taught the material were from NESCent (Hilmar Lapp and Karen Cranston), BEACON (Tracy Teal) and Utah State University (Ethan White). Assistants were from SESYNC (Mike Smorul), iDigBio (Deborah Paul and Matt Collins) and iPlant (Darren Boss) reflecting the broad participation and interest in these workshops. The supplement also supported Tracy Teal from BEACON to continue development of materials and workshop organization. Three more workshops have since been run at SESYNC, BEACON (http://datacarpentry.github.io/2014-07-24-beacon/) and iDigBio (https://www.idigbio.org/wiki/index.php/Data_Carpentry). Workshops have been filling within hours of being announced and have received very positive feedback. The team developed formative assessments for the iDigBio workshop that can be used in future workshops to better assess learning outcomes and synthesize feedback from the courses. Teal and Jason Williams (iPlant) are working to develop a genomics-focused workshop.

From these initial workshops, Data Carpentry has become an independent organization. Teal, through BEACON, received an award from the Moore Foundation to continue to develop the workshops and run them more broadly. Data Carpentry has 7 upcoming workshops scheduled and is growing a pool of instructors and expanding its domains to include not only genomics, but also geoscience, neuroscience, social science and economics. Teal also is submitting an NIH R25 to support the modularization of lessons into videos for just-in-time delivery of content.

Funding from this supplement also supported Kevin Wall, a graduate student in BEACON to assist with development of Data Carpentry materials as well as in another course providing computational training to microbial ecologists - Explorations in Data Analyses for Metagenomic Advances in Microbial Ecology (EDAMAME). This course was developed and run by BEACON faculty member Ashley Shade with co-instructors from BEACON Teal and Josh Herr. This intensive one-week summer workshop taught attendees the computational approaches necessary to ecologically analyze microbial communities using next-generation sequencing data. This course was well received and will be offered again next year. Shade and Teal submitted an NIH R25 to support the continued development and running of the course.

Activity Name	**Undergraduate Education in Computational Evolutionary Biology**
Led by	Claus Wilke and Art Covert (UT)
Intended Audience	Undergraduates
Approximate # of attendees	24

Drs. Claus Wilke and Art Covert continue run the computational evolution stream of the University of Texas Freshman Research Initiative (FRI). The Computational Evolution (CE) research stream is a year-long inquiry-based class for undergraduate students. In this class, freshmen and sophomores learn to conduct computational research using *in silico* experimental

evolution with digital organisms as a model system. In the spring semester, freshmen take a lab-based course taught as an inverted-class model, to learn the core competencies of computational research and constructing and testing a well-reasoned hypothesis. In the summer and fall semesters, students carry out individual research projects, supervised either by Dr. Covert at UT or a graduate student at a BEACON partner institution. At the completion of the stream, students have worked on a research project intended for publication, and have gained extensive experience in programming, data analysis, high-performance computing, and evolutionary biology. BEACON support is allowing the instructors to focus on three new long term goals, in addition to the on-going research projects: (1) assessing teaching techniques with a focus on how well students accept evolution as an active ongoing process; (2) student-driven development of software tools for simulating and analyzing *in silico* evolution and sharing these tools with BEACON partner institutions; (3) offering undergraduate students a complete research experience by visiting BEACON labs at partner institutions and participating in scientific conferences as well as the BEACON Congress.

In the spring 2014, Dr. Covert taught the FRI (Freshman Research Initiative) course to 30 UT undergraduates. During the summer of 2014, 3 FRI students visited MSU for the summer, and two are continuing their work this fall. In addition, 2 students from NCA&T were hosted at UT Austin. Nine undergraduates from the stream attended the BEACON Congress. In the fall of 2014, Covert is teaching the follow-up FRI course to 17 UT undergraduates. 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	7

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 2014, a diverse pool of applicants was again attracted to the KBS REU/URA program. Although the total number of applicants decreased, both the number and percentage of applicants who identified as African-American and first-generation college students increased. BEACON funding supported seven students in the KBS REU/URA program in 2014: four URAs (two from MSU, two from HBCUs) and three REUs. One student left the program early, so we recruited a student who was able to participate until September and complete that project. All students participated in professional development that included RCR training, and presented their

research at an Undergraduate Symposium at KBS; several plan to present their research at their home institutions as well.

BEACON provided training in mentoring for the graduate students and postdocs involved in this program as part of an Academic Success seminar offered in Spring 2014 and in two meetings over the summer. We (re)submitted a NSF REU site proposal in August 2014: *Ecological and Evolutionary Dynamics in a Changing World: A scaffolded undergraduate research experience.*

Evaluation of the program is continuing; we are using an assessment tool developed by the National Science Foundation to survey the recent participants in the KBS REU/URA program. This tool compiles and compares data for NSF-funded REUs sites nationally.

Activity Name	**Avida-ED Controlled Assessment Study**
Led by	Robert Pennock, Jim Smith, Louise Mead, Wendy Johnson (MSU)
Intended Audience	Undergraduates
Approximate # of attendees	150

This project is a continuation of the current Avida-ED Curriculum Development and Assessment Study that was largely the dissertation research of Dr. Amy Lark. In response to efforts to obtain external funding for further dissemination and research with Avida-ED, NSF reviewers requested a controlled experiment. The major research aim for this study is to determine how well Avida-ED helps students achieve key learning objectives related to understanding evolutionary mechanisms. The study population is made up of undergraduate students in the Lyman Briggs Residential College at Michigan State University. The team hypothesizes that students exposed to Avida-ED will be able to predict whether (and explain why) mutations in populations growing under positive selection will first appear earlier, later or at the same time as mutations in populations growing under neutrality (no selective advantage). The second hypothesis addresses student understanding of why (and how) mutations that arise in populations experiencing positive selection are more likely to persist and become more frequent in these populations than mutations that arise in populations growing under neutrality. They conducted a controlled experiment in two sections of LB 144: Organismal Biology, one teaching some evolutionary concepts using Avida-ED and one teaching the same material without it. The main data collection and preliminary analysis is in progress but preliminary analysis suggests significant gain in student learning in the Avida-ED classroom for the core evolutionary concepts we investigated. This group is also continuing to explore the effects of Avida-ED more deeply. They have developed a lab manual with a series of exercises for Smith's course, and are piloting it this semester. In addition, BEACON seed funding has now resulted in the procurement of two major grants. The first, a five-year grant from Howard Hughes Medical Institute (HHMI), funds continuing software and curriculum development and testing as part of implementation of Avida-ED in gateway biology courses at MSU. The second, a five-year grant from NSF, funds development of major new user-requested features in Avida-ED plus concomitant curricula and instructor-support materials; a series of national faculty development workshops, and a series of national assessment studies.

Activity Name	Assessing Student Perceptions & Explanations of Microbial Evolution
Led by	Alita Burmeister, Richard Lenski, Jim Smith (MSU)
Intended Audience	Undergraduates
Approximate # of attendees	50

Evolution is a core concept for biological literacy at the undergraduate level. However, evolution is often overlooked in microbiology classrooms. Evolution instruction especially lags in laboratory-based courses where the inertia is strong due to the effort involved in revising curricula. The team used a theme of antibiotic resistance and evolutionary applications in an upper-level undergraduate microbial genetics laboratory course with the goals of (1) increasing students' ability to explain the details of evolutionary microbial genetics and (2) increasing students' acceptance and valuing of microbial evolution. Instructors presented core concepts and applications of microbial evolution during the course's weekly lecture. One half of the class also completed a three-week *E. coli* evolution experiment ("treatment" group) while the other half completed only the traditional exercises ("control" group). Instructors assessed the effectiveness of these activities using pre- and post-attitude surveys and open-ended content questions about microbial variation, inheritance, and selection. Students in both groups highly accepted and valued microbial evolution at the beginning of the semester and had slight but nonsignificant positive attitude gains at the end of the semester. Surprisingly, scores on the content questions did not improve by the end of the semester for either group. This result may be due in part to a lack of grade-based incentives and students' seemingly less earnest attempts on the post assessment. Of greater interest to microbial evolution curricula and assessment, the group also observed the potential for traditional microbiological instruction to inadvertently reinforce misconceptions and confound definitions of the key terms "variation" and "selection." To develop suggestions for teachers to avoid these issues, they continue to investigate subdiscipline-specific definitions and language use.

2b. Professional development activities

Activity Name	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 Implementation 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." 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." Through BEACON seed funding, and now a Templeton Foundation grant, Pennock and his team are coordinating a national SV survey on the ethical views of scientists about the scientific character of virtues, and developing presentations, workshops, and Toolbox-style modules (Eigenbrode et al. 2007) that embody this virtue-based approach. They are continuing to pilot test these modules in BEACON weekly

meetings and the annual Congress, which will also help grad students and post-docs fulfill their RCR requirements.

2c. External education activities

Across our consortium, BEACONites are engaged in education and outreach efforts, both formally through the development and testing of novel tools, lessons, and curriculum, as well as more informal efforts through participation in community and public outreach events. In all cases we aim to provide participants with an experience of evolution in action – showing them that evolution is an ongoing process happening now, that evolution can help us solve complex problems, and that evolutionary science is a good example of how science works.

Activity Name	**A Learning Laboratory for Pre-service Teachers to Understand and Teach "Evolution in Action"**
Led by	Katherine Gross, Louise Mead, David Stroupe, Kara Haas (MSU)
Intended Audience	Undergraduate pre-service teachers
Approximate # of attendees	(in prep)

This project will provide pre-service teachers with field-based research and educational experiences at the Kellogg Biological Station (KBS) that combine course work in ecology with discussions of how ecological processes lead to evolutionary change in a program that is designed to give them a deeper understanding of how ecological processes contribute to evolutionary principles. By being in residence at KBS, these pre-service teachers will be part of a 'living and learning community' that includes students and faculty interested in ecology and evolution. The team expects that pre-service teachers exposed to this environment will use their experiences at KBS to teach evolution more effectively. A unique feature of the program will be the inclusion of a practicum experience for the pre-service teachers working with in-service teachers, along with faculty in ecology and teacher education, to develop curricular materials (classroom examples, laboratory, field exercises or computer labs) that demonstrate "evolution in action" and address performance expectations that meet current Michigan Content Standards and Benchmarks and Next Generation Science Standards for middle (life science) and high school (biology) science curricula.

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

For the past four years, BEACON has offered the BEACON High School Summer Institute Residential Program by teaming up with Michigan State University (MSU) College of Engineering Recruitment, Scholarships, and K-12 Outreach. The weeklong summer program focuses on exposing a diverse group of high-achieving high school students to concepts, activities, and tools related to evolution-in-action, with activities and lessons on evolutionary biology, computational science, and engineering. The intent of the program is to explore the variety of educational and career opportunities within BEACON-related fields and STEM. The

program emphasizes the value of research and focuses on demonstrating how students can participate in STEM despite varying interests and perspectives.

The program was held July 6-10, 2014 at Kellogg Biological Station. The program focused on three main areas: (1) BEACON-related: natural selection, predation, simulating evolution, biosystems evolution, computer engineering, and related software (e.g., BoxCar2D); (2) Research-related: statistics, giving research presentations, research poster design; (3) Education and Career related: high school and college course requirements, MSU admissions, MSU Honors College. Of the 26 students who attended in 2014, 17 (65.38%) were female and 10 (34.62%) were male. Six students (23.08%) were entering grade 11, 14 (53.85%) were entering grade 12, and 6 (23.08%) were entering college. An external evaluation and subsequent report appears below. The majority of students (92.3%) rated the program *good* or *excellent*. When asked if they would recommend this program to a friend, 21 (81%) students said, "yes," four (15%) students said they would but added qualifiers specific to biology; one said, "I recommend it to students that are passionate about biology," and the other said, "Depending on what they were interested in; the program did not fit what I was looking for" and another student commented "This program has offered a great experience to me and has definitely open up my eyes as to how college works and also validated my intention on studying engineering."

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 6 – 10, 2014

Kellogg Biological Station

Summary

The evaluator communicated via e-mail with College of Engineering staff, BEACON Education Director and EHRD Chair, and instructors to discuss the program agenda, objectives, and outcomes. The evaluation plan was based on this discussion, as well as, the 2013 program evaluation report. Data collection was collected in three stages. On the first day of the program, students completed an online survey designed by the evaluator. The pre-program survey was intended to gather demographic information, demonstrate students' knowledge about evolution, and ascertain their expectations for the week.

When the program concluded, students completed a post program online survey, designed by the evaluator. The survey included the same evolution-related questions as the pre-program survey and their responses are used in this report to illustrate any change in evolution-related knowledge students experienced as a result of the program. Questions related to students' satisfaction with the program were also asked.

The final phase of data collection involved soliciting feedback from program staff (administrators, instructors, and undergraduate mentors). Feedback was collected through an online survey program and was anonymous. 12 surveys were completed, with most of staff providing feedback.

Having reviewed student responses to pre- and post-program surveys, along with feedback from senior program staff, we are able to make a number of recommendations about the BEACON summer program. Anecdotal comments from program staff indicated this year's summer program included a

number of improvements based on experience and recommendations coming out of the 2013 program. Overall, students were satisfied with their experience and it seems there is a good foundation for this program. Although this specific program will not be continuing, specific recommendations can be used for similar programs.

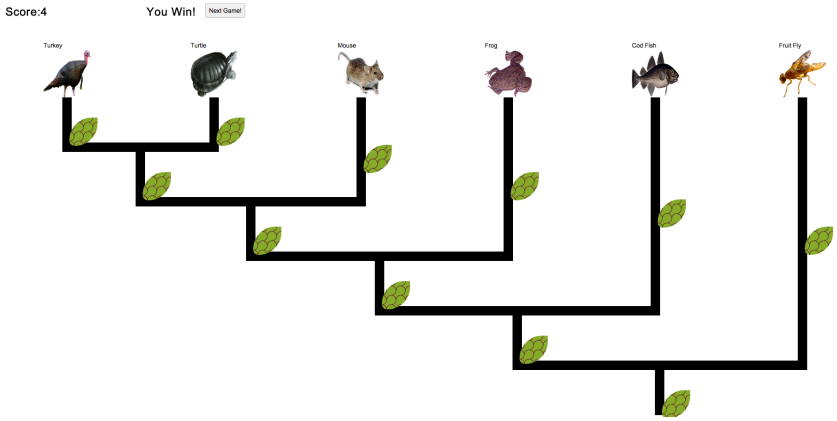
Activity Name	**Continuation for Podcast**
Led by	Randall Hayes (NCAT)
Intended Audience	K-12 Teachers
Approximate # of attendees	~ 90,000

As of September 2014, 68 episodes of *VSI* have been produced. Year 3 Guests have included 2 academic scientists at various stages of their careers, as well as students. Hayes 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 3700 times, and hits to the blog site are accelerating. Subscribers alone have accessed the web page 128,854 times, and before Podbean stopped publishing web hits, this site registered over 250,000. The website has been visited by people from at least 50 countries, on every continent except Antarctica. The BEACON website reposts links to all blog posts and episodes. The podcast also has a Facebook page (facebook.com/vsibeaconpodcast) that provides an opportunity for Dr. Hayes to engage his students.

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 focused on the development of 2 digital educational games on the topic of evolution. The games address several "intuitive" but inaccurate conceptions of evolution, and cover topics that are relevant to BEACON research (epidemics; phylogenetic inference). The games were designed with simple, appealing interfaces to enhance interactivity in museum evolution exhibits and other informal learning settings. The project directly addresses several BEACON goals: (1) to teach fundamental concepts of evolution and watch it "in action", (2) to introduce the public to BEACON research projects, (3) to provide multidisciplinary training to graduate students, and (4) to encourage people's understanding and acceptance of evolution in informal learning settings (at museums and online). The goals and steps of this project were to: (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 the development of the games and share them with the public through installations in museum exhibits and/or on museum websites. Versions of the Clickademic game

have been finalized (with Dr. Tom Hladish) that will be compatible with Windows and OS X operating systems. UT graduate students Laura Crothers and Ammon Thompson developed a beta version of the Treethinking game that was presented at a large public outreach event in Austin (*Hot Science, Cool Talks*). They collected survey data and recorded observations of people of various age groups as they played the game. The evaluator (Beth Jonson, of EMJ Associates), aided in performing and analyzing our formative evaluations of the TreeThinking game. Using the feedback provided by the public, Laura Crothers and Ammon Thompson created a tutorial for the TreeThinking game and worked with the digital design company PowersCombined to put together a final version of the game (http://evotreethink.appspot.com/). The completed tutorial for the game is being integrated into the website this fall.



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.

