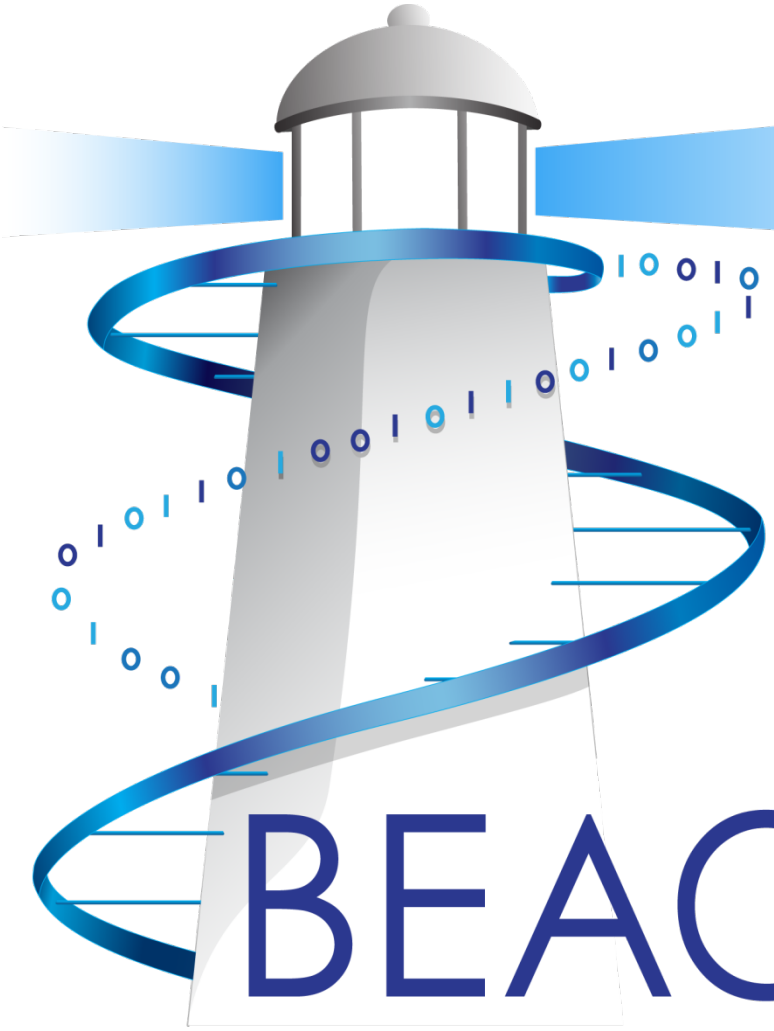

BEACON

An NSF Center for the Study of Evolution in Action

BEACON Center for the Study of Evolution in Action

ANNUAL REPORT
November 1, 2015

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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.

STC Renewal

BEACON's renewal proposal generated extremely positive feedback, from anonymous written reviews as well as external reviewers at our annual NSF site visit. Below, we offer a sampling of comments from reviewers.

> *This Center's focus on evolution in action is certainly of the highest importance. Its marvelously interdisciplinary goals of studying complex evolutionary dynamics (focusing on a suite of very important, exciting specific 'thrusts' and projects) and using the results for training, education (on evolution and science, in general) and for industrial applications is highly laudable.*

BEACON has created a vibrant, innovative environment for research and learning. This proposal offers a well-reasoned and exciting plan for how the PIs and other affiliates will build upon that momentum in the coming years.

…the researchers are clearly talented, committed, and have done an excellent job of meeting their goals during the first round of funding

BEACON has been producing some of the best young scientists being trained in this area.

BEACON is an extremely valuable and impressive NSF Center, there is no reason not to continue its excellent research and educational programs. It is particularly exciting to the see the inter-disciplinary and inter-instititional collaboration carried out across such complex and normally competitive research areas. A well-justified and highly fundable project.

This is exactly the kind of work the NSF should be supporting.

BEACON's renewal proposal was approved for funding in July 2015. This reporting period covers the last 6 months of the first STC grant, and the first 6 months of the renewal grant.