Mead, Kjelvik, and Schultheis are working with science education researchers to develop our assessment of Data Nuggets. They wrote and received a grant from NIMBioS to hold a Working Group at their institution to bring together science education researchers, teachers/professors, mathematicians, and biologists. During the workshop, scheduled for January 7-9th 2015, they will identify a quantitative learning progression for K-16 students, create an assessment to determine how Data Nuggets help move students through this progression, and adapt Nuggets for use in undergraduate classrooms. They submitted a proposal to the NSF DRK-12 Program,

collaborating with Biological Sciences Curriculum Study (BSCS), seeking funding to carry out a full efficacy study over the next four years.

While the original Data Nugget structure was designed to accommodate and supplement instruction at the K-12 level, the team repeatedly received feedback and excitement from undergraduate educators at conferences suggesting that the concepts within Data Nuggets should be extended to post-secondary instruction. For undergraduate use, more flexibility than is currently offered in the K-12 resources is needed, while also ensuring Nuggets align with the quantitative skills required for undergraduates. Extension possibilities will be discussed during the NIMBioS working group. Graduate student Johnson has created a prototype interactive interface to help students and teachers work with large, freely available online sources of data, including Dryad and citizen science data. This interface should be up on website soon.

The team held professional development workshops for graduate students, post docs, and professors at the 2014 BEACON Congress at Michigan State, the University of Washington, University of Idaho, University of Texas, and University of Denver. They reached 33 members of the BEACON community and helped them to create Data Nuggets based on their own evolutionary research. They have also created a beautiful and user friendly website for teachers and scientists to use and create Data Nuggets, found at www.datanuggets.com and www.datanuggets.org. Google Analytics shows that hundreds of users are accessing the site each month. A feedback system is in place for teachers who use Nuggets in their classroom and would like to request additional resources or contact scientists. The team also held workshops for teachers, sharing how they can use Nuggets in their classroom, or create their own based on data collected during student inquiry projects. These workshops were held at the Michigan Science Teacher Association's annual meeting, the University of Washington partnering with the Seattle Aquarium, the ESA Life Discovery Conference, and the National Association of Biology Teachers' annual meeting.

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

BEACON and the Seattle Aquarium (SA) teamed up to promote scientific literacy in young people using the using the shores of Puget Sound as a classroom. Three BEACON graduate students joined the SA's Citizen Science (CS) program to assist in outreach that serves approximately 450 students from 14 high schools. The graduate mentors taught students to evaluate biodiversity on the shores of Puget Sound, collect and analyze their own data, and implement critical thinking skills using the scientific method. Graduate mentors led a few specially selected high school interns through immersive summer research about regional biodiversity and ecosystem health that transformed some students' attitudes toward science. The results of an independent education evaluation affirm that this collaboration impacted scientific literacy and interest in STEM careers among young people in many different positive ways.

An important goal of this project was the creation of immersive research opportunities for high school students with close mentorship by BEACON graduate students. While these outcomes were reported in 2013, follow-up interviews with the CS interns in 2014 indicate that the mentoring partnership with BEACON graduates had a large impact. Interns expressed interest in pursuing STEM-related studies in college and careers, and were able to leverage their experiences toward college admissions. The independent education evaluator described some of these impacts as "transformative." This project also supported teacher-training workshops, the Think Evolution Workshop in summer 2013 and the Data Nuggets Workshop in spring 2014.

A comprehensive evaluation of all programs was carried out by Andrea V. Anderson of SoundView Evaluation and Research. A summary of her conclusions follows:

Citizen Science-BEACON Project Executive Summary

As noted in the previous report, Citizen Science program has matured and tripled in size. Data collected each year shows that students are gaining knowledge, skills, and improved attitudes about the Puget Sound environment (Anderson and Plude 2008, Anderson 2005, 2006, 2004, 2013).

The addition of BEACON's *Think Evolution* and the *Data Nuggets* teacher workshops enhanced teachers' understanding of evolution, use of Excel and online data sets and showed that teachers had strong stated intentions for including this content into their instruction. While there was no direct follow up with students to determine if the content was taught, there was some indirect evidence that suggested that students were gaining skills in data analysis, design of experiments and understanding of the nature of science. Specifically, students responded to open- ended questions with explicit descriptions about the comparative studies they were doing as independent projects and how they were doing simple statistical analysis with their data.

Not all teachers attended the two workshops, but the essential content might be included in the annual training provided teachers before the Citizen Science program starts in the spring. At that time, the Seattle Aquarium might include a review of Excel and statistical analysis as they provide a refresher about the different field study methodologies. Some of the Think Evolution activities might be appropriate to include in the training as well. Those teachers who had participated might lead the instruction on these components.

The Seattle Aquarium is also considering a post-program interview with teachers about what instruction they provided students about these topics. The students' pre-post/then survey might also include specific questions relevant to this content. This would better demonstrate the impact the workshops had on the Citizen Science participants.

Finally, the engagement of (underserved and minority) high school interns in research laboratories and working with research scientists had a profound impact on the participating students, as well as the graduate students involved. As noted in the previous report, the graduate students developed significant mentoring skills and capacities. However, the evidence from student interviews show that the internship was a truly transformative experience for the participating students. College and career plans changed

because of this experience, with interest in STEM increasing dramatically. Based on these results, it is recommended that the Seattle Aquarium consider working with academic and research partners to sustain this kind of effort.

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

Hands-on, student-driven evolution demonstrations are lacking in the classroom, as observable phenotypic changes may not be apparent/suitable for classrooms with limited time and resources. However, *in vitro* directed evolution (IVDE) permits the evolution of small molecules in a short period and, when paired with a simple colorimetric reporter, provides methodology suitable for a classroom. More specifically, IVDE "fast tracks" the evolution process by beginning with a population of diversified species. Additionally, this demonstration links changes at the RNA level directly to function and, when paired with a simple colorimetric report, evolution leads to an observable phenotypic change that can be seen in a classroom environment.

This demonstration involves the "evolution" of the T500 ribozyme, which has ligase activity, joining an oligonucleotide ("substrate") to the ribozyme's 5' end. To demonstrate a selection, the work begins with a population or pool of candidate ribozymes, whose sequences are based on the sequence of the parental T500 ribozyme. Three nucleotides critical to T500 ribozyme's activity are synthetically varied, creating a pool of 4^3 (64) T500 variants or "candidate ribozymes." To begin the selection, the ribozyme pool is diluted (i.e. selection pressure); reaction reagents are added, such as enzymes (i.e. reverse transcriptase and RNA polymerase), and a substrate containing a T7 promoter ("T7-substrate") is added. Only those ribozyme variants capable of catalyzing the ligation of the "T7-substrate" to itself generate template suitable for transcription, thus amplifying functional ribozyme variants. Followed by multiple rounds of dilution, the selective pressure of the demonstration generates functional ribozymes in just a few days. To observe the accumulation of functional ribozymes, a simple fluorescent probe strand displacement scheme is used. The fluorophore-probe recognizes the T7-substrate-ribozyme region of the functional ribozyme, thus displacing the fluorophore-probe from its quencher-oligonucleotide pair and generating a fluorescent signal. Testing pools from multiple rounds of the selection, the selection and accumulation of functional ribozymes is observed by the increase in fluorescence over multiple rounds, thus generating a ribozyme evolution demonstration suitable for a classroom environment.

The goals of this project include: (1) mentor undergraduate students in the development of research-based educational demonstrations and modules; (2) provide experiential learning opportunities to high school students; (3) develop an evolution and selection demonstration suitable for classrooms with limited time and resources; (4) optimize the evolution and selection demonstration for use by high school educators and students with limited background and familiarity on the subject and techniques; (5) distribute the demonstration kits and train educators and instructors on the use of the kits; (6) evaluate the student learning outcomes of the demonstration.

Since February 2012, students from the UT-Austin Freshman Research Initiative have continued to develop a reliable continuous evolution scheme that is capable of demonstrating the evolution of improved catalytic function in ribozyme ligases within a high school classroom. To date, 4 undergraduate students have been instrumental in the development and implementation of this project. One of those undergraduates, Michael Ledbetter, upon publishing the results of his work in *Biochemistry and Molecular Biology Education* (2013) and presenting his research at numerous conferences (noted in "Outputs & Activities"), graduated and is now attending graduate school at Scripps Research Institute. Most recently, and with the addition of new undergraduate researchers (Kimberly Khoo and Katherine Klein), the team successfully regenerated the ribozyme pool, ribozyme ligation, and fluorescence detection control reactions. Furthermore, optimization work is underway, examining the robustness of the methodology and the procedures. The team has been in contact with a couple of high schools and anticipate further collaboration in the testing and development of the kits. This includes a recent collaboration with a high school instructor to draft a demonstration protocol appropriate for high school students. In collaboration with Julie Libarkin (MSU), an assessment instrument (i.e., survey) has been generated to evaluate the student learning outcomes of the demonstrations. To provide another experiential learning opportunity, further expand the catalog of high school demonstrations, and "evolve" the high school experience, the team is preparing multiple "Data Nugget" exercises, which are educational modules based on real evidence and data (http://datanuggets.org/).

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 goals of the BEACON iGEM project include: (1) carrying out education and outreach activities related to synthetic biology and evolution; (2) participating in iGEM 2013 as a BEACON sponsored joint UT-Austin and NC A&T iGEM team; and (3) preparing NC A&T for participation in 2014 iGEM as an independent team. The Greensboro-Austin BEACON iGEM team performed a number of research and outreach activities over the last year. Groups of students from UT Austin and NC A&T traveled to the other institution for two separate week-long workshops. The team organized an FBI biosecurity workshop for law enforcement, scientists, and students in Austin. Additionally, the team took part in events such as "Hot Science, Cool Talks", SXSW Create, the "Geeksboro Science Café" and the North Carolina Biosciences Symposium, where they educated the public on the topics related to synthetic biology and evolution. As the culmination of their research over the summer on projects GluE.coli, Bacto-Art, and D. odori, 14 supervisors and members of the Greensboro-Austin joint iGEM team attended the North American Regional Jamboree Oct. 4–6, 2013. They were awarded a Gold Medal for their projects. In the spring, students continued their outreach by demonstrating measurements made by caffeine-degrading *E. coli* of the potency of drinks collected from >40 local coffeeshops at the free South by Southwest (SXSW) Festival Create event in Austin (Mar. 7-9).

2014 UT Austin and NC A&T iGEM teams. As planned for after the end of BEACON sponsorship, each institution is fielding an independent iGEM team for the 2014 competition. The UT Austin team has worked on incorporating *o*- nitrobenzyl-O-tyrosine (ONBY) into proteins. This "photocaged" amino acid can be used to make proteins that are activated by light. The NC A&T team continued their Bacto-Art project and is developing a project focused on the degradation of condensed tannins present in coffee and tea. Both teams look forward to reconnecting and showing off their science in about a month when they present their work at the "Giant Jamboree" taking place in Boston this year that will include all iGEM teams participating from around the world.

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

This group's goals were to develop, implement, evaluate, and disseminate curriculum modules (6-8 curriculum hours) on evolution using both computational tools and living organisms for high school students. Specific project goals included: 1) teaching students the basic mechanisms of evolution by natural selection through interactive and engaging exercises using the Finger-painting Fitness Landscapes application and Picbreeder; 2) teaching inquiry-based science using both Finger-painting Fitness Landscapes and living organisms (plants and soil bacteria) in classroom experiments; and 3) providing educational resources for teachers and education researchers.

Finger-painting Project: A Mac and Windows version of the Finger-painting Landscape app is currently available on Johnson's personal website at https://sites.google.com/site/anyaejohnson/finger-painting-fitness-landscapes-app. An iPad version was submitted to the first round of review to the Apple App Store; due to updates in the latest iPad release, the app requires additional functionality to be made more widely available.

Plant-rhizobia project: Suwa has worked on a publication for American Biology Teacher (ABT) and it is in press for the November 2014 issue. This paper introduces plants and rhizobia as a great study system to teach ecology, evolution and inquiry-based science. In collaboration with Jen Lau (MSU), Dylan Weese (St. Ambrose University) and Brad Williamson (AP biology teacher and co-authoer of ABT paper), Suwa plans to write an additional education paper to explore rapid evolution of rhizobia in response to fertilizer. She also mentored two high school students from Kalamazoo Area Math and Science Center (KAMSC) to conduct an independent research project, using plant and rhizobia as a study system. This will be a great opportunity to pilot some of the classroom activities we're considering.

Picbreeder project: Goldsby has made progress along two fronts. First, she concurrently trained 4 classrooms of fourth grade students at a local elementary school. To accomplish this, she led a team of 15 volunteers, who served as general discussion leaders and small group leaders. Additionally, she has written a lesson plan for using Picbreeder within elementary schools to ensure dissemination of the program.

2d. Integrating research and education

Across our entire consortium, our programs seek to integrate research and education, both by bringing current BEACON research exemplifying Evolution in Action to a variety of audiences, as well as applying education research methods to studying the efficacy of our materials where appropriate. Perhaps most notably, our graduate students have published six articles that demonstrate their work on education projects (Royer and Schultheis, 2014; Lark et al., 2014; Weigel et al., 2014; Tran et al., 2014; Suwa and Williamson, 2014; Schultheis and Kjelvik, 2015). BEACON members also routinely bring their research to general public audiences, through programs such as Darwin Discovery Day at Michigan State University, science nights at local schools, and national venues like the US Science and Engineering Festival. Our database lists 90 Education and Outreach activities, distributed across the following audiences:

Audience	People in attendance	Number of events
K-12 students and teachers	10-50	37
General public	50-1000s	27
Undergraduates	50-150	7
Faculty and graduate students	30	5
Alumni and administration	10	4
Conference attendees	100s	5
Other	100 – 1000s	5

We highlight a few of these programs below.

The Michigan State University Museum continues to work on exhibits that highlight BEACON research. We have continued to update the current exhibit, adding signage, improving "Mutation Station" (redone with longer lasting materials), and adding a new natural selection game installed this month - "Hungry Birds" - that visitors are engaging and having fun with. We will be continuing to update the exhibits over the next year, with plans to add the touch screen interactive Tree Thinking Game developed by Laura Crothers (UT) and colleagues (http://evotreethink.appspot.com) as well as the Ladybug Game developed by Terry Soule (UI) which will include an interactive component investigating variation in natural populations. We are also working on identifying what new research we will highlight in the exhibit area, with plans to have this completed by the fall of 2015.

BEACON members also routinely bring their research to general public audiences, through programs such as Darwin Discovery Day at Michigan State University, science nights at local schools, and national venues like the US Science and Engineering Festival. BEACON participated in the Darwin Day Roadshow organized by the National Evolutionary Synthesis Center (NESCent). We sent scientists and graduate students to three rural K-12 schools in Michigan to give a total of 11 presentations to classes and groups within the schools. Presentations included an introduction to BEACON, and presentations by the scientists of their research. Zachary Blount and Danielle Whittaker (MSU) brought science to their classrooms, and conversations with students included inquiries about bird personality and how religious beliefs can be integrated with science.

The US Science and Engineering Festival held in Washington DC was another exciting event for BEACON. By the third day, we'd extended our booth across three spaces, with interactive

presentations including how to do serial transfers, a challenge to identify hyenas "in the field" by finding matching animals based on their coat patterns, and a demonstration of an evolved robotic car that followed the color red.

BEACON collaborates with NESCent to organize the Evolution Symposium at the National Association of Biology Teachers annual professional development conference. On November 14, 2015 the symposium will feature a series of BEACON scientists introducing the audience to Evolution in Action, followed on Saturday by a workshop presentation by BEACON graduate students based on an activity they developed and recently published in *American Biology Teacher*.

A number of our faculty and graduate students are also involved in evolution education research efforts, each providing an opportunity to bring BEACON resources to broader audiences. Louise Mead is Curriculum Director for A New Genomic Framework for Schools and Communities. This is a Science Education Partnership Award from the National Institutes of Health that is bringing innovative curriculum that meets the Next Generation Science Standards to middle school classrooms in Detroit and Flint, and we are making connections between the curriculum and BEACON science. Peter White and Jim Smith (MSU) collaborated with Richard Lenski (MSU) to create an Evo-Ed Case Study on the evolution of citrate in *E. coli*. Smith is also collaborating with Pennock, Mead, Ofria, and Lenski (all MSU) in a newly funded project that will further test and work to disseminate Avida-ED to undergraduate biology classrooms across the country. Finally, Ben Kerr (UW) is working with Dr. Scott Freeman to bring an Experimental Evolution lab experience into a large undergraduate biology course at the University of Washington, the project funded by the Howard Hughes Medical Institute.

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, 59 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	2 (33%)	8 (47%)		
Postdoc			16 (57%)	1 (12%)
Faculty Position			4 (14%)	5 (63%)
Industry	3 (50%)	5 (29%)	7 (25%)	2 (25%)
Government		1 (6%)		
K-12 Education		1 (6%)		
Unknown	1 (17%)	2 (12%)	1 (4%)	
Total # graduates	6	17	28	8

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

- Educational research on the efficacy of Avida-ED suggests that interacting with this educational platform and experimenting with evolutionary processes significantly increases student understanding and acceptance of evolution (Lark et al. in prep; Johnson et al. in prep).
- Numerous outreach events have given us an opportunity to share Evolution in Action research and educational materials across a wide array of audiences, and while these single outreach events are challenging to assess, we view the positive interactions we have with the general public an indication that we are engaging them in thinking about how evolutionary processes operate.
- A number of our graduate students wrote (and published on our website) Evo101 Blog Posts, introducing the general public to basic evolutionary concepts and principles. Writing the blog posts was an assignment in the Evolutionary Biology for Non-life Scientists course, and the innovation received the AT&T Faculty-Staff Instructional Technology Award for Best Enhanced Course.
- Bjørn Østman and Randal Olson created a video to show how fitness landscapes can be used to visualize evolution in action. This video was submitted to the ALife 2014 Science Visualization Competition.
- BEACON students and faculty have published a total of 6 articles in *American Biology Teacher* and participated in numerous workshops and presentations, bringing our evolution education materials to classrooms across the country.

3. Increased interest in STEM careers

- Our work with the Citizen Science at the Seattle Aquarium, administered through the University of Washington, indicates we had a profound impact on the high school interns. Evaluations suggest the internship was transformative and that students' college and career plans changed because of this experience, with interest in STEM dramatically increasing.
- Funding from the above program also provided an opportunity for 30 of the high school students who had been working at the Seattle Aquarium all year to have an overnight trip to FHL. There were 90 students, so they had to do a lottery to decide who got to come. They met with many scientists at FHL, who talked to them about the BEACON program,

they went out in FHL's boat, the Centennial, and watched some dissections. Here is a video summarizing their experience http://youtu.be/rBnlq3th2hU.

2f. Educational plans for next reporting period

We will continue to develop, test, and review all our educational projects. In particular, we have submitted two DRK12 proposals that specifically seek funding to further the development and nationally assess our educational projects. We will also continue to bring curriculum developed at one institution to other institutions, placing a high priority on cross-fertilization. We are also providing training for our graduate students interested in education in both DBER and knowledge of current science education reform. And finally, we are working to revitalize the education pages of the BEACON website and to initiate programs that are discovery driven, and in particular, engage science educators.

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 revised its approach to knowledge transfer last year 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	In addition to working with existing industrial collaborators, this past year, BEACON has added 6 additional industrial collaborators with a seventh one under NDA negotiation as of October 2014.
	Number of joint grant proposals submitted with industrial partners	One proposal has been submitted, and another is 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 10 companies are providing challenge problems and feedback.
Spinoffs formed	Number of spinoffs formed	Existing spinoff with Risto Miikkulainen, Digital Certainty, is continuing to do well. No new spinoffs to report in the current period, but foundations are being laid

		for one to be rolled out in 2015 involving bio-inspired aquatic robots.

1c. Problems encountered and resultant changes

No significant problems encountered in this reporting period. The changes made to the Strategic Plan in previous years have worked well with our activities.

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

Newly Initiated KT Activities

Metron: Several BEACON researchers at MSU met with representatives from Metron to discuss mutual areas of interest and different types of possible research collaborations, ranging from individual contracts and grants, joint research proposals (e.g., SBIR), to MSU serving as subcontracts on larger grants awarded to Metron. As of October 2014, a non-disclosure agreement is being negotiated between MSU and Metron, where initially the focus is on specific collaboration between Philip McKinley, Betty Cheng, and Metron.

Ship Design: Led by Kalyanmoy Deb (MSU). Deb has received funding from the Office of Naval Research (ONR) for a project titled "Development of a Knowledge Informed Tradespace for Resilient Systems (KITRS)" (August 2014 - January 2015), where he is developing a reliability-based ship design methodology from given uncertain data and the use of a knowledge-based management tool. This is a new collaboration between MSU and University of New Orleans.

Optimal Casings and Covers for Electronic Equipment: Led by Kalyanmoy Deb (MSU). Deb is leading a Danish Agency for Science, Technology and Innovation-funded project titled "IN SPE: Innovation consortium for sustainable performance in electronics" with researchers from Denmark Technical University. This project uses evolutionary optimization methods to design optimal casings and covers for electronic equipments for different criteria. This is a new collaborative project with DTU and European industrial partners, including Danfoss A/S (Denmark), Grundfos A/S (Denmark), Vestas Wind Systems A/S (Denmark), Bosch (Germany), Bombardier (Sweden).

Ribozyme Evolution: Led by Andy Ellington (UT Austin). Ellington and his lab are extensively involved in translational research and product development. As part of their interactions with the BEACON Center, the University of Texas at Austin received an award to develop K-12 experiments focused on ribozyme evolution; this work was carried out by the Aptamer Stream of the Freshman Research Initiative, run by Dr. Gwen Stovall. Students within the Stream frequently gain skills that make them valuable additions to companies, and in particular, several of the FRI students have worked during their undergraduate years with **Altermune**, a local company sited within the University's "Tech Dorm."

Continuing KT Activities

Ford: Led by Betty Cheng (MSU). Cheng is continuing to collaborate 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. Recently, Ford has provided high-level project requirements, MSU students and Dr. Cheng work together with the Ford contacts have created software models that can be analyzed for various properties.

WISDOM Project (formerly in collaboration with Scion, a New Zealand Crown Corporation; now under negotiation with Living PlanIT, a Swiss-registered company headquartered in UK):

History: 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 obtained funding from sources in New Zealand to support a graduate research student there until June, 2014, 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. 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.

Status: The MSU team is in negotiations with the CEO of Living PlanIT, Mr. Steve Lewis, for support to continue their research and to produce a commercial tool to apply to large, "wicked" problems globally, integrated with the firm's "Urban Operating Systems" offerings in support of "smart cities" and related projects. In preparation for the project, BEACON has hired Dr. Chikumbo as a Research Associate Professor at Michigan State University, beginning in May, 2014. Individual and institutional non-disclosure agreements with Living PlanIT have been negotiated and signed, enabling next steps anticipated in the near future. In October, Mr. Lewis met (via Skype) with Mr. Charles Hasemann, Director of MSU Business Connect, and the faculty members involved and expressed his strong interest in moving forward with MSU. Dr. Chikumbo, Dr. Deb, Dr. Goodman and Mr. Couvertier have continued working on developing further tools to improve convergence in many-objective optimization problems and visualization tools to assist in understanding and highlighting the tradeoffs among the many solutions on the Pareto front.

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. Based on the preliminary results, they teamed with Northrup Grummon to submit a proposal to the Office of Naval Research.

NASA: Led by Gerry Dozier (NCAT). Dozier continues to work 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.

Continental Automotive: Led by Betty Cheng (MSU). Cheng has continued to collaborate with Continental, both in terms of class projects for Cheng's undergraduate and graduate software engineering classes, as well as for research purposes. 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 are continuing to model and analyze the impact of environmental uncertainty on an automated pedestrian collision avoidance system, with an emphasis on safety properties.

BAE Systems: Led by Betty Cheng (MSU). Cheng has continued to collaborate with 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. During this past year, Cheng and her students have been applying their techniques to a new challenge problem involving e-commerce.

General Motors: Led by Betty Cheng (MSU). Cheng has been collaborating with General Motors to explore 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. During this past year, the focus has been on safety standards, how to model safety properties in relation to functional properties, how to represent the impact of environmental uncertainty on the safety properties. In addition, Cheng is working with a new GM collaborator who specializes in safety modeling, who has also provided a new challenge problem involving the next generation smart, adaptive cruise control.

Chrysler: Led by Betty Cheng (MSU). Cheng is working with Chrysler to investigate the use of model-driven engineering of onboard automotive systems that are exposed to environmental uncertainty, where safety is a primary concern. The Chrysler contact has provided another challenge problem involving electronic steering from multiple inputs for Cheng and her students to use for their work.

StoneAge Robotics: Led by Risto Miikkulainen (UT Austin). Miikkulainen is continuing to work 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

Gliding robotic fish: Led by Xiaobo Tan (MSU) Computational evolution has been exploited to optimize the design of bio-inspired robotic fish, including the morphology, control, and flow-sensing system of such robots. A ***provisional US patent*** has been filed for Gliding Robotic Fish, 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 is of great interest to both the aquatic environmental monitoring industry and the defense industry. Working with Spartan Innovations, Dr. Xiaobo Tan is currently leading the commercialization effort of this technology, and a start-up company is expected to be launched in 2015. This will provide a vehicle for transferring

additional related technologies enabled by BEACON, including soft underwater robots and novel flow sensing-based navigation methods.

Dr. Andy Ellington has two additional research projects that have also been funded by BEACON: the development of synthetic bacteriophage (with Dr. Holly Wichman at Idaho) and most recently the development of self-regulating genetic circuitry (with Dr. Eric Klavins at Washington). The first project relied heavily on the Gene Synthesis Facility at the University of Texas at Austin, which Dr. Ellington helped establish and which is a fully translational enterprise that sells synthesis services to the community. The second project relies on novel T7 RNA polymerase variants; while the initial development of these variants was not funded by BEACON per se, the funded project should now help to better showcase these variants. A variety of companies, including **Enzymatics, Illumina,** and **New England Biolabs** have shown initial interest in these polymerases, and they have been made available (for a fee) to the reagent distribution company **Kerafast**.

Dr. Deb is maintaining a repository of technical reports written on evolutionary-computation-related research from **COIN (Computational Optimization and Innovation) Lab**, much of it in collaboration with other universities: University of Michigan, University of Skovde in Sweden, Aalto University School of Business in Finland, and also internally within BEACON. These papers are kept for circulation at http:/www.egr.msu.edu/~kdeb/reports.shtml.

2c. Progress towards indicators/metrics listed above

1. Establishing collaborative research relationships with industrial sponsors. BEACONites are working with at least 15 external industrial/governmental organizations at this time. Several publications submitted in this reporting period have resulted from collaborations with industry partners, including publications by leaders of the respective projects and their collaborators.

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, Chrysler, and BAE Systems. Erik Goodman is working on one problem that originated with Scion, Inc., and Charles Ofria & Philip McKinley are working with Northrop Grumman. Kalyan Deb is working on several challenge problems in collaboration with his local and international collaborators. Andy Ellington and his collaborators are working on real-world challenge problems with industrial interactions. Collaborations are emerging from ongoing discussions with Metron.

3. Spinoffs formed. While no spinoffs were originally anticipated in the first five years of the Center, one spinoff, Digital Certainty, was successfully established by Risto Miikkulainen in the 2011 reporting period and is continuing to operate successfully. A second one is planned for 2015 by Xiaobo Tan involving the bio-inspired robotic fish.

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.

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, including publications, presentations, grant proposals, and educational activities, as part of our overall outcomes.

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), iDigBio, and iPlant Collaborative.

Narrative: BEACON received a $200K supplemental grant to address the cyberinfrastructure across multiple NSF centers. Led by C. Titus Brown, the project brought together people from SESYNC, NESCent, iDigBio, iPlant and BEACON, to establish course objectives and develop materials for Data Carpentry workshops. Funding has supported four Data Carpentry workshops. Instructors who developed and taught the material were from NESCent (Hilmar Lapp and Karen Cranston), BEACON (Tracy Teal) and Utah State University (Ethan White).

Activity: BEACON External Faculty Affiliate Program

Organizations/people involved: University of California Irvine/Adriana Briscoe, Yale University/Paul Turner, University of Texas Pan American/Laura Grabowski

Narrative: In 2012, BEACON launched its External Faculty Affiliate Program to partner with faculty at non-BEACON institutions in support of the diversity goals. 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 project led to a proposal to NSF for external funding, which was funded at $440K. Our second Affiliate, appointed in 2013, was Dr. Paul Turner of Yale University. We have recently appointed our third Affiliate, Dr. Laura Grabowski of the University of Texas Pan American. Dr. Grabowski has been involved in several BEACON undergraduate research initiatives, and will contribute greatly to forming a pipeline for undergrads to our graduate programs, especially for URM students.

Activity: Bringing Data Nuggets to a national audience and assessing their effect on quantitative literacy.

Organizations/people involved: NIMBioS (National Institute for Mathematical and Biological Synthesis) and BSCS (Biological Sciences Curriculum Study)

Narrative: BEACON graduate students Elizabeth Schultheis and Melissa Kjelvik, advised by Education Director Louise Mead, have been working to bring Data Nuggets to a national level. They received funding to hold a working group at NIMBioS and submitted a DRK12 grant proposal to NSF to work with BSCS to carry out an efficacy study to address the following questions: (1) Do students in classrooms using Data Nuggets have better achievement, interest in science, and motivation outcomes than students in "business as usual" classrooms? (2) How much does teacher practice function as a mediator of treatment effects on student motivation, interest, or achievement? (3) To what extent do student motivation and interest function as mediators on the effects of treatment on student achievement? (4) To what extent do treatment effects differ on the basis of gender, race/ethnicity, free/reduced-price lunch status, English language learner status, or baseline achievement of the students?

Activity: Bringing 3D learning materials that integrate science practices, cross-cutting concepts and the disciplinary core ideas of genetics and evolution to K-12 classrooms.

Organizations/people involved: CREATE for STEM Institute (MSU), University of Michigan, Concord Consortium

Narrative: Louise Mead is collaborating with the CREATE for STEM Institute (Collaborative Research in Education, Assessment, and Teaching Environments for Science, Technology, Engineering, and Mathematics) at MSU, and with the University of Michigan and the Concord Consortium, on an NIH SEPA (Science Education Partnership Award) focused on developing a genomics framework for middle school classrooms and communities. Mead is also co-PI on a DRK12 proposal with CREATE and Concord to develop and assess 3D materials for high school biology classrooms. The focus on genetics and evolution in these curriculum projects provides unique opportunities to share BEACON research with K-12 audiences.

Visiting researchers during this reporting period: Dr. Benjamin Kerr (from BEACON at UW), Professor Lihong Xu (Tongji University), Haiqiang Nie (Tongji University), Professor Meng Yao (East China Normal University), Weiming Ji (East China Normal University), Professor Stephan Winkler (University of Applied Sciences Upper Austria).

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

Visiting speakers: BEACON has hosted a number of visiting speakers in 2014, 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:

- Jennifer Fewell, Arizona State University
- Mark Riemers, Virginia Commonwealth University
- Kim Hoke, Colorado State University
- Jonathan Losos, Harvard University
- Christopher Cherniak, University of Maryland
- David McDonald, University of Wyoming
- Greg Wray, Duke University

2c. Progress towards goals

Because the BEACON external partnerships are so intertwined with our broader research and education goals, we aren't tracking these activities as separate goals. Researchers supported on sabbatical (including Charles Ofria and Ben Kerr) are closely involved in BEACON research and jointly supervise many BEACON graduate students and postdocs. Visiting scholars are strong participants in several BEACON-funded activities, as are our Faculty Affiliates. The education-related partnerships listed here are all reported on in greater detail in the Education section of this report.

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

BEACON will issue a fourth annual 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

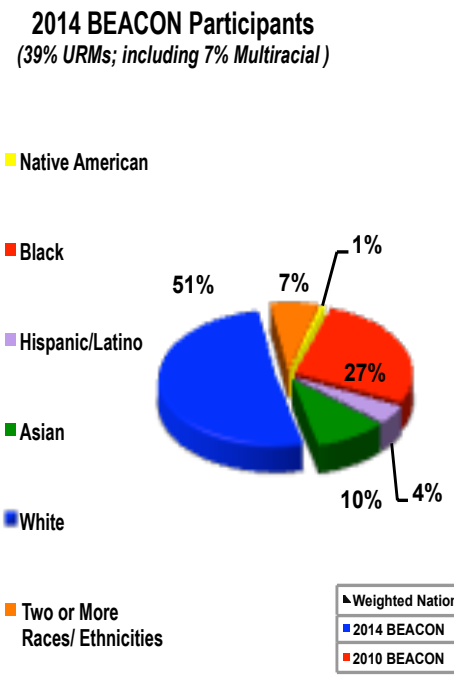
BEACON's two overarching diversity goals are to: 1) ensure diversity is represented as an inclusive and connecting thread through all aspects of BEACON, and 2) exceed national norms for diversity at all levels in the Center. In the original 2010 proposal, section *4.e Diversity Program*, BEACON stated, "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."