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. 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	67 projects currently underway, 849 publications to date (203 submitted 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	None to report in this period
	Number of new journals and societies	None to report yet
	New or increased funding for biocomputational research	BEACON researchers submitted 72 proposals for external funding concerning evolution in action, and >$22M in external funding was granted in this reporting period.
Increase in publications related to evolution in action	Number of BEACON faculty participants writing such publications and the number of citations of their work.	BEACON publications and citations thereof are increasing steadily every year.
	High visibility science journalism about BEACON research	12 press releases and >50 media pieces since previous annual report, including high profile pieces in *New Scientist*, *The New York Times,* CBS, *Fox News*, *The Daily Mail*, NPR, and two episodes of Science Channel's *Through the Wormhole with Morgan Freeman*.
Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	Number of requests for information	4,508 downloads of Avida-ED. Over 3,600 visits to BEACON website monthly.
Ethical Research Goal		

Center participants will understand shared and discipline-specific practices of Responsible Conduct of Research (RCR) and will embody general scientific norms/virtues, including objectivity, integrity, community, and transparency.	Number of RCR training opportunities provided	4 Scientific Virtues sessions offered at BEACON seminars and Congress, including 1 new module piloted
	Number of BEACONites who attended RCR training sessions offered by BEACON	29
	Number of BEACON seminars offered	28 BEACON seminars have been offered since Feb 1, 2015.
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	203 publications submitted, 189 conference or other presentations, 72 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. Many of these projects seek to observe and understand adaptation in action at a molecular level. Current areas of focus include (1) genome evolvability; (2) adaptation in action; (3) evolution of resistance to therapeutic treatments; and (4) illuminating evolutionary processes with synthetic biology. A total of 19 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, cognition, communication, coordination, social dominance, and mate choice. 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 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. Seventeen 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) evolution-based software engineering and robotics; and (3) using evolution for biotechnology and synthetic biology. 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 (14 PhD's, 5 Master's, 2 Bachelor's). Of the PhD graduates, 71% are currently in postdoc positions, 7% are in faculty positions, and 7% are working in industry. Of 7 postdocs who left BEACON this year, 4 took faculty positions, 2 are now postdocs 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 continues. Evaluation instruments are being used to assess effectiveness.
	Adoption of materials by teachers; frequency of public use of online materials and visits to museum exhibits.	Cross-institutional dissemination of materials is underway.
Increased interest in STEM careers in both academia and industry	Pre- and post-program survey instruments administered to K-12 participants, university students, and the public	Diversity surveys are being administered across education projects where appropriate. Data are presented in diversity section.
	Feedback from the External Advisory Committee	Positive feedback. See Appendix C

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

evolutionary biology is a good example of how science works; (3) evolutionary processes can help us solve complex biological and engineering problems.

Internal Education Activities. BEACON continues to offer a series of courses specifically designed to train graduate students across disciplines. Courses include Computational Science for Evolutionary Biologists taught by Dr 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 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. These courses also engage senior graduate students as co-instructors, providing unique opportunities for communicating science as well as developing instructional materials under the guidance of our faculty.

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 numerous outreach events, REU experiences at both KBS and FHL, and new projects to engage with undergraduate biology education. We piloted two new programs this summer, one aimed at providing research experiences for preservice teachers (URIT) and a second program that provided research experiences for inservice teachers (BEACON TEACHER REVOLUTION). 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 new museum exhibits at MSU.

Knowledge Transfer

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

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

	Number of joint grant proposals submitted with industrial partners	At least 3 proposals have been submitted, and others are 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 plans are continuing to develop for another spinoff 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, Hyundai, Toyota, Continental Automotive, Chrysler, BAE Systems, General Motors, and StoneAge Robotics.

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 (Socio-Environmental Synthesis Center), NESCent (National Evolutionary Synthesis Center), iDigBio, iPlant Collaborative , National Earth Observatory Network (NEON) and Data Carpentry 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 Rio Grande Valley.

Diversity

BEACON has effectively institutionalized its two overarching diversity goals: 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 BEACON is achieving and sustaining diversity through inclusive recruiting, and the leveraging of strong partnerships and programming to ensure consistency and sustainability. To summarize our diversity statistics:

- *URMs*: BEACON participants are: 51% White, 25% Black, 10% Asian, 5% Hispanic/Latino, 1% Native American, and 8% two or more races/ethnicities. Currently 39% of BEACON participants are self-reporting as URMs, which is above the National Norm (31.0%) for URM.
- *Women*: BEACON successfully surpassed female participation (39.1%) across all level in the consortium, which is above the National Norm of 32.8%.
- *Individuals with Disabilities*: Currently 5.2% of our participants self-reported as having a disability, which exceeds the National Norm (3.3%).