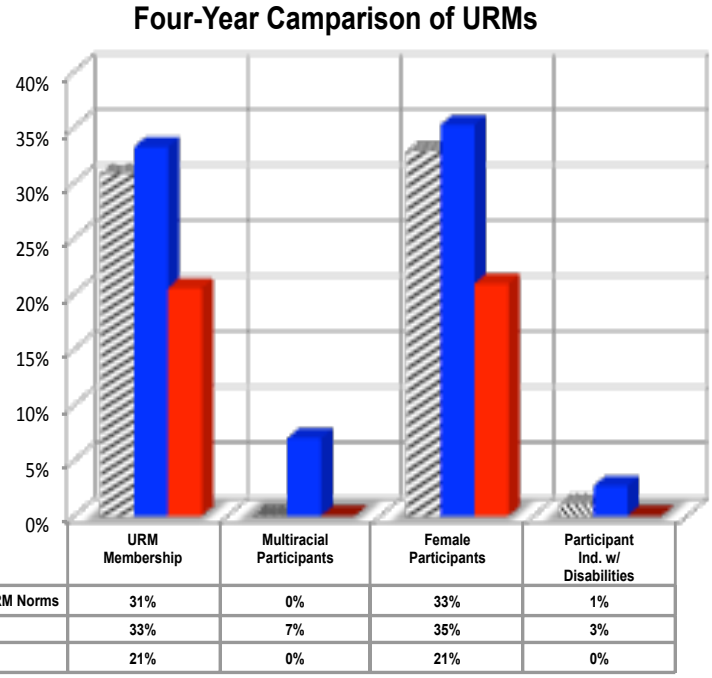
BEACON decided to be the most diverse, world-class scientific research center in the United States. To do that, we adopted the stretch goal of exceeding national norms across the STEM disciplines. At first glance, it might not seem to be a "stretch" goal simply to exceed national norms at all levels, but given that the norms are based on involvement of underrepresented groups in many less scientifically sophisticated research and education institutions than an NSF STC, it is actually very difficult to attain. Each year, BEACON self-assesses and incorporates data-driven results and "lessons learned" from the prior year into its strategic efforts. We are pleased to report that BEACON is achieving and sustaining diversity through inclusive recruiting, and the leveraging of strong partnerships and programming to ensure consistency and sustainability.

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 using NSF's 2012 data tables (see http://www.nsf.gov/statistics/wmpd/start.cfm).

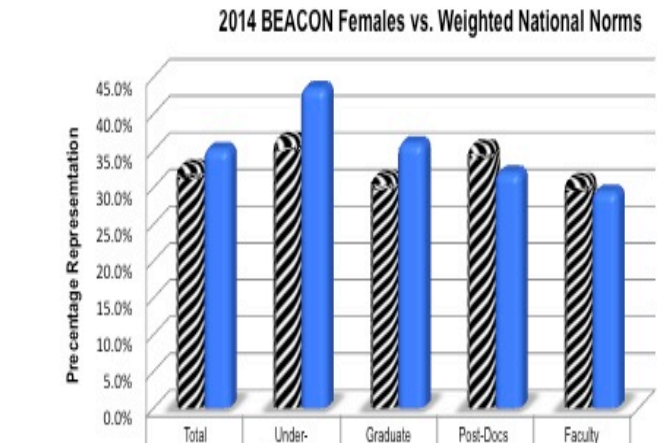
Underrepresented minorities (URMs): Currently BEACON participants are: 51% White, 27% Black, 10% Asian, 4% Hispanic/Latino, 1% Native American, and 7% two or more races/ethnicities. BEACON's target was to achieve a 5% increase over the National Norms (30.8%) for BEACON-specific disciplines by October 2013. Currently 33.2% of BEACON participants are self-reporting as URMs, which is 7.8% above the National Norm for URM. This is also an impressive 62% increase over BEACON's Year One (2010) baseline of 20.5%. Much of this diversity has been achieved at BEACON's lead institution, Michigan State University, where 21% (12 of 57) of BEACON participant graduate students are URM's, as are 35% (9 of 26) of the undergraduates (principally REU students), 14% (8 of 57) of faculty; and across the partner schools, where 12% (7 of 58) of the post-docs are URMs. There will be more effort paid to increase the number of URM post-docs, and explore possible support mechanisms for URMs in post-bachelors research opportunities.





	URM Membership	Multiracial Participants	Female Participants	Participant Ind. w/ Disabilities
Weighted National URM Norms	31%	0%	33%	1%
2014 BEACON	33%	7%	35%	3%
2010 BEACON	21%	0%	21%	0%

Women: BEACON's overall effort to increase female participation was accomplished: currently 35.2% of BEACON participants are female, versus the National Norms of 32.8%. However, there are still opportunities to increase female post-docs and faculty. BEACON currently has 58 post-docs, and 32% are women – a significant increase compared to last year's 26.9%, which was well below the National Norms of 35%. Working collectively, we recruited graduate students from across our partner schools and coordinated with faculty advisors at HBCUs and HSIs to communicate post-doc opportunities.

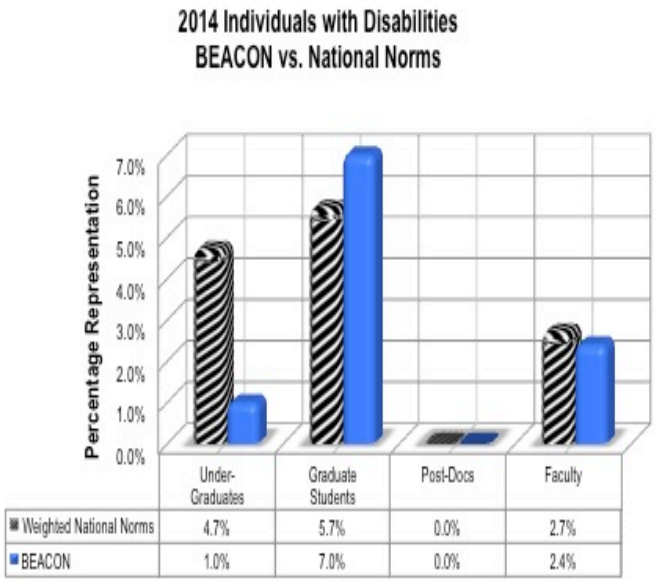


	Total	Under-Graduates	Graduate Students	Post-Docs	Faculty
Weighted National Norms	32.8%	36.6%	31.3%	35.5%	31.0%
BEACON	35.2%	43.5%	36.0%	32.0%	29.4%

Female faculty at BEACON is 29.4%, which is slightly below the National Norm (31.0%). In 2012, BEACON was at 22.1%, well below the National Norm. Within two years we see this 33% increase as a positive response to our efforts, including recruiting current faculty at BEACON partner schools to collaborate on research, teach classes, submit grants, and/or write publications related to BEACON's mission.

By the next annual reporting cycle, we expect that BEACON will surpass the national norms for female participants at all sub-levels. We are confident that our strategic efforts will sustain and further increase female participation throughout BEACON and the STEM community at-large.

Individuals with Disabilities: BEACON is establishing itself as a best-practice model for increasing diversity in STEM education; as a result, its learning environments are enriched and enhanced. In order to sustain these benefits, BEACON needs to strategically recruit and support underrepresented groups. Many individuals with disabilities state they underreport their status due feelings of vulnerability and/or that it will bias people against them.



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 at 1.1% by 152%. While we are pleased that more individuals have self-reported, we acknowledge that our participant numbers are still underreported.

1c. Problems encountered

Individuals with disabilities are a priority within our strategic diversity efforts; to address the above-stated challenges, BEACON used its internal budget process to fund the Disability Action Plan. The goal of this project is to provide safe, inclusive and adaptive environments for individuals with disabilities.

The enablers of this plan are BEACON's Diversity Committee and the graduate students/post-doc representatives, who will share and implement best practices at their respective partner schools. This includes helping to populate the webpage, filming examples of BEACONites with disabilities, creating opportunities to blog on the issues around disabilities, facilitating sessions at BEACON Congress addressing adaptive labs and classrooms, and creating a matrix to measure & capture success. This also includes creating a repository of best practices and adaptive software in an effort to provide scalable models and tools. Our outreach efforts will includes the creation of a portable museum display about scientists with disabilities and adaptive science strategies.

This year, BEACON produced a film called *ThisABILITY*, which highlighted BEACONites with disabilities. Since the showing of this video, numerous BEACONites have self-disclosed that they have disabilities. We also hosted a BEACON Disability Plan working session at the BEACON Congress looking at adaptive learning environments and how support efforts could occur at the partner schools. One BEACON Ph.D student has started blogging about her personal journey and experiences navigating her disability in graduate school.

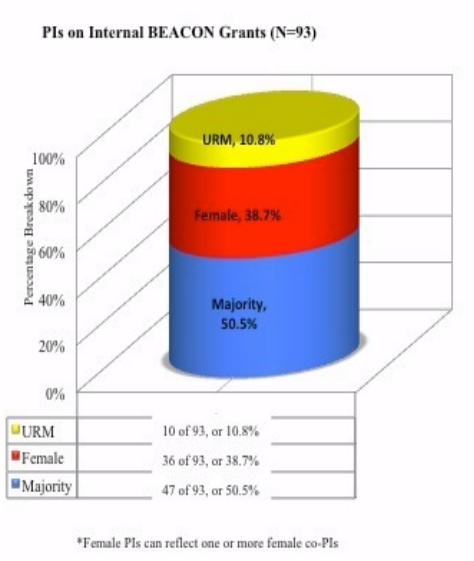
2a. Center activities which contribute to the development of US human resources in science and engineering at the postdoc, grad, undergrad and pre-college levels

BEACON funds specific programs to enhance diversity at every level at the center (more details below), but also promotes furthering diversity in every aspect of our work.

Diversity as common thread in all activities: BEACON challenges the perception that diversity efforts are limited to programming and recruiting. BEACON works hard to foster a culture in which all participants reach their full potential by creating a unified community of inclusion. We know it is not easy to effect change; therefore, we will continue to diligently support the unique needs of minorities, females and individuals with disabilities. One of the key efforts that BEACON has implemented includes ensuring that when an internal budget request is submitted, it states (if applicable) how it addresses and enhances diversity.

Across BEACON's consortium, we are extremely proud to report that **the thread of diversity is becoming institutionalized within the core activities** of what we do, and whom we do it with. In 2014, ninety-three internally funded projects for research and educational activities were in operation across the five partner schools. A closer examination of the participants on these grants revealed the following:

Regarding PIs and co-PIs, 38.7% of all projects had one or more women listed and an additional 10.8% had URMs listed. While some individuals are listed on more than one project, there is diverse PI leadership on 49.5% of all internal BEACON projects.



The 93 projects list 99 URM participants, including 49 undergraduate students, 28 graduate students, 13 faculty and 9 post-docs. Again, please note that some individuals are listed on more than one project; however, this shows there is URM diversity across all levels and disciplines of our research efforts.

Collectively there are 210 women listed on the 93 projects, including 76 undergraduate students, 78 graduate students, 46 faculty, and 10 post-docs. As stated before, some individuals are listed on more than one project; regardless, the fact remains that women are becoming increasingly more visible on BEACON research teams and educational/outreach efforts.

Faculty Program: The **BEACON Faculty Affiliate Program** is a mini-grant of up to $100,000 awarded to a faculty member outside of BEACON's five institutions over a two-year period to conduct research and explore the possibility of becoming permanent member of BEACON. This grant has a two-year overlapping funding cycle, which now supports recipient Dr. Adriana Briscoe, Professor of Ecology and Evolutionary Biology at the University of California, Irvine; Dr. Paul Turner, Professor and Chair of the Department of Ecology and Evolutionary Biology, Yale University; and our most recent awardee Dr. Laura Grabowski, Associate Professor of Computer Science, University of Texas-Pan American. Sixty-six percent of awardees are women, and 66% are URMs.

Postdoctoral Program: The **BEACON Distinguished Postdoctoral Fellows Program** funds post-doctoral scholars to pursue interdisciplinary research on evolution in action with BEACON faculty members, in the fields of biology, computer science, and/or engineering. Applicants

propose a research project within the scope of BEACON's mission and must have two BEACON faculty sponsors that will serve as research mentors. One sponsor must be MSU faculty, and the other sponsor may be from any of the five BEACON institutions. Preference is given for interdisciplinary research. Fellowships last two years and include a salary of $50,000/year and modest funds to support research and travel. The successful applicants help foster collaborations among faculty and disciplines, and serve as a professional model for pre-doctoral trainees. BEACON has used this Fellowship award to attract an inclusive pool of candidates; as a result, 50% of the awardees are females and 50% are URMs.

BEACON Day @ NCAT: Dr. Gerry Dozier (NCAT) will host the annual **BEACON Day** in November 2014, highlighting the accomplishments and partnerships between the BEACON consortium and NCAT. On an annual basis, this event introduces and educates NCAT faculty and administration about BEACON, provides a forum for discussion of BEACON research across the Center, provides an opportunity for faculty across the Center to come to NCAT and discuss possible collaborations, and provides a showcase for getting NCAT students excited about research at BEACON institutions or other universities. Two collaborative workgroups from this event have organized efforts to submit three proposals for internal BEACON funds as *proof of concept* for ultimate submission to external funding organizations.

Supplemental Student Support: BEACON has **travel awards** for students to attend professional conferences and present their research. Many of our URM graduate and undergraduate students are taking advantage of this funding opportunity and are gaining valuable exposure to professional networks, research peers, and content experts.

Undergraduate Programs: BEACON's **Research Experience for Undergraduates (REU) Program** is a 10-week intensive residential program targeting the recruitment of a diverse group of students to conduct research with faculty, graduate students and post-doc mentors. Each summer, BEACON funds students across the BEACON partner schools, at seven different sites. Settings included wet labs, dry labs, computer/simulations, field experiences, and/or a combination.

Participants				**Funding Model**		
Year	Total	URMs	Female	BEACON $	Leveraged $	Total $
2011	17	17 or 100%	8 or 47%	$28,500	$82,000	$110,500
2012	67	41 or 61%	25 or 37%	$133,820	$295,040	$428,860
2013	73	46 or 63%	38 or 52%	$106,400	$243,079	$349,479
2014	63	43 or 68%	33 or 52%	$105,171	$190,736	$295,907
TOTAL	**203**	**147**	**104**	**$373,891**	**$810,855**	**$1,184,746**

Over the past four summers, BEACON has served 203 undergraduate students (freshman to seniors) and spent $1,184,746 by leveraging funding from several sources. The average cost per 2014 participant was $7,498 (housing/meals - $2,698; travel - $700; stipend - $4,000). The 2014 summer's total program costs were $295,907, reflecting 35.5% BEACON funds, and 64.5% leveraged funds from other sources. For every $1 dollar spent, BEACON has consistently blended/braided/matched approximately $3 dollars from external sources. To date, 7 students (or 43% of the REU graduating seniors) are now enrolled in graduate programs at BEACON universities; and an additional six students are enrolled in STEM graduate programs at non-

BEACON schools. This is an 86% (13 of 15) placement rate; the remaining two students have delayed acceptance into graduate school for a year.

A distinguishing feature of this summer research program is that (typically) graduate students or postdocs in the student's laboratory directly mentor the REU students. Before the program begins, all mentors received **formal training in mentoring** from BEACON's Diversity Director, who is also available to both mentors and mentees over the course of the summer to help solve problems that have arisen, as well as to enhance the mentors' professional development and cultural competency. The long-term goal of the program is to train graduate students and postdocs to build mentoring relationships that can be used to increase recruitment and retention, share cultural and organizational knowledge, and help individuals achieve personal and professional objectives. The short-term goals are to ensure that undergraduate interns have an explicit mentor to help guide their research and laboratory training, and that the graduate and postdoctoral mentors have the formal skills and resources necessary to serve as effective mentors.

In May 2014, Dr. Brown Clarke provided a training session for 53 graduate student and postdoc mentors. This training has become so popular that it has expanded to other summer programs at MSU's campus. Each week throughout the summer, REU students submitted formal reports describing their activities and progress during the preceding week and their plans for the following week. These forms had to be approved by the mentor before being submitted to the program director, who read each form and followed up as needed. This system worked well for ensuring clear communication between students and their mentors, as well as for signaling potential problems as they might arise. Dr. Brown Clarke facilitated a weekly discussion among the mentors in which they could discuss challenges that arose, and was also available for private discussions as needed. Social activities were scheduled throughout the summer to allow interns to interact informally with their mentors. Informal discussions with mentors indicate that they found the training to be useful, and found the availability of Dr. Brown Clarke for trouble-shooting to be reassuring. In addition, all interns were productive and appeared to develop good working relationships with their mentors. Feedback from the faculty members involved in the program indicate that they were extremely pleased and impressed both with the productivity of their interns and with the success of the mentoring program.

In an effort to establish sustainability, multiple grants have been submitted to external funding sources. 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 ten neuroscience undergraduates in summer 2013-15. In this year's cohort of ten interns, 40% (4) were ethnic minorities, and 50% (5) were female.

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 MSU funding for the

summer, and an additional $20,000 for the academic year, which helped to support ten (10) MSU undergraduate students.

K-12 Programs: BEACON supported numerous outreach events that exposed K-12 underrepresented students to evolutionary science/STEM education. The **Girls' Math and Science Day Conference** is a one-day, hands-on conference for 120 girls grade 6th -8th providing math and science experiences. BEACON also funded **citizen science days** at aquariums and in urban & rural classrooms.

The **BEACON High School Summer Residential Program** advances three of the four BEACON goals for public and K-12 education. BEACON and MSU's College of Engineering's Recruitment, Scholarships, and K-12 Outreach Office offered 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 group of faculty, staff, and students. This year's program included 65% (17 of 26) female students.

Outside of BEACON: BEACON's Diversity Director Brown Clarke is also assisting other centers with their diversity missions. She collaborated with the state of 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 is currently a member of their External Advisory Committee, and the first meeting convened this past March, 2014.

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

BEACON was founded with a fairly diverse membership and has excellent leadership in pursuing further diversity, particularly its Diversity Director and the Chair of the Diversity Steering Committee. Its annual budget request process allowed for projects aimed at increasing or preserving diversity to be considered annually, reviewed primarily by the Diversity Steering Committee, which spans all of the BEACON universities. As described and documented above, many of the projects undertaken have been extremely successful and have become "institutionalized." We are also beginning to enjoy the fact that undergraduate and graduate students, post-docs, faculty and knowledge-transfer partners are self-identifying their interest in evolutionary science and are coming to BEACON as a destination for learning and collaboration; this is extremely critical to having a sustainable pipelines for recruitment and partnership.

The success of the recruitment activities, particularly the activities aimed at formal mentoring and enriching the educational experiences of all BEACON students and postdocs, means that the majority of BEACON resources dedicated to assuring diversity in all its forms will go to existing

programs, including the strong staff support needed to operate them. Additionally, each year's budget request process will provide opportunities to propose innovative and creative ways to further improve these efforts.

2c. Progress towards goals

To summarize our diversity statistics:

- *URMs*: Currently BEACON participants are: 51% White, 27% Black, 10% Asian, 4% Hispanic/Latino, 1%Native American, and 7% two or more races/ethnicities. Currently 33.2% of BEACON participants are self-reporting as URMs, which is 7.8% above the National Norm for URM.
- *Women*: BEACON's overall effort to increase female participation was accomplished; we are currently at 35.2% versus the National Norm of 32.8%.
- *Individuals with Disabilities*: Currently 2.7% of our participants self-reported as having a disability, which exceeds the National Norm of 1.1% by 152%.

With the involvement Dr. Percy Pierre, Chair of BEACON's Diversity Committee and Dr. Judi Brown Clarke, BEACON's Diversity Director, the Alfred P. Sloan Foundation and National Action Council for Minorities in Engineering, Inc. (NACME) awarded a grant to the SLOAN/BEACON Program for $60,000 (AY 2014-2017). This program targets increasing URM Ph.D recruitment and retention efforts in the Electrical & Computer Engineering Department and the BEACON Center.

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.

Under the direct leadership of BEACON Professor Gerry Dozier (NCAT), the Computer Science (CS) Department at NCAT launched its own doctoral program in fall 2013. This effort was greatly assisted by collaborations between NCAT faculty and their BEACON computer science colleagues. We are now seeing an increase in participation of females and URMs in computer science.

2d. Plans for the next reporting period

- BEACON will continue its efforts to increase female participation, specifically focusing on faculty positions.
- BEACON will implement the recommendations and action items identified in the Disability Action Plan
- BEACON will continue 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 continuing to exceed 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 URM

VII. MANAGEMENT

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

The Center's overall organizational strategy and rationale is largely unchanged since the last reporting period. We have added a fourth thrust group, made very minor refinements to our project selection process, and have had a couple of personnel changes.

Thrust Group Reorganization. After careful consideration, we determined that our original research categorization was not as effective as we had hoped. BEACON research was organized around three broad Thrust Groups that cut across computational and biological thinking, but at different hierarchical levels: 1) Evolution of Genomes, Networks, and Evolvability; 2) Evolution of Behavior and Intelligence; and 3) Evolution of Communities and Collective Dynamics. These three thrust groups were united by three cross-cutting themes: Biological Evolution, Digital Evolution, and Evolutionary Applications. We found that projects in the Evolutionary Applications cross-cutting theme had a difficult time fitting into any one of the three thrust groups, and as a result were not getting the attention they deserved when discussing BEACON research. As a result, we have re-designated Evolutionary Applications as a new, fourth thrust group. This group will draw together work previously distributed among the other thrust groups that is relevant to addressing real-world problems, be they computational or biological.

As before, to promote the two-way flow of discoveries and concepts, each thrust group includes team leaders and researchers from both biological and computational fields. The Thrust Group leaders for thrust groups 2 and 3 remain unchanged: Kay Holekamp and Robert Pennock lead the Behavior and Intelligence group, while Fred Dyer and Philip McKinley lead the Communities and Collective Dynamics group. Determining the best fit for the new thrust group 4 led to some changes for thrust group 1; the Genomes, Networks, and Evolvability group will now be led by Chris Waters and Bill Punch, and the new Evolutionary Applications group will be led by Kalyanmoy Deb and Christoph Adami.

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, 3, or 4; 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 implemented 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 can now see how many reviews have been assigned to each BEACON member. Assigned reviewers now have the ability to decline, and to suggest a different reviewer. Finally, members who submit budget requests commit to reviewing up to 5 budget requests for each one they submit.

Personnel changes. As described above, there have been some changes to the Thrust Group leaders and Cross-Cutting Theme leaders as a result of the minor reorganization. Our updated Organizational Chart (Appendix B) reflects these changes. Additionally, our Information Technologist has been replaced; Tim Schmidt now fills this role.

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.

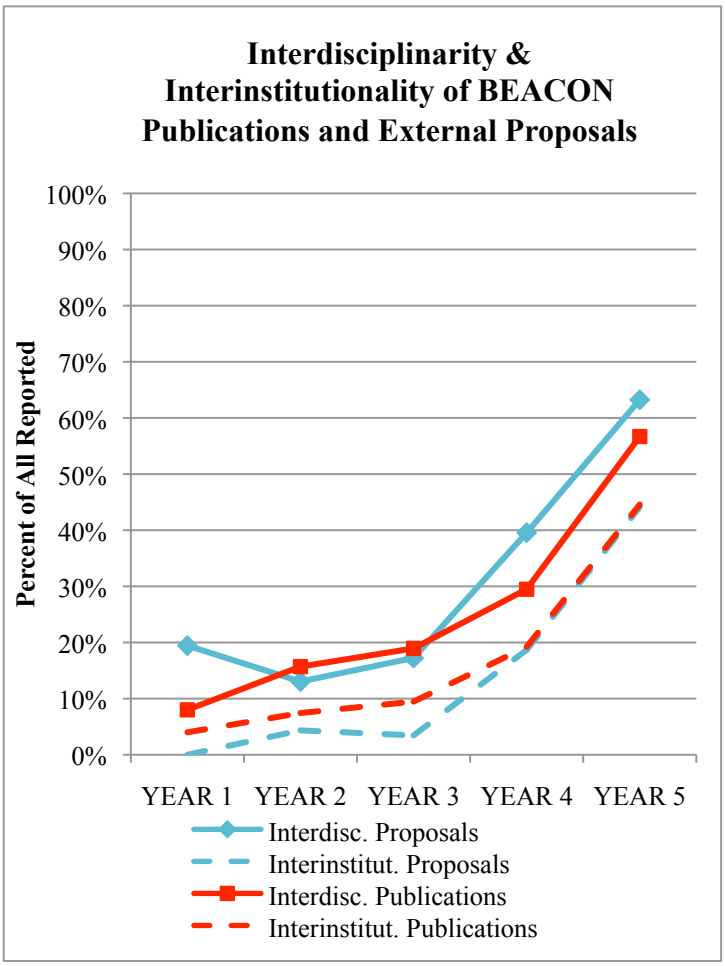
Management Goals		
GOAL	**METRICS**	**PROGRESS**
Increase in cross-disciplinary research and education	Number of paper/conference submissions by BEACON authors	The number of cross-disciplinary submissions continues to increase; in this period, 57% of all reported publications (see graph below) and 47% of presentations
	Number of new courses	After consideration, we have determined that adding new university courses every year is not a reasonable goal, and we have removed this metric from our plan.
	Number of students enrolled in cross-disciplinary courses	~30 in semester-long courses, plus hundreds in workshops on computational science for

		biologists
	Number of funding proposals submitted	43 of 68 grant proposals submitted (63%) reported as interdisciplinary; 30 of 68 (44%) inter-institutional
Increase in cross-institutional research and education	Number of paper/conference submissions	Reported cross-institutional publications continues to increase; in this period, 45% of all reported publications (see graph below) and 30% of presentations
	Number of new courses and workshops	New Data Carpentry, EDAMAME workshops
	Number of students in cross-institutional courses	~30 in semester-long courses, plus hundreds in workshops on computational science for biologists
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	BEACON researchers submitted 68 proposals for >$60M of external funding, and >$12M in external funding has been granted
	Award dollars	BEACONites have been awarded over $12M in this funding period (~$9M 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 2010) by October 2015]	These targets were exceeded in 2012. We are now focusing on increasing the interdisciplinarity, diversity, and academic distinction of our participants.
Effective support of Center operations by Management team	Survey for participants about management team	Year 4 evaluation was very positive but revealed some areas for improvement, which we are addressing
	Feedback from External Advisory Committee	Feedback has been positive and encouraging (Appendix C)
Center is perceived by NSF as exemplary	Renewal of NSF funding	Renewal was approved for our fifth funding increment, and we have received positive feedback from NSF. Our

		renewal proposal for phase 2 has been submitted.
	Number of public mentions made by NSF about BEACON	At least three BEACON studies were featured on the front page of nsf.gov in 2014

Cross-disciplinary and cross-institutional research, education, and funding. We ask BEACON participants to self-report on our Intranet whether their reported outputs & activities are interdisciplinary or interinstitutional.

Research: The graph below illustrates the reported percentage of paper and grant proposal 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 since Year 3 (2012).



Education: The BEACON interdisciplinary graduate courses have continued, as described in section III: Education, and have served about 30 students this year. In addition, major efforts by C. Titus Brown, Tracy Teal, and collaborators at NESCent, SESYNC, iDigBio, and iPlant developed 2-day Data Carpentry workshops to teach researchers to retrieve, view, manipulate, analyze, and store their and others' data in an open and reproducible way. Four initial workshops

have been held so far this year, and 7 more are planned for the near future. An intensive, one-week summer workshop was also offered at BEACON to provide computational training to microbial ecologists: Explorations in Data Analyses for Metagenomic Advances in Microbial Ecology (EDAMAME), taught by Ashley Shade and co-instructors Teal and Josh Herr.

Funding sources: BEACON researchers reported submitting 68 grant proposals for a total of over $60M during this reporting period, 43 (63%, compared to last year's 40%) of which are interdisciplinary, and 30 (44%, compared to last year's 24%) of which are interinstitutional. Of these, 27 were funded so far (17 [63%, compared to last year's 38%] interdisciplinary and 13 [48%, compared to last year's 25%] inter-institutional) for a total of over $12M in external funds, from NSF, NIH, USDA, the Department of Agriculture, the Office of Naval Research, USGS, and private foundations including the Howard Hughes Medical Institute. 11 submitted proposals were declined, and no decision has yet been reported for another 30 proposals.

Other metrics:

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. For 2014, Farrell-Cole and Amey conducted a qualitative impact study focusing on in-depth interviews to capture input from an individual and organizational perspective. The questions centered on (1) expectations when joining and if the expectations have been met and changed over time, (2) ways in which the organization is meeting its mission, (3) how the Center is having impact, (4) expectations and recommendations for the next five years, and (5) BEACON's legacy. Many BEACONites expressed that their work would not have been possible without the Center, and that BEACON has created important new ways to study evolution in action. Through their participation in BEACON, members have increased their networks outside their discipline, a fact that is reflected in their work. Many members also commented favorably – without being asked – on BEACON's efforts to increase diversity. Interviews highlighted a desire for more opportunities for students, increasing potential impact of BEACON research on the field, and for BEACON leadership to increase their impact beyond BEACON, especially in advocating for evolution in action research and interdisciplinary research.

External Donor Support Highlights BEACON's Pre-eminence in Evolutionary Computation. BEACON received its second Endowed Chair in 2014. The donor, Dr. John R. Koza, is a pioneer in genetic programming, a form of evolutionary computation. In September, 2014, he made a gift to BEACON Center at Michigan State University to establish the John R. Koza Endowed Chair in Genetic Programming. The search to fill this chair is commencing in November, 2014. This position will help to assure BEACON's legacy, while greatly contributing to its research in its second five years of STC support. Because Dr. Koza is not an alumnus of MSU, this is an unusual gift that, according to the donor, results from BEACON's leadership in the field.

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. Replacement technology to improve the quality and reliability of videoconferencing is currently under study.

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 was repeated in 2014. Beginning with the 2012 Congress, we began holding a Student/Postdoc Retreat day at the beginning of Congress. Topics covered 2012-2014 included 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), careers in academia, industry, and government (Terran Lane, now at Google, formerly from University of New Mexico), and a roundtable on avoiding burnout. 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. Our new Information Technologist, Tim Schmidt, is in the process of migrating the database and the user interface over to Wordpress systems, which will improve functionality for users and also make the process of reporting much easier.

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, 365 "likes" as of 10/20/14, an increase of 20% since the last annual report) and Twitter (@BEACON_Center, 554 followers as of 10/20/14, an increase of 46%). 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. Last year, we began producing the "BEACON Buzz," a bi-monthly newsletter reporting on accomplishments of BEACONites and upcoming events. The newsletter is written by BEACON's Science Communications Fellow, a position first held by graduate student Emily Weigel, and taken up by Leigh Sheneman in summer 2014. 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).

Videocommunications systems. For our weekly Friday all-location meetings we are 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).

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

In 2014, there was one change to our External Advisory Board. Kathleen Smith (formerly of NESCent, Duke University) has retired from the board. We now have a total of 8 members on 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 Inc.
Allen Rodrigo	NESCent, Duke University
Joan Strassman	Washington University in St. Louis

The fourth meeting of BEACON's External Advisory Board was held August 20, 2014, at Michigan State University, immediately after the BEACON Congress, which was attended by some of the members. The summary report from that meeting is provided in Appendix C.

4. Changes to the Center's strategic plan

BEACON's first four years have produced remarkable achievements that have often exceeded the goals of our original strategic plan. Nonetheless, important lessons have been learned about ways to improve our operations and new knowledge transfer directions are becoming relevant, with implications for our structure and strategic plan. Some were reflected in our earlier annual updates to our strategic plan, and others are captured in the revised strategic plan for the second five-year period that was submitted at the time of the renewal proposal.

One important goal will be to increase the amount of knowledge transfer between BEACON and partners in industry and other organizations. This is a natural progression in the life of a center—success in research leads to increasing benefit from such technical exchanges for both parties. BEACON has already changed the vehicle for its KT interactions from being centered around a consortial Industrial Affiliates Program to being centered on relationships with individual companies. We are seeking multiple relationships with companies eager to provide challenging (and publishable) research problems, with donors to make gifts that support research and education, and with funding sources for formal research contracts and grants. Early successes in such relationships assure that BEACON will be able to continue finding companies interested in relating to BEACON in some important way.

Another major goal is to address some concerns with the internal review process for members' annual budget requests to BEACON. As more evolutionary applications have emerged (both computational and biological), it has become apparent that these topics should have their own thrust group with reviewers who are knowledgeable about the subject matter of the requests. Therefore we have added a fourth thrust group, Evolutionary Applications, and reduced the cross-cutting themes to two—biological and computational. We believe this reorganization will have a positive effect on achievement of the revised goals of the second funding phase.

Yet another important goal concerns the nature of BEACON's education/outreach activities in Phase 2. While Phase 1 activities centered on tool and curriculum development and small-scale (and often, local) testing, Phase 2 will be oriented toward increasing the impact of these activities. Training of teachers, collaboration with other centers, taking over some key EHRD activities of NESCent, introduction of more evolution-in-action content into national discussions on science curricula, and such larger-scale activities are expected to thrive during Phase 2.

Other, more minor, revisions to the Strategic Plan reflect BEACON's success and the growing sense that its operation will continue after the NSF STC funding is completed.