While our stretch goal of surpassing the national norms for women across BEACON has been reached, the subsequent goal (which may prove harder) will be to maintain these numbers by ensuring an environment that supports and advances female participation throughout BEACON and the STEM community at-large.

Individuals with disabilities are a priority within our strategic efforts; and to address the above-stated challenges, BEACON has 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.

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	50% of publications and 49% of presentations reported as interdisciplinary
	Number of students enrolled in cross-disciplinary courses	20+ in semester-long courses, plus hundreds in workshops on computational science for biologists
	Number of funding proposals	36 of 72 grant proposals

	submitted	submitted (50%) reported as interdisciplinary; 25 of 72 (35%) inter-institutional
Increase in cross-institutional research and education	Number of paper/conference submissions	37% of all publications and 33% of presentations reported to be cross-institutional
	Number of new courses and workshops	New Data Carpentry, EDAMAME workshops
	Number of students in cross-institutional courses	This year only MSU students participated in semester-long BEACON courses, though the courses were available to students at the partner institutions. Hundreds participated in workshops on computational science for biologists
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	BEACON researchers submitted 72 proposals for external funding concerning evolution in action, and >$22M in external funding was granted
	Award dollars	BEACONites have been awarded over $22M from outside BEACON in this funding period (~$17M for cross-disciplinary proposals, compared to last year's $9M), far exceeding goal of $5M/year
Effective support of Center operations by Management team	Survey for participants about management team	2015 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	BEACON's 5-year renewal proposal was approved and funded.
	Number of public mentions made by NSF about BEACON	Over 40 tweets, retweets, favorites, and mentions by @NSF_BIO Twitter account; at least one piece on NSF

		media (Science 360 Radio)

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). This process continues to encourage BEACONites to engage in new collaborations that include interdisciplinary and interinstitutional work. 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. In Spring 2015, Farrell-Cole and Amey conducted a survey of BEACON faculty, postdocs, and graduate students. The questions were closely aligned with the previous survey conducted in 2013, to allow for comparison across time. The questions centered on (1) how well BEACON is meeting its mission statement, (2) satisfaction with BEACON leadership and management, as well as the climate among colleagues, (3) impressions of BEACON's impact in research, education, and outreach. All sections included open-ended questions where respondents could identify issues that concerned or interested them. The survey revealed that overall satisfaction with BEACON leadership and management is still quite high. Climate and respect among BEACON colleagues is very highly rated, particularly within institutions. We were very pleased to see that the perception of BEACON as "a catalyst for the creation of new research" has increased very favorably over 2013. Areas of focus for the year ahead include continuing efforts to socialize new members of BEACON – and keep more senior members engaged, and assuring a culture of respect and constructive feedback in the budget request review process (addressed above).

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. 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. MSU has appointed Dr. Wolfgang Banzhaf, currently at Memorial University of Newfoundland, to fill this chair, beginning August 2016. Banzhaf is one of the co-authors of *Genetic Programming: An Introduction*, a classic text in the field, as well as the sole author of *Linear Genetic Programming*, which provided a new basis to view genetic programming, extending the original work of Koza to new domains. In addition, Banzhaf served as the founding editor of the journal Genetic Programming and Evolvable Machines. He currently chairs the Association for Computing Machinery's Special Interest Group on Genetic and Evolutionary Computation (SIGEVO). At MSU, Banzhaf's primary appointment will be in the Department of Computer Science and Engineering, and through BEACON he will be interacting with many other researchers from many disciplines.

Center-Wide Outputs

Publications submitted: 203 reported

Conference presentations and other dissemination activities (including lectures, seminars): 189 reported

Awards and Honors: 37 awards and honors reported

Students that graduated (reported): 13 PhDs, 5 Masters, 2 Bachelors

General outputs of knowledge transfer activities: 2 provisional patents

Participants: 364 participants, plus another 353 affiliates (under 160 hours/year in Center activities), for a total of 717 BEACONites

Media publicity: Since the previous annual report, we have put out 12 press releases so far. Over 50 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; Meng Yao, East China Normal University; Professor Hailin Liu, Guangdong University of Techology) to work with Erik Goodman on BEACON research projects. Ongoing work on using Multi-objective Evolutionary Optimization for solution of land use problems is continuing, with Mr. Jonas Schwaab joining BEACON as a visiting scholar from ETH Zürich to collaborate with Goodman and Kalyanmoy Deb.