VIII. CENTER-WIDE OUTPUTS AND ISSUES

1a. Center publications

Peer-Reviewed Publications

1. Adami C. Submitted. Information-theoretic considerations concerning the origin of life. Origins of Life and Evolution of the Biospheres. http://arxiv.org/abs/1409.0590
2. Albantakis L, Hintze A, Koch C, Adami C, Tononi G. Submitted. Evolution of integrated causal structures in animats exposed to environments of increasing complexity. PLoS Computational Biology.
3. Alnahhas R, Slater B, Huang Y, Mortensen C, Monk J, Okasheh Y, Howard M, Gottel N, Hammerling M, Barrick JE. Submitted. The case for decoupling assembly and submission standards to maintain a more flexible registry of biological parts. Journal of Biological Engineering.
4. Atwell JW, Cardoso GC, Whittaker DJ, Price TD, Ketterson ED. In press. Testosterone mediates successful establishment of a songbird population in a novel environment. The American Naturalist.
5. Baker Y. 2014. Applying Machine Learning Techniques in Diagnosing Bacterial Vaginosis. Master's thesis, North Carolina A&T State University.
6. Baker Y, Agrawal R, Beck D, Foster JA, Dozier G. 2014. Applying machine learning techniques in detecting bacterial vaginosis. International Conference on Machine Learning and Cybernetics (ICMLC).
7. Baker Y, Agrawal R, Foster JA, Beck D, Dozier G. 2014. Detecting bacterial vaginosis using machine learning. 52nd Annual ACM Southeast Conference.
8. Barrick JE, Colburn G, Deatherage D, Traverse C, Strand MD, Borges JJ, Knoester DB, Reba A, Meyer AG. Submitted. Identifying structural variation in haploid microbial genomes from short-read resequencing data using breseq. BMC Genomics.
9. Beck D, Foster JA. 2014. Machine learning techniques accurately classify microbial communities by bacterial vaginosis characteristics. PLOS One 9: e87830.
10. Benson-Amram S, Holekamp KE. In press. Limited social learning of a novel technical problem by spotted hyenas. Behavioral Processes.
11. Bryson DM, Wagner A, Ofria C. 2014. There and back again: gene-processing hardware for the evolution and robotic deployment of robust navigation strategies. GECCO.
12. Chapman S, Harrison SH, Bikdash M. 2014. The bustle of bioinformatics: Cloudy with a chance for big data. International Workshop on Big Data Analytics for Predictive Organization and Big Transformations.
13. Clark TJ, McKinley PK, Tan X. 2014. On-Board evolution of a model-free adaptive controller for a robotic fish. Proceedings of Evolution of Physical Systems Workshop, held in conjunction with the 14th International Conference on the Synthesis and Simulation of Living Systems (ALIFE 14).
14. Conlin P, Chandler J, Kerr B. 2014. Games of life and death: antibiotic resistance and production through the lens of evolutionary game theory. Current Opinion in Microbiology 21: 35-44.

15. Conner J, Cooper IA, La Rosa R, Perez S, Royer A. 2014. Patterns of phenotypic correlations among morphological traits across plants and animals. Philosophical Transactions of the Royal Society B: Biological Sciences 369: 20130246-20130246.
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18. DeVault T, Marulanda JF, Heckendorn R, Soule T. Submitted. Learning from Demonstration for On-line, On-board, Evolutionary Intelligence.
19. DeVries L, Lagor F, Lei H, Tan X, Paley D. In press. Distributed flow estimation and closed-loop control of an underwater vehicle with a multi-modal artificial lateral line. Bioinspiration & Biomimetics.
20. Dyer F. 2014. Evolution of negative incentive contrast effects in foraging bees. 15th Conference of the International Society for Behavioral Ecology.
21. Echave J, Jackson E, Wilke C. Submitted. Relationship between protein thermodynamic constraints and variation of evolutionary rates among sites. Phys. Biol. http://biorxiv.org/content/early/2014/09/19/009423
22. Fleet B, Yan J, Deller JR, Knoester DB, Yao M, Goodman ED. 2014. Breast Cancer Detection using Haralick Features of Image Reconstruction from Clinical Data of Ultra Wideband Microwave Signals. Proc. 3rd Workshop on Clinical Image-based Procedures: Translational Research in Medical Imaging (CLIP).
23. Foster JA. 2014. Introduction to special section: Best of EuroGP/EvoBIO. Genetic Programming and Evolvable Machines 14: 429-430.
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27. Gersick AS, Holekamp KE. In press. Long-distance communication facilitates cooperation among spotted hyaenas (*Crocuta crocuta*). Animal Behavior.
28. Goldman BW, Punch W. Submitted. Analysis of Cartesian Genetic Programming's Evolutionary Mechanisms. IEEE Transactions on Evolutionary Computation.
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36. Hagey T, Harmon L. Submitted. Temporal Microhabitat Variation in *Phelsuma*. Journal of Herpetology.
37. Hagey T, Harmon L. Submitted. Ecological Morphology of Australian Geckos. Functional Ecology.
38. Hagey T, Harmon L, Uyeda J. Submitted. Independent Origins and Adhesive Performance of Padded Lizards. Evolution.
39. Haley P, Olson RS, Dyer F, Adami C. 2014. Exploring conditions that select for the evolution of cooperative group foraging. Artificial Life 14.
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41. Hausknecht M, Lehman J, Miikkulainen R, Stone P. Submitted. A Neuroevolution Approach to General Atari Game Playing. IEEE Transactions on Computational Intelligence and AI in Games.
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43. Hintze A, Olson RS, Adami C, Hertwig R. Submitted. Variability risk aversion as an evolutionary adaptation. Scientific Reports. http://arxiv.org/abs/1310.6338
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45. Hofmann HA et al. 2014. An evolutionary framework for studying mechanisms of social behavor. Trends in Ecology and Evolution 29: 581-589.
46. Hofmann HA, Harris RM, et al. 2014. The genomic substrate for adaptive radiation in African cichlid fish. Nature 513: 375-381.
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53. Lau JA. Submitted. Evolution of increase biomass does not result in increased competitive ability during invasion. Biological Invasions.

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96. Stovall GM, Bedenbaugh R, Singh S, Ellington AD. Submitted. In Vitro Selection Using Modified or Unnatural Nucleotides. Current Protocols in Nucleic Acid Chemistry.
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107. Waters C et al. 2014. What is the role of cyclic di-GMP signaling in the human gut microbiome? Microbiome Science and Medicine. DOI: 10.2478/micsm-2014-0001.
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Book Chapters

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9. Newman R. 2014. The design and application of genetically encodable biosensors based on fluorescent proteins. In *Fluorescent Protein-based Biosensors: Methods and Protocols*, Eds Newman R, Zhang J. 1-16.
10. Stovall GM. Submitted. The Freshman Research Initiative as a model for addressing shortages and disparities in STEM engagement. In *Conference: New Directions for Mathematics Research Experience for Undergraduates (REUs) - Mt. Holyoke College*.
11. Whittaker DJ, Theis KR. In press. Bacterial communities in junco preen glands: ramifications for chemical signaling. In *Chemical Signals in Vertebrates 13*. Eds. Schulte B, Goodwin T.

1b. Conference presentations

Talks

1. Blount ZD. 11/15/2014. Examining the Evolution of a Novel Trait in a Long-Term Experiment with *E. coli*. National Association of Biology Teachers 2014 Professional Development Conference. Cleveland, OH.
2. Blount ZD, Lenski R, Weatherspoon K, Rowles M, Quandt E. 10/15/2014. Ecological Specialization and Incipient Speciation in an Experimental Population of *E. coli*. EMBO Conference Series: Experimental Approaches to Evolution and Ecology using Yeast & other Model Systems. Heidelberg, Germany.

3. Blount ZD, Weatherspoon K, Rowles M, Quandt E, Lenski R. 6/08/2014. Ecological Specialization and Incipient Speciation in an Experimental Population of *E. coli*. SMBE 2014. San Juan, Puerto Rico.
4. Blount ZD, Weatherspoon K, Rowles M, Quandt E, Lenski R. 6/20/2014. Genetic Basis of Ecological Specialization and Incipient Speciation in an Experimental Population of *E. coli*. Evolution 2014. Raleigh, NC.
5. Blount ZD, Weatherspoon K, Rowles M, Quandt E, Lenski R. 6/19/2014. Genetics of Ecological Specialization and Incipient Speciation in an Experimental Population of *E. coli*. 1st ASM Conference on Experimental Evolution. Washington, DC.
6. Burmeister A, Lenski R, Smith J. 6/24/2014. Assessing Student Perceptions & Explanations of Microbial Evolution. Annual national meeting of the Society for the Study of Evolution. Raleigh, NC.
7. Clark TJ, McKinley PK. 2014. On-Board Evolution of a Model-Free Adaptive Controller for a Robotic Fish. ALIFE 2014. New York City, NY, USA.
8. Deb K. 1/2014. Keynote speaker. ISCI-2014 (Intl. Simulation Conference of India). Pune, India.
9. Deb K. 7/2/2014. Keynote speaker. EVOLVE 2014. Beijing, China.
10. Deb K. 7/8/14. Invited speaker. WCCI-2014. Beijing, China.
11. Farrell-Cole PL, Amey M. 11/20/2014. Research Challenges & Issues for Studying Multi-Institutional Organizational Change Initiatives. Association for the Study of Higher Education. Washington, D.C.
12. Fleet B. 9/14/2014. Breast Cancer Detection using Haralick Features of Images Reconstructed from Clinical Data of Ultra Wideband Microwave Signals. MICCAI CLIP 2014. Boston, MA.
13. Getty T, Gering E. 2014. Post-Invasive Evolution of Hawaii's Feral Chickens. Evolution. Raleigh, NC.
14. Goodman ED. 7/12/2014. Conference Tutorial: Introduction to Genetic Algorithms. 15th Genetic and Evolutionary Computation Conference (GECCO), ACM SIGEvo. Vancouver, BC, Canada.
15. Goodman ED. 7/15/2014. How to Start a Company: A Tale of a Startup. 15th Genetic and Evolutionary Computation Conference (GECCO), ACM SIGEvo. Vancouver, BC, Canada.
16. Haley P, Olson RS. 9/1/2014. Exploring conditions that select for the evolution of cooperative group foraging. Artificial Life 14. New York, New York.
17. Hammerling M, Ellefson J, Boutz DR, Marcotte EM, Ellington AD, Barrick JE. 7/17/2014. Bacteriophages use an expanded genetic code on evolutionary paths to higher fitness. Synthetic Biology, Engineering, Evolution, and Design (SEED) Conference. Manhattan Beach, CA.
18. Hammerling M, Ellefson J, Boutz DR, Marcotte EM, Ellington AD, Barrick JE. 2014. Exploring the biological implications of expanded genetic codes via experimental evolution of bacteriophage T7. Molecular Genetics of Bacteria and Phages Meeting. Madison, WI.
19. Holekamp KE. 8/13/2014. Brains, brawn, and sociality: A hyena's tale. Animal Behavior Society. Princeton, NJ.
20. Holekamp KE, Ilany A. 8/12/2014. Multiple factors affect long-term social network dynamics in a wild spotted hyena population. Animal Behavior Society. Princeton, NJ.

21. Keagy J, Borgia G. 2014. Sexual selection on male bowerbird cognitive performance. International Society of Behavioral Ecology Meeting. New York, New York.
22. Keagy J, Boughman J. 2014. Sympatric species of stickleback differ in cognition and brain structure in ways consistent with adaptation to divergent environments. Evolution 2014. Raleigh, NC.
23. Kjelvik M, Schultheis EH. 3/7/2014. Data Nuggets: Addressing NGSS Standards using data from contemporary research. Michigan Science Teacher's Association. Lansing, Michigan.
24. Kremer C, Thomas MK, Litchman E, Klausmeier C. 6/2014. Dissimilar thermal sensitivities may alter the response of phytoplankton functional groups to warming oceans. Oceans Global Change Biology, Gordon Research Conference. Waterville Valley, NH.
25. Laubach Z, Holekamp KE. 8/11/2014. Social environment, epigenetics, and stress response: an ethological extension in spotted hyenas. Animal Behavior Society. Princeton, NJ.
26. Lee DV, McGowan C. 2014. Modeling and scaling of spring constants in 'bouncing' gaits. 7th World Congress of Biomechanics. Boston, MA.
27. Lenski R. 05/17/2014. What is Adaptation by Natural Selection?. American Society for Microbiology. Boston, MA.
28. Lessin D, Fussell D, Miikkulainen R. 7/12/2014. Trading Control Intelligence for Physical Intelligence: Muscle Drives in Evolved Virtual Creatures. GECCO 2014. Vancouver, BC, Canada.
29. Lessin D, Fussell D, Miikkulainen R. 2014. Adapting Morphology to Multiple Tasks in Evolved Virtual Creatures. ALIFE 2014.
30. McFetridge S, Covert AW. 2014. Structured Populations with Limited Resources Exhibit Higher Rates of Complex Function Evolution. 14th Conference on Artificial Life. New York.
31. McGowan C. 2014. Bipedal Hopping: Bouncing With and Without Springs. 7th World Congress of Biomechanics. Boston, MA.
32. Miikkulainen R. 7/13/14. Evolving Neural Networks. Genetic and Evolutionary Computation Conference (GECCO). Vancouver, Canada.
33. Miikkulainen R. 8/1/2014. Evolving Neural Networks. Artificial Life Conference (Alife). New York, NY.
34. Miller C, Miura TA. 6/23/14. Transcriptome analysis of lung epithelial cells upon pairwise co-infection by respiratory viruses. American Society for Virology. Fort Collins, CO.
35. Morris JJ, Zinser ER, Johnson Z. 2014. Diel regulation of hydrogen peroxide defenses in open ocean microbial communities. Joint Aquatic Sciences Meeting 2014. Portland, OR.
36. Olson RS. 3/27/2013. Evolution of swarming is shaped by how predators attack. MSU Graduate Academic Conference. East Lansing, MI.
37. Ribeck N, Lenski R. 6/18/2014. Theoretical model of long-term asexual adaptation is consistent with pervasive diminishing returns epistasis. Mechanisms, Strategies, and Evolution of Microbial Systems. Bad Honnef, Germany.
38. Schultheis EH. 2014. Evolving Better Cars: Teaching Evolution by Natural Selection Using BoxCar2D. ESA Life Discovery - Doing Science. San Jose State University, San Jose, CA.

39. Schultheis EH, Kjelvik M. 2014. Data Nuggets: Addressing NGSS using data from contemporary researc. Michigan Science Teachers Association 61st Annual Conference, Pure Michigan Science – Bridges to the Next Generation. Lansing, MI.
40. Schultheis EH, Royer A. 10/3/2014. Evolving better cars: teaching evolution by natural selection using BoxCar2D. Ecological Society of America Life Discovery Conference – Doing Science Education. San Jose, CA.
41. Smith JE, Holekamp KE. 8/10/2014. Collective movements and leadership decisions associated with reunions in spotted hyenas. Animal Behavior Society. Princeton, NJ.
42. Swalla BJ. 2/13/2014. Evolution and Development of Innate Immunity. 2014 Biomedical & Comparative Immunology Symposium at Florida International University. Miami, FL.
43. Tan X. 2014. Hydrodynamic object localization and tracking with an IPMC artificial lateral line. Symposium 3: Modeling, Simulation, and Control of Adaptive Systems, ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems. Newport, Rhode Island.
44. Theis KR. 2/13/14. Symbiotic bacteria mediate hyena social odors. AAAS General Meeting. Chicago, IL.
45. Top E. 2014. Rapidly evolving multi-drug resistance plasmids: the main threat in a 'post-antibiotic era'. SMBE Satellite Meeting on Reticulate Microbial Evolution. Kiel, Germany.
46. Top E. 09/21/2014. The plasticity of of plasmid host range. The History of Plasmids. Cold Spring Harbor Laboratory, Long Island, New York.
47. Top E. 10/27/2014. Rapidly improving persistence of multi-drug resistance plasmids in well-mixed populations and spatially structured biofilms. International Society for Plasmid Biology meeting. Palm Cove, Australia.
48. Turner C, Blount ZD, Lenski R. 3/1/14. The evolution of ecological complexity in a 50,000 generation experiment with *E. coli*. Midwest Ecology and Evolution Conference. Dayton, OH.
49. Turner C, Lenski R. 6/23/2014. Evolution of elemental composition in *E. coli* under carbon and nitrogen limitation. Evolution. Raleigh, NC.
50. Turner C, Wade B, Meyer JR, Lenski R. 2/23/14. Changes in the nitrogen and phosphorus content of bacteria during a 50,000 generation evolution experiment. Ocean Sciences 2014. Honolulu, HI.
51. Vaelli PM. 2014. A deadly neurotoxin as a chemical cue in the rough-skinned newt (*Taricha granulosa*). Chemical Signals in Vertebrates/Society for Chemical Ecology. University of Illinois Champaign-Urbana.
52. Vaelli PM. 2014. Microbial origins and physiological consequences of tetrodotoxin toxicity in the rough-skinned newt (*Taricha granulosa*). International Society for Neuroethology Amphibian Neuroethology Workshop. Hokkaido University, Sapporo, Japan.
53. Waters C. 2014. Breaking Biofilms: Understanding and Targeting in vivo Biofilms of Enteric Pathogens. ERIN Annual Meeting. Ann Arbor, MI.
54. Waters C. 2014. Control of a small RNA in *Vibrio cholerae* by a 3'-encoded cyclic di-GMP riboswitch. Molecular Genetics of Bacteria and Phages 2014. Madison, WI.
55. Weigel EG, Boughman J. 3/1/2014. "Low" and Behold: Short-term exposure to low-density conditions is enough to positively influence male reproductive success in

Threespine stickleback (*Gasterosteus aculeatus*). Midwest Ecology and Evolution Conference (MEEC). University of Dayton, Dayton, Ohio, USA.

56. Weigel EG, Boughman J. 2014. Short-term density exposure affects male reproductive success in threespine stickleback (*Gasterosteus aculeatus*). Evolution 2014. Raleigh Convention Center, Raleigh, NC.
57. Whittaker DJ. 7/10/2014. Silent songs: Content and context of avian chemical signals. International Society of Chemical Ecology/Chemical Signals in Vertebrates XIII. Urbana, IL.
58. Whittaker DJ, Theis KR. 7/9/2014. Keeping it in the family: Social environment drives avian preen gland microbiome structure. International Society of Chemical Ecology/Chemical Signals in Vertebrates XIII. Urbana, IL.
59. Whittaker DJ. 11/2014. Chemical Communication in Songbirds: Signal Content, Production, and Inheritance. Third Congress of the Latin American Association of Chemical Ecology (ALAEQ). Bogota, Colombia.
60. Wichman H. 2014. Synthetic biology and vaccine design meets experimental evolution of phage. Invited seminar. Gonzaga University.
61. Wilke C. 2014. Manipulating and predicting viral evolution. Viral Mechanisms and Evolution Retreat. UCSF.
62. Wilke C. 2014. Biophysical perspective on molecular evolution. 2nd Annual Symposium on Big Data in Biology. UT Austin.
63. Wilke C. 2014. A structural perspective on molecular evolution. March meeting, American Physical Society. Denver, CO.
64. Zakon H. 2014. Electric fish in the age of genomics. Sapporo Japan.
65. Zakon H. 2014. Electric fish: a test for parallel evolution. German Zoological Society. Göttingen, Germany.

Posters

1. Alnahhas R, Monk J, Mortensen C, Gutierrez A, Kessel A, Shin N, Watkins E, Halekote E, Mishler D, Hammerling M, Barrick JE. 2014. How much BUZZ is in your cup of joe? Use synthetic biology and *E. coli* to find out. South By Southwest (SXSW) Create. Austin, TX.
2. Blount ZD, Weatherspoon K, Rowles M, Quandt E, Lenski R. 5/17/2014. Genetic Basis of Ecological Specialization and Incipient Speciation in an Experimental Population of *E. coli*. 114th General Meeting of the American Society for Microbiology. Boston, MA.
3. Bruger E, Waters C. 2014. Quorum Sensing promotes the maintenance of public goods production in experimental populations of *Vibrio harveyi*. Evolution 2014. Raleigh, NC.
4. Bullock B, Whitaker S, Barrick JE, Harrison SH. 03/28/2014. Degeneracy and Reassignment of Instruction Sets in a Digital Evolution Experiment. 111th Annual Meeting of the North Carolina Academy of Science. Raleigh, NC.
5. Burmeister A, Lenski R, Smith J. 2/20/2014. Integration of Evolution into an Undergraduate Microbial Genetics Laboratory Course: Student Perceptions and Explanations of Microbial Evolution. CREATE for STEM Mini-Conference. MSU.
6. Cipolla E, Weigel EG, Boughman J. 7/24/2013. The effects of a density shift on nesting and mating behavior in a species of stickleback fish. Mid-Michigan Symposium for Undergraduate Research Experiences. East Lansing, MI.

7. Cipolla E, Weigel EG, Boughman J. 3/1/2014. Differences observed in nesting and mating behavior in high and low density treatments of male stickleback fish. Midwest Ecology and Evolution Conference (MEEC). University of Dayton, Dayton, Ohio, USA.
8. Clark TJ, McKinley PK, Tan X. 8/19/2014. Evolving Adaptive Control for Robotic Fish. BEACON Congress 2014. East Lansing, MI, USA.
9. Delcourt M, Wiench C, Hohenlohe P. 2014. Multivariate additive and epistatic (co)variation of gene networks of stress tolerance in yeast. Evo-WIBO. Port Townsend, WA.
10. DeVault T, Soule T. 9/8/2014. Smart Phone Robotics. Idaho Unmanned Aerial Systems (UAS) Working Group Symposium. University of Idaho.
11. DeVault T, Soule T, Pokharel J, Marulanda JF, Heckendorn R. 9/8/2014. On-Board Evolution of Robotic Agents. Idaho Unmanned Aerial Systems (UAS) Working Group Symposium. University of Idaho.
12. Doney K, McGowan C. 2014. Moment Arms in the Hind Limb of Desert Kangaroo Rats. Idaho Conference on Undergraduate Research. Boise, ID.
13. Dotson J, McGowan C. 2014. Modulation of Proximal and Distal Muscle Function During Level vs Incline Hopping by Desert Kangaroo Rats. Idaho Conference on Undergraduate Research. Boise, ID.
14. Fodor AC, Tassia M. 2014. Determining the Presence of Mesoderm in the Ctenophore *P. bachei* through Gene Expression Analysis. Society for Developmental Biology annual meeting. Seattle, WA.
15. Foster S, Weigel EG, Boughman J. 3/1/2014. Is bigger really better?: Nest size doesn't influence female mate choice in Threespine stickleback (*Gasterosteus aculeatus*). Midwest Ecology and Evolution Conference (MEEC). University of Dayton, Dayton, Ohio, USA.
16. Foster S, Weigel EG, Boughman J. 4/42014. Is bigger really better?: Nest size doesn't influence female mate choice in threespine stickleback (*Gasterosteus aculeatus*). University Undergraduate Research and Arts Forum. East Lansing, MI, USA.
17. Gering E, Getty T. 7/31/2014. Post-Invasive Evolution of Hawaii's Feral Chickens. International Society for Behavioral Ecology.
18. Getty T, Gering E. 2014. Post-Invasive Evolution of Hawaii's Feral Chickens. Gordon Conference: Genes and Behavior. Galveston, TX.
19. Getty T, Gering E. 2014. Post-Invasive Evolution of Hawaii's Feral Chickens. Invasion Genetics: The Baker-Stebbins Legacy. Asilomar, CA.
20. Gupta A. 03/09/14. Ultra-deep whole genome sequencing of HIV populations reveal the viral population structure and the extent of HIV genomic diversity. Keystone Symposium on HIV Pathogenesis: Virus vs Host. Banff, Canada.
21. Hagey T. 2014. 3D Imaging of the Gecko Adhesive System. EvoWibo conference (Evolutionary Biologists of the Pacific Northwest. Port Townsend, WA.
22. Hether T, Hohenlohe P. 2014. Genetic network architecture, mutation rate, and correlational selection affect G-matrix stability. Evolution 2014. Durham, NC.
23. Hether T, Hohenlohe P. 2014. Genetic network architecture, mutation rate, and correlational selection affect G-matrix stability. Evo-WIBO. Port Townsend, WA.
24. Hope E, Dunham M. 2014. Ploidy-regulated variation in biofilm-related phenotypes in natural isolates of *Saccharomyces cerevisiae*. Yeast Genetics 2014. Seattle, WA.

25. Johnson AE, Goldsby H, Ofria C. 4/11/2014. Evolving Solutions to Computational Solutions using Division of Labor. CRA-W. Santa Clara, CA.
26. Johnson AE, Johnson BZ. 6/10/2014. Teaching Evolution Through Simulation: The Finger-Painting Fitness Landscape App. Games Learning and Society 2014. Madison, WI.
27. Kami C, McGowan C. 4/16/2014. The effects of incline and speed on bipedal hopping mechanics in kangaroo rats. The University of Idaho Innovation Showcase. Moscow, ID.
28. Kami C, McGowan C. 2014. Across the Desert: How Kangaroo Rats Achieve Speed Increases over Uneven Terrain. Idaho Conference on Undergraduate Research. Boise, ID.
29. Ko R, McKenzie R, Parent C, Wichman H, Miura TA. 2014. Are two really better than one? A comparison of single viral infections with co-infections. Idaho Undergraduate Research Conference. Boise, ID.
30. Luttrell SM, Swalla BJ. 2014. Morphological and Genetic Mechanisms of Regeneration in the Hemichordate, *Ptychodera flava*. Society for Developmental Biology 73rd Annual Meeting. University of Washington.
31. Macias-Muñoz A, Briscoe A. 2014. Visual transcriptomics of seasonal forms of the butterfly *Bicyclus anynana*. Society for Molecular Biology and Evolution. San Juan, Puerto Rico.
32. Macias-Muñoz A, Briscoe A. 2014. Visual transcriptomics of seasonal forms of the butterfly *Bicyclus anynana*. Evolution Meeting. Raleigh, North Carolina.
33. Mead LS, Jenkins K, Baum D, Halverson K. 6/23/2014. Seeing the forest by interpreting the trees: As assessment instrument for evaluating undergraduate student understanding of evolutionary trees. Evolution 2014. Raleigh, NC.
34. Moradi Kordmahalleh M, Gorji Sefidmazgi M, Homaifar A, Karimoddini A, Graves JL, Guiseppi-Elie A. 2014. Gene Regulatory Network Based on Evolvable Partially Connected Artificial Neural Network. SIAM Conference on the Life Sciences. Charlotte, NC.
35. Morris JJ, Follows M, Dutkiewicz S, Dyhrman S, Lenski R. 2014. Meta-analysis of laboratory studies predicts large changes in phytoplankton communities in an acidifying ocean. Gordon Research Conference: Ocean Global Change Biology. Waterville Valley, NH.
36. Morris JJ, Papoulis SE. 2014. Black Queen Evolution in the Laboratory and in the Ocean. Experimental Approaches to Evolution and Ecology (EMBO Conference Series). Heidelberg, Germany.
37. Newman R. 2014. BactoArt: A Multicomponent Inducible Expression System for Teaching and Learning. North American International Genetically Engineered Machines (iGEM) Jamboree. Toronto, Ontario, Canada.
38. Papoulis SE, Morris JJ, Kerr B, Zaman L, Lenski R. 5/17/2014. Black Queen Gene Loss in a Structured Environment. ASM 2014. Boston, Massachusetts.
39. Perez S, Conner J, Schemske D. 2014. Patterns and mechanism of a nonfunctional trait loss. Society for the Study of Evolution. Raleigh, NC, USA.
40. Perez S, Conner J, Schemske D. 09/13/2014. Patterns and mechanism of a nonfunctional trait loss. AGEP Conference.
41. Rienne G, Weigel EG, Boughman J. 4/4/2014. Seasonal patterns of male stickleback (*Gasterosteus aculeatus*) courtship and nesting activity. University Undergraduate Research and Arts Forum. East Lansing, MI, USA.

42. Ryerkerk M, Deb K, Goodman ED, Averill R. 03/27/2014. Generative Variable-Length Genetic Algorithms. Engineering Graduate Research Symposium. Michigan State University.
43. Singh S. 04/10/2014. Development of a Classroom Evolution Demonstration. Undergraduate Research Forum. University of Texas at Austin.
44. Singh S. 08/22/2014. Regeneration of the Thymic Microenvironment by in vitro Cell Seeding of a Thymus Scaffold. Rejuvenation Biotechnology Conference 2014. San Jose, California.
45. Singh S, Ledbetter M, Stovall GM, Ellington A, Ellington AD. 4/2014. Development of a classroom evolution demonstration. UT-Austin Undergraduate Research Forum. UT-Austin.
46. Strauss E, Holekamp KE. 8/13/2014. Intraspecific varia. Animal Behavior Society. Princeton, NJ.
47. Tillotson M, Foster S, Mobley R, Weigel EG, Boughman J. 4/4/2014. Testing the effect of reproductive state on olfaction in threespine stickleback. University Undergraduate Research and Arts Forum. East Lansing, MI, USA.
48. Vaelli PM. 2014. Microbial origins and physiological consequences of tetrodotoxin toxicity in the rough-skinned newt (*Taricha granulosa*). International Congress for Neuroethology. Sapporo, Japan.
49. Weigel EG, Boughman J. 2014. Short-term density exposure affects male reproductive success in threespine stickleback (*Gasterosteus aculeatus*). International Society for Behavioral Ecology. CUNY Animal Behavior Institute, Hunter College, City University of New York, NYC.
50. Weigel EG, Mead LS, McElhinny TL. 2014. How and why can knowledge of concepts in genetics improve student understanding of concepts in evolution? Society for the Advancement of Biology Education Research (SABER). University of Minnesota - Twin Cities, Minnesota.
51. Wilson E, Anast J, Scott L, Wichman H. 2014. The pitfalls of courtship: Is there sex-bias in viral transmission. Idaho Undergraduate Research Conference. Boise, ID.
52. Wingo M, Weigel EG, Boughman J. 2014. Seasonal Patterns of Male Stickleback (*Gastrosteus* Spp.) Courtship and Nesting Activity. University Undergraduate Research and Arts Forum. MSU.

1c. Other dissemination activities

Talks

1. Barrick JE. 08/27/2014. Engineering microbial evolvability to improve synthetic biology. NC A&T Biology Department Seminar. NC A&T, Greensboro, NC.
2. Burmeister A. 2/07/2014. Assessing Student Perceptions and Explanations of Microbial Evolution. Bad Bug Club. Michigan State University.
3. Fleet B. 2/6/2014. Application of Evolutionary Computation for the Detection and Classification of Breast Tumors based on Microwave Technology. AGEP Crosstalk. East Lansing, MI.

4. Goodman ED. 02/03/2014. Using Evolutionary Principles to Improve Environmental Aspects of Development. MSU Honors College Series “Sharper Focus, Wider Lens”. MSU Union, East Lansing.
5. Goodman ED. 02/04/2014. A Different Approach to the Study of Evolution in Action. ECE Department Brownbag Lunch series. Michigan State University, East Lansing.
6. Hagey T, Harmon L. 2014. Geckos! University of Idaho Herpetology course. University of Idaho.
7. Hayes R. 9/16/13. Feathered Dinosaurs. Science Cafe. Greensboro, NC
8. Hohenlohe P. 2014. Introgression in westslope cutthroat trout: a case study in conservation genomics. University of Kentucky Department of Biology invited seminar. University of Kentucky.
9. Hohenlohe P. 10/2/2014. Natural selection, introgression, and the efficacy of genetic swamping in hybridized trout populations. School of Aquatic and Fisheries Sciences seminar series. University of Washington.
10. Holekamp KE. 2014. Social complexity and the evolution of intelligence. Bucknell University.
11. Holekamp KE. 2014. Complexity & the evolution of intelligence. NIMBioS, University of Tennessee.
12. Kerr B. 3/5/2014. Eternal seas of space and time: Experimental evolution in structured communities. Tempo and Mode. Canberra, Australia.
13. Lenski R. 02/10/2014. Time Travel in Experimental Evolution. University of Arizona.
14. Lenski R. 02/12/2014. Time Travel in Experimental Evolution. Harvard Museum of Natural History Public Lecture. Harvard Museum.
15. Lenski R. 02/26/2014. Time Travel in Experimental Evolution. Darwin Day at Duquesne University. Duquesne University.
16. Lenski R. 03/04/2014. Time Travel in Experimental Evolution: Phenotypic and Genomic Dynamics Across 50,000 Generations. Princeton University.
17. Lenski R. 04/01/2014. Time Travel in Experimental Evolution. University of Illinois, Chicago.
18. Morris JJ. 2014. The microbes of future past: 100,000 years of *Prochlorococcus* evolution. University of Alabama in Birmingham Faculty Job Interview. Birmingham, AL.
19. Morris JJ. 9/30/14. The Invisible Hand of the Black Queen: Microbial Marketplaces in the Open Ocean. University of Southern California, Los Angeles, California.
20. Stovall GM. 2014. Aptamer Stream. UT 32nd Honors Colloquium. UT-Austin.
21. Swalla BJ. 3/27/2014. Origin, Evolution & Development of the Chordates. SUNY Stony Brook, NY.
22. Swalla BJ. 4/21/2014. Origin and Evolution of the Chordate. Genetics Graduate Program Seminar Series. University of Iowa.
23. Weigel EG. 3/5/2014. How and why can knowledge of concepts in genetics improve student understanding of evolution? Biology Education Research Group Seminar. University of Georgia, Athens, Georgia, USA.
24. Weigel EG. 3/7/2014. Traveling Through Time and Space: The CIRTL-Exchange Journey. NSF Center for the Integration of Research, Teaching, and Learning (CIRTL) Network Leaders Meeting. University of Georgia, Athens, Georgia, USA.