Prof. 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. Prof. Deb is also extensively working with foreign collaborators in the area of evolutionary multi-criterion optimization and their applications, including visiting students from Egypt, China, Turkey, and Germany, who spent a considerable amount of time with Prof. Deb to progress their doctoral/master's thesis work funded by their own university/government. Several post-doctoral researchers from Turkey, South Africa, Mexico, and Canada also visited MSU on a grants from their own university and worked with Prof. Deb on evolutionary dynamic optimization, parallel evolutionary methods, visualization and opposition-based optimization methods.

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 67 research projects were supported by BEACON, including 33 projects that just began in summer/fall 2015. 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	67 projects currently underway, 849 publications to date (203 submitted 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	None to report in this period
	Number of new journals and societies	None to report yet
	New or increased funding for biocomputational research	BEACON researchers submitted 72 proposals for external funding concerning evolution in action, and >$22M in external funding was granted
Increase in publications related to evolution in action	Number of BEACON faculty participants writing such	BEACON publications and citations thereof are increasing

	publications and the number of citations of their work.	steadily every year.
	High visibility science journalism about BEACON research	12 press releases and >50 media pieces since previous annual report, including high profile pieces in *New Scientist*, *The New York Times,* CBS, *Fox News*, *The Daily Mail*, NPR, and two episodes of Science Channel's *Through the Wormhole with Morgan Freeman*.
Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution	Number of requests for information	4,508 downloads of Avida-ED. Over 3,600 visits to BEACON website monthly.
Ethical Research Goal		
Center participants will understand shared and discipline-specific practices of Responsible Conduct of Research (RCR) and will embody general scientific norms/virtues, including objectivity, integrity, community, and transparency.	Number of RCR training opportunities provided	4 Scientific Virtues sessions offered at BEACON seminars and Congress, including 1 new module piloted
	Number of BEACONites who attended RCR training sessions offered by BEACON	29
	Number of BEACON seminars offered	28 BEACON seminars have been offered since Feb 1, 2015.
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	203 publications submitted, 189 conference or other presentations, 72 grant proposals submitted during this reporting period
BEACON research output will be perceived as making an important contribution to the literature.	Feedback from the External Advisory Committee	Positive feedback. See Appendix C.

1c. Problems in making progress towards these goals.

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

- **Annual meeting**, with sessions designed to stimulate new collaborations and networking sessions for students and postdocs: We held our sixth annual BEACON Congress in August 2015. 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. We anticipate full completion by early 2016.
- **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 supports research in four thrust groups, including three based on natural levels of organization (genomes, behavior among individuals, and community-level dynamics) and a fourth group focused on evolutionary applications. These thrust groups are united by 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. Many of these projects seek to observe and understand adaptation in action at a molecular level. Current areas of focus include (1) genome evolvability; (2) adaptation in action; (3) evolution of resistance to therapeutic treatments; and (4) illuminating evolutionary processes with synthetic biology. A total of 19 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.

Genome evolvability

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. The research team is detecting potentiation using co-culture competition assays and measuring metabolic flux, testing whether potentiated clones exist in other LTEE populations, and determining whether ecological interactions played a role in potentiation.

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, using the gar as a basal lineage to examine how the teleost visual system is organized in the absence of a duplicated genome. The team is also investigating whether the ability to regenerate their retina is present in these basal groups. They are also examining the visual opsins and the sensory environments of multiple stickleback populations, which undergo selection depending on the color of the water in which they live.

Verónica Di Stilio (UW) and David Tank (UI) are investigating the **evolutionary and ecological consequences of polyploidy**. Polyploidy, or whole genome duplication, has a long history of recognized relevance to the evolution of plants. It likely contributed to Darwin's "abominable mystery" – the rapid rise and early diversification of angiosperms. Both ancient and recent episodes of polyploidy have now been confirmed in a variety of eukaryotes, emphasizing its broader role in biological diversification. The large-scale effects on gene expression resulting from polyploidy can produce immediate changes in morphology and ecological interactions, leading to speciation. The team recently showed that polyploidy is significantly correlated to wind pollination in one of the few angiosperm genera that combines wind and insect pollinated species with variation in ploidy level. A suite of morphological traits commonly associated with the 'wind pollination syndrome' includes long stigmatic surfaces for pollen capture. These stigmas consist of papillae resulting from the activity of a gene that the team hypothesizes underwent a gain-of-function mutation, resulting in the extended or "feathery" stigmas of wind-pollinated flowers. This group plans to determine whether polyploidy has evolutionary consequences on gene function and pollination syndrome in the flowering plant genus *Thalictrum* by: (1) increasing the resolution of phylogenetic reconstructions for comparative studies, (2) reconstructing the evolutionary history of a candidate gene underlying a key floral trait associated with pollination syndrome, and (3) determining changes in the pattern of gene expression of this and other candidate genes in diploid vs. polyploid species.

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. The team has implemented Horizontal Gene Transfer (HGT) in Avida, and is using it to examine a series of hypotheses regarding evolutionary pressures that promote HGT, and HGT's impact on genetic architecture and evolvability.

Graduate student Rohan Maddamsetti, postdoc Jim Stapleton, and Rich Lenski (all MSU) are **studying recombination in evolution experiments**. While researchers have studied how recombination can speed up adaptation in laboratory evolution experiments, observing genome dynamics in populations undergoing recombination and horizontal gene transfer remains a challenge. Genome assembly algorithms often have difficulty dealing with structural variation, such as complex genetic rearrangements, transpositions of selfish genetic elements, and mutations in repetitive regions, due to ambiguities and errors in short read (~ 250 base pair) data. The team is revisiting an evolution experiment in which *E. coli* K-12 periodically recombined into replicate populations of *E. coli* B, and will look for evidence of parallel evolution in genome architecture in these recombinant strains, focusing on regions in *E. coli* B that are resistant to replacement by homologous regions of *E. coli* K-12. These analyses will provide a guide for researchers studying the spread of pathogenicity islands and antibiotic resistance in microbial populations through recombination.

Rich Lenksi and graduate students Alita Burmeister and Carina Baskett (all MSU) are studying **evolutionary and ecological effects of parasitism on host genomes**. Antagonistic coevolution is predicted to accelerate evolution by increasing the rate at which populations encounter new selective pressures, caused by the back-and-forth evolution of host resistance and parasite infectivity. The relationship between coevolution and genetic diversification has generally been understudied, in part because coevolution experiments typically don't include non-coevolving, host-only populations. This team will work with bacterial host populations evolved with and without phage present, thereby manipulating the effects of a natural mode of coevolution. They will test whether the relationship between antagonistic coevolution and diversity holds true for host populations with their much larger genomes, in two natural evolutionary contexts: with coevolution and without coevolution. The host population genome data will also provide signatures of selection in the presence of phage, mutations will likely be associated both with phage resistance and growth in the complex environment generated by phage-host interactions, specifically the ability to use the macronutrients released from hosts upon phage lysis. The host sequence data will be used to explore potential resistance and nutrient recycling mutations and investigate how phage lysis indirectly changes selection on the host.

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. They also measured the changes in stoichiometry throughout 60,000 generations in

one population of *E. coli* in the long-term evolution experiment (LTEE). The proportion of nitrogen in biomass increased most rapidly early in the experiment, but showed signs of continuing to increase even after tens of thousands of generations.

Rebecca Young (UT postdoc), Heather Goldsby (UW postdoc), Arend Hintze (MSU), and Hans Hofmann (UT) are studying **developmental evolution in action by testing the "hourglass model."** Embryos exhibit the greatest morphological similarity at their "phylotypic stage," *i.e.*, the point in development when species of a given lineage most closely resemble one another. This hourglass model of development is supported by recent comparative transcriptomic analyses, possibly due to interdependence (pleiotropy, epistasis) of gene regulatory networks (GRNs) during at the phylotypic stage. Embryonic GRN topology itself should thus also transition from more plastic (e.g., modular) to more robust (e.g., highly interconnected) and back. The team is testing this novel hypothesis by examining public gene co-expression data across development – followed by topological network analyses. Further, an *in silico* evolutionary model of a developing tissue is under development, which will allow comparison of different mechanisms of pattern formation, and can show whether intermittent developmental patterns resemble each other.

Adaptation in action

Louise Mead (MSU) is collaborating with Melissa Wilson Sayres (Arizona State University) to assess **human-specific evolutionary pressures on genes involved in early puberty**. In typical human females, breast development and pubic hair usually signify the onset of puberty, which is followed later by menarche, and research suggests these two events are occurring earlier and earlier in modern humans. Recent studies have found that the average age of onset of puberty has dropped, with breast development showing more significant changes than menarche, suggesting these are, or are becoming, decoupled. This raises several questions: are these changes examples of evolution in action in humans? What selective factors may be influencing these changes? What are the health implications? This team aims to investigate the patterns of evolution across humans and mammals in genes implicated in the onset of puberty. To investigate genes implicated in the onset of puberty, they focus on a condition called precocious puberty. They will assemble sets of genes involved in precocious puberty, assess levels of purifying and positive selection on the human lineage in each of these genes, assess genetic diversity across human populations in genes implicated in precocious puberty, and examine genes that may interact with genes associated with precocious puberty.

Brenda Murdoch, James Foster, and Mark McGuire (all UI) are testing **whether human milk sugars evolved in response to a biocultural sweet tooth**. Human milk provides optimal nutrition during infancy, and its composition is used to estimate nutrient requirements of neonates and the gold standard for composition of infant formula. However, milk produced by healthy women around the globe varies dramatically in its composition, and little is known about the genesis of this variation. The team is examining a paradigm-shifting hypothesis that milk composition is evolutionarily customized to optimize infant health in a particular sociocultural and environmental niche by investigating the relationship between maternal genetic diversity and variation in human milk oligosaccharide (HMO) profiles. They will evaluate milk collected from 480 women living in 8 countries as part of an NSF-funded project comparing differences in HMO profiles around the world and relate them to sociocultural and ethnic factors. This project will extend the parent study by examining the genetic variation of candidate genes thought to

drive variation in HMO differences. Sequence variation in 4 HMO-related genes (FUT2, FUT3, LALBA, and B4GALT1) will be determined to identify functional polymorphisms. Importantly, these genetic variation data will be used to perform neutrality tests and association studies with differences in HMO isoforms and quantities, across and within the study population. This research will provide critical preliminary data needed for larger grant applications allowing investigation of genetically-driven differences in other milk constituents important to infant health while allowing us to determine if molecular evolution is occurring in these genes.

Martha Mulks, Richard Lenski, and graduate student Elizabeth Baird (all MSU) are studying **long term parallel evolution of a pathogen within the lungs of cystic fibrosis patients**. Cystic fibrosis (CF) patients are highly susceptible to chronic lung infections with bacterial pathogens and thus provide ideal (though unfortunate) reservoirs for parallel bacterial evolution. *Burkholderia cenocepacia* (*Bcc*) is normally a soil organism associated with the rhizosphere of plants and an occasional opportunistic pathogen of CF patients. However, several epidemic strains arose in the 1980s that were capable of patient-to-patient transmission. One strain, the Bcc Midwest clone, predominated in Michigan and neighboring states. Some patients infected with this clone died rapidly of a severe systemic infection, but a few have survived over 25 years with this pathogen. Recent studies following genetically distinct strains of *Pseudomonas aeruginosa* as well as an epidemic strain of *B. dolosa* over time within multiple patients have shown convergent (*P.a.*) and parallel (*B.d.*) evolution and adaptation of these pathogens within the CF lung, but these studies have revealed different adaptive mechanisms for these two pathogens. The team's preliminary studies on Bcc Midwest clone suggest that this organism has followed its own unique adaptive pathway. Analyzing isolates of this *Bcc* epidemic clone that span over 27 years will lead to obtain new insights that will inform the breadth and diversity of each of these systems. Novel pathways of infection, adaptation, and long term survival of a pathogen within its host may be uncovered by comparing functional gene evolution between species. The goal of this project is to determine how the Midwest clone has evolved and adapted to the CF lung during long term chronic infections.

MSU postdocs Aditi Gupta, Bjørn Østman (now at UC Santa Barbara), and Tao Zhou worked 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 previously been investigated in viral populations. The team hypothesized 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. They serially introduced 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). To test whether valley crossing occurs in evolving virus populations, mutated (low fitness) proteases were reintroduced into the virus to test whether fitness is restored by subsequent cycles of replication that introduce new mutations. They found that the fitness landscape of HIV-1 protease is indeed rugged, and found that most of the mutations are destabilizing, explaining their low frequencies in population sequence data.

Noah Ribeck (MSU postdoc), Brian Connelly (UW postdoc), Luis Zaman (UW postdoc), and Rich Lenski (MSU) are developing a **general theory of asexual adaptation** called **lineage interference**. We lack a comprehensive theoretical framework for describing the dynamics of

adaptation of asexual populations by accumulation of beneficial mutations by natural selection. The canonical clonal interference theory accounts for the possibility of multiple beneficial mutations segregating simultaneously, which then must compete with each other for fixation in the population. However, this theory breaks down for asexual populations that are large or have a high beneficial mutation rate, since in this regime, multiple beneficial mutations can accumulate in a particular lineage before any one mutation fixes. To remedy this issue, the team is developing a "lineage interference" theory of asexual adaptation, which will be the first theoretical framework that can be consistently applied an asexual population of any size, with any mutation rate.

Chris Adami (MSU), with Thomas LaBar (MSU graduate student) and Masoud Mirmomeni (former MSU graduate student, now at University of Michigan), is working on **theory and experimental verificiation of "free fitness" maximization**. A major goal of evolutionary dynamics is to explain how the mean fitness of a population changes over time. A first attempt to explain these dynamics was proposed by Fisher in his Fundamental Theorem. In this theorem, fitness was showed to never decrease, and the increase is proportional to the population's additive genetic variance in fitness. However, this theorem only holds under limited conditions; it requires an infinite population and ignores genetic drift and mutation. Recently, an extension of Fisher's Fundamental Theorem was introduced by Sella and Hirsch that argues, using connections with statistical physics, that it is Free Fitness that increases during evolution, not just fitness. Free fitness extends Fisher's theorem to finite populations and includes the effects of genetic drift; like fitness in Fisher's theorem, free fitness never decreases over time and is maximized by evolution. This team is using digital evolution experiments to test whether the Free Fitness theorem explains the evolutionary dynamics of asexual populations better than Fisher's Fundamental Theorem.

Evolution of resistance to therapeutic treatments

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. Their results indicate that the HIV-1 protease evolves resistance to treatment by increasing the mutual information significantly over time, even though the sites becaome more entropic. They also

found that several pseudogenes are differentially expressed in infected T-cells, and parent genes of half of these pseudogenes are implicated in viral infections.

Joseph Graves, Jr. (NCAT), Jeff Barrick (UT), and Rich Lenski (MSU) are examining the **evolution of resistance to metallic/metallic oxide nanoparticle resistance in bacteria**. The spread of antibiotic resistance has produced an increasingly aggressive search for new antimicrobial agents. Metallic/metallic oxide nanoparticles have been proposed due to their high surface-to-volume ratio and their unique chemical and physical properties. Silver has been successfully used as an antimicrobial against 16 major species of bacteria. The release of Ag+ ions is the primary mode of action for Ag nanoparticles. Due to the multiple mechanisms impacted by metallic/metallic oxide nanoparticles it was widely thought that bacteria could not readily evolve resistance to them. However, the Graves laboratory at the Joint School of Nanoscience and Nanoengineering (JSNN) has produced AgNP resistant *E. coli* via experimental laboratory evolution. The team is determining candidate genetic mechanisms for silver resistance and testing whether the shape of the metallic nanoparticles influence the selection response.

Claus Wilke (UT), Patrick McPhail Martin (NCAT), and Checo Rorie (NCAT) are investigating the **evolution of chemotherapeutic resistance in glioblastoma multiforme**. 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 five-year survival rate of significantly less than 10%. Patients diagnosed with this disease typically undergo surgical resection to remove the bulk of the tumor, followed by an aggressive course of chemotherapeutics and radiation to try and remove the rest. Despite aggressive treatment, survival to 3-5 years remains low, in large part because GBM tumors evolve