25. Weigel EG. 3/7/2014. Temporal Patterns in Sexual Selection in Threespine Stickleback (*Gasterosteus aculeatus*). EDGE (Enthusiasts of Diversity, Genetics, and Evolution) Seminar. University of Georgia, Athens, Georgia, USA.

2. Awards and Honors

	Recipient	Reason for Award	Award Name and Sponsor	Date	Award Type
1	Judi Brown Clarke		MSU Dept of Kinesiology, Professional Achievement Award	4/12/14	Education-Related
2	Brian Connelly; Sylvie Estrela; Ben Kerr		Google Research Cloud Credits Award	8/5/14	Scientific
3	Emily Louise Dolson		NSF Graduate Research Fellowship	2014	Fellowship
4	Andrew Ellington		UT Austin President's Associates Teaching Excellence Award	3/20/14	Education-Related
5	Andrew Ellington		Fellow of the American Academy of Microbiology	1/24/14	Fellowship
6	Alexander Charles Andrew Fodor		Friday Harbor Laboratories Charles Lambert Fellowship, University of Washington	2014	Fellowship
7	Brian W Goldman; William Punch		GECCO Best Paper - Genetic Algorithms Track	2014	Scientific
8	Aditi Gupta	Travel Award	MSU Postdoctoral Association Travel Award	Fall 2013	Other
9	Rayna M Harris; Hans A. Hofmann	Poster Presentation at SICB 2014	SICB, Best Poster Award in the Division of Neurobiology	2/7/14	Scientific
10	Eleisha Jackson		NSF GFRP	2014	Fellowship
11	Cory Brandon Kohn	Professional development	MSU Graduate School Tracy A. Hammer Award for Professional Development	3/17/14	Other
12	Zachary Laubach		Dr. Marvin Hensley Endowed Scholarship in Zoology	2014	Fellowship

13	Zachary Laubach		Ecology, Evolutionary Biology and Behavior Program Summer Fellowship	2014	Fellowship
14	Joel Lehman; Risto Miikkulainen		GECCO Best Paper - Artificial Life, Robotics, and Evolvable Hardware	2014	Scientific
15	Kenna Lehmann		MSU EEBB Summer Fellowship	2014	Scientific
16	Kenna Lehmann		MSU Zoology Shaver Award	4/16/14	Fellowship
17	Liliana Lettieri		University of Denver, Marsico Visiting Scholar award	10/13	Scientific
18	Aide Macias-Muñoz	Travel grant to attend SMBE	Associated Graduate Students Travel Grant	4/21/14	Other
19	Aide Macias-Muñoz		William D. Redfield Graduate Fellowship Award, Francisco J. Ayala School of Biological Sciences	2014	Fellowship
20	Steven Kevin McCormick		NSF Graduate Research Fellowship Program	4/1/14	Fellowship
21	Steven Kevin McCormick		MSU, EEBB Summer Fellowship	4/8/14	Fellowship
22	Louise Souther Mead; Caroline Turner; Emily Weigel		2014 AT&T Faculty & Staff Award Competition in Instructional Technology, Best Technology-Enhanced Learning Innovation	2014	Education-Related
23	Randal S Olson		MSU Engineering Dissertation Completion Fellowship	8/14/14	Fellowship
24	Spiridon Evangelos Papoulis		ASM Student Travel Award	4/4/14	Other
25	Sam Perez		Paul Taylor Travel Award, MSU Dept of Plant Biology	2014	Other
26	Sam Perez		MSU Graduate School Travel Award	2014	Scientific
27	Percy Pierre	Selected as one of 30 change	Change Maker, the Johns Hopkins University School of	11/13	Scientific

		makers over the last 100 years	Engineering		
28	Percy Pierre	life time achievement	Outstanding Graduate, Class of 1961, University of Notre Dame Alumni Society	7/14	Scientific
29	Gavin Rienne		University Undergraduate Research and Arts Forum, Best Poster Presentation Award	2014	Scientific
30	Jacob Schrum; Risto Miikkulainen		GECCO Best Paper - Digital Entertainment and Arts	2014	Scientific
31	Gwendolyn M Stovall	Teaching Award	UT College of Natural Sciences Teaching Excellence Award	4/23/2014	Education-Related
32	Eva Top		University of Idaho Excellence in Research or Creative Activity Award	4/29/14	Scientific
33	Patric M Vaelli		Heiligenberg Student Travel Award, International Society for Neuroethology	2014	Scientific
34	Lauren Elizabeth Vandepas; Billie J. Swalla		Lerner-Gray Grants for Marine Research, American Museum of Natural History	2014	Scientific
35	Chris Waters		MSU 2014 Undergraduate Research Faculty Mentor of the Year	2014	Education-Related
36	Chris Waters		MSU College of Osteopathic Medicine Early Promise of Research Excellence Award	2014	Scientific
37	Emily Weigel	Conference Travel	MSU EEBB Program Summer Travel Award	2014	Scientific
38	Emily Weigel	Award for dedication to service	Michigan Campus Compact Heart and Soul Award	2014	Other
39	Emily Weigel		MSU EEBB Travel Fellowship	2014	Scientific

40	Emily Weigel		Women's Center of Greater Lansing Tribute to Women Award Nominee	2014	Other
41	Emily Weigel		MSU Graduate Student Leader of the Year, Honorable Mention	2014	Other
42	Emily Weigel		Travel Award, MSU Graduate School	2014	Scientific
43	Emily Weigel		MSU College of Natural Science Excellence-in-Teaching Award	2014	Education-Related
44	Claus Wilke		Kavli Frontiers of Science Fellow	2014	Scientific
45	Mark Wingo		Best Poster Presentation, UURAF at MSU	2014	Scientific
46	Luis Zaman		NSF Postdoctoral Fellowship in Biology	3/1/14	Fellowship

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

	Student Name	**Degree**	**Years to Degree**	**Placement**
1	Yolanda Baker	Masters	2	Bank of America
2	Daniel Beck	PhD	5	
3	Nicholas Chaumont	PhD	9	Research Associate, Stanford Univ.
4	Jeff Clune	PhD	5	Assistant Professor, Univ. of Wyoming
5	Tony Hwang	PhD	8	Postdoc, UT Austin
6	Thomas Erasmus Keller	PhD		Postdoc, Georgia Tech
7	Colin Kremer	PhD	5	Postdoc, Yale University
8	Alycia Lackey	PhD	7	Postdoc, Murray State Univ.
9	Michael Ledbetter	Bachelors	4	
10	Alshae Logan	Masters	2	PhD program, MSU
11	Juan Felipe Marulanda	Masters	2	
12	Eamon O'Dea	PhD	5	Postdoc, Georgetown Univ.
13	Jayandra Pokharel	Masters	2	Univ. of Minnesota, Ruby on Rails developer
14	Michael Scherrer	PhD	6	Sapling Learning
15	Jacob Schrum	PhD	7	Assistant Professor, Southwestern Univ.
16	Mridul Thomas	PhD	6	Postdoc, Eawag, Switzerland
17	Jianxun Wang	PhD	5	Apple, Inc

18	Nate Ward	Masters	2	PhD program, MSU
19	Cody Wiench	Bachelors	4	Graduate school
20	Lindsey Wolf	Masters	5	
21	Junjun Xin	PhD	5	ULC Robotics

4a. General outputs of knowledge transfer activities

Patents: Provisional US patent filed for Gliding Robotic Fish (Xiaobo Tan, MSU).

Startup company: Agnosia Media, LLC, founded by Randall Hayes (NCAT). Main product: Educational media.

4b. Other outputs of knowledge transfer activities

None to report

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/ 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	Living PlanIT	Company	21 Ruelle des Moulins, 1260 Nyon, Switzerland	Steve Lewis	KT	Y
4	Metron	Company	1818 Library Street, Suite 600 Reston, VA 20190		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	iDigBio	Other	105 NW 16th Street Gainesville, FL 32611		Research, Education	N
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)	16
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	$878,577
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)	335

8. Media publicity

Press Releases

- 10/27/14: MSU to help students learn genomics and evolution
- 9/24/14: Robofish gets a new mission: finding Nemo
- 8/27/14: Facts and values: What's it take to be an effective scientist?
- 8/12/14: Addressing the effect of agriculture on global health
- 7/28/14: Evolutionary compromises drive diversity [VIDEO]
- 7/15/14: Undergraduates present at summer research symposium
- 6/26/14: Sequencing electric eel genome unlocks shocking secrets
- 5/22/14: Delegating the dirty work is a key to evolution
- 3/10/14: Impersonating poisonous prey
- 12/20/13: Computing a football season
- 11/14/13: No peak in sight for evolving bacteria [VIDEO]
- 11/11/13: Bacteria may allow animals to send quick, voluminous messages

Media Coverage

- 10/27/14: mLive: Flint school district students, community to get lessons in genetics following $1.2 million grant
- 10/1/14: FishSens Magazine: Robofish research vehicle to help track living fish and their habitats
- 9/29/14: Africa Geographic: Hyenas: Bucking the trends and wearing bling
- 9/28/14: The Associated Press: US aids Michigan State to build better robofish
- 9/24/14: WILX News 10: MSU's robofish is getting an upgrade
- 9/24/14: Michigan Radio: Move over, Robocop. Robotic fish is here
- 9/1/14: Virology (cover of September issue): Three-dimensional reconstructions of the bacteriophage CUS-3 virion reveal a conserved coat protein I-domain but a distinct tailspike receptor-binding domain
- 8/25/14: Bioscience: For Microbes, Devolution Is Evolution
- 8/2/14: Coeur d'Alene Press: Building better 'bots
- 8/1/14: SIGEVOlution newsletter: BEACON Center Teams Biologists with Computer Scientists and Engineers to Study Evolutionary Processes and Solve Problems
- 7/29/14: io9: A winged cat helps explain the principle of evolutionary trade-offs
- 7/29/14: Futurity: Compromise is key to evolving new creatures
- 7/22/14: Quanta Magazine: The New Science of Evolutionary Prediction
- 7/7/14: Nautilis Magazine: If the world began again, would life as we know it exist?
- 6/26/14: NPR: A shocking fish tale surprises evolutionary biologists [AUDIO]
- 6/26/14: Wired: How evolution gave some fish their electric powers
- 6/26/14: Spokesman Review: UI Program Bytes Gender Gap
- 6/26/14: Coeur d'Alene Press: Girls 'Dign'IT' this summer
- 6/20/14: The East African: Saving the intelligent Mara hyena
- 6/9/14: Futures (MSU AgBioResearch newsletter): Priming the Pipeline: Exploiting weakness

- 5/21/14: UW: Marine apprenticeships give UW undergrads role in animal-ancestor breakthrough
- 5/8/14: Nautilus: Want to get out alive? Follow the ants…
- 4/15/14: io9: These Sweet 3D Fitness Landscapes Show Evolution At Work
- 4/11/14: VICE Motherboard: A Simple Visualization of How Species Evolve
- 3/13/14: Cell Reports: Bacteria Evolve with No Limit in Sight
- 3/12/14: Futurity: Why some critters give up camo to look toxic
- 3/11/14: International Science Times: Animals 'impersonate' poisonous prey to survive
- 3/10/14: ScienceDaily: Impersonating poisonous prey: Evolution of interspecific communication
- 2/22/14: The Economist: Spot the difference – Hyenas talk to each other, as it were, through their backsides
- 2/11/14: Proceedings of the National Academy of Science: Microbes take charge
- 2/7/14: NSF.gov Discovery Video: Hofmann explains how environment and genetics influence the brains and behavior of cichlid fish
- 1/16/14: WKAR: MSU scientist considers perils of a post-antibiotic world [AUDIO]
- 1/7/14: Audubon Magazine: Birds can smell, and one scientist is leading the charge to prove it
- 1/6/14: National Geographic Phenomena – The Loom: Evolution hidden in plain sight
- 1/4/14: Detroit Free Press: Pick your spots: Chance encounter leads MSU professor to career studying hyenas
- 12/23/13: NSF Research Highlight: Tropical phytoplankton feel the heat
- 12/11/13: MSU AgBioResearch: BEACON: Guiding a new era of revolutionary research
- 12/5/13: NOVA – The Secret Life of Scientists and Engineers: Danielle Whittaker, Evolutionary Biologist [VIDEOS]
- 12/3/13: NOVA – The Secret Life of Scientists and Engineers: 30 Second Science with Danielle Whittaker [VIDEO]
- 11/21/13: Astrobiology Magazine: No peak in sight for evolution
- 11/20/13: Lansing State Journal: Bioengineering building at MSU, renovation of science building at LCC signs of progress
- 11/17/13: Ars Technica: After 50,000 generations, bacteria are still evolving greater fitness
- 11/15/13: National Geographic Phenomena – The Loom: A long way left up Darwin's mountain
- 11/15/13: New Scientist: Perfection is a myth, show 50,000 bacterial generations
- 11/15/13: Futurity: No 'fitness peak' in sight for evolving bacteria
- 11/15/13: Spectroscopy now: Social scent networking: Hyena analytics
- 11/15/13: French Tribune: Experiment shows evolution never stops
- 11/14/13: NSF News from the Field: No peak in sight for evolving bacteria
- 11/14/13: NPR: Bacterial competition in lab shows evolution never stops [AUDIO]
- 11/14/13: Science: Podcast interview with Rich Lenksi [AUDIO]
- 11/14/13: Science: The man who bottled evolution
- 11/14/13: ScienceDaily: No peak in sight for evolving bacteria
- 11/14/13: Wild Mammal Blog: Hyena scent posts use symbiotic microbe messengers
- 11/13/13: io9: Hyenas may be using bacteria to communicate
- 11/12/13: Scientific American: Smelly microbes help hyenas to communicate
- 11/12/13: ABC News: Hyena identity linked to odor molecules made by bacteria

- 11/12/13: French Tribune: Scientist says animal scents can manipulate animal behavior
- 11/12/13: The Register: Hyenas can Facebook with their arses: true fact
- 11/12/13: Futurity: Microbe-rich pastes key to hyenas' smelly signals
- 11/12/13: Nature World News: Mr. Stinky – Bacteria in scent gland help hyenas communicate
- 11/11/13: ScienceDaily: Bacteria may allow animals to send quick, voluminous messages
- 11/11/13: The Scientist: Microbial mediators
- 11/11/13: Los Angeles Times: Hyenas send smelly signals on sex and species with microbes' help
- 11/11/13: International Business Times: A hyena's smelly social network is reinforced by bacteria: Study
- 11/11/13: LiveScience: Bacteria control hyena communication
- 11/11/13: National Geographic: Bacteria power social lives of hyenas
- 11/11/13: Nature: Smelly microbes help hyenas to communicate
- 11/1/13: MSU Developments Magazine: Closer to a Cure

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 BEACON for extended periods in 2013-14, each funded primarily by the visitor's host institution or a grant from their government. During the reporting period, one of Prof. Xu's students (Haiqiang Nie) and one of Prof. Yao's students (Weiming Ji) spent time as visiting scholars in BEACON. The projects in which they are involved are the Greenhouse Control project and the Ultrawideband Microwave Breast Cancer Detection project, respectively (reported in the Research section).

As a result of the international project involving collaboration of Erik Goodman and Kalyanmoy Deb (MSU) with Dr. Oliver Chikumbo (then of Scion, a crown research laboratory in New Zealand), Dr. Chikumbo was hired as a Research Associate Professor at Michigan State University. This project is described under the Knowledge Transfer section as it is aimed at collaboration with Living PlanIT, a "smart cities" company headquartered in the U.K.

To facilitate continuation of the extensive collaboration going on between Dr. Goodman and Prof. Zhun Fan and his colleagues in the newly established Guangdong Provincial Key Laboratory of Digital Signal and Image Processing of Shantou University, BEACON signed a five-year agreement establishing the International Joint Research Center for Evolutionary Intelligence and Engineering Applications, dated July 25, 2014. Both in-person visits and videoconferences will be employed to further the collaboration.

Kalyanmoy Deb is working with international collaborators in Denmark, Germany, and Sweden for the project “IN SPE: Innovation consortium for sustainable performance in electronics,” funded by the Danish Agency for Science, Technology and Innovation, and described in the Knowledge Transfer section of this report.

BEACON hosted a sabbatical visit of Prof. Stephan Winkler, of the HEAL (Heuristic and Evolutionary Algorithms) Laboratory of the Upper Austria University of Applied Sciences. An informal plan to fund student exchanges between the two organizations has resulted, and some software created within BEACON will likely also be distributed through the HEAL website, which provides source code for many evolutionary algorithms.

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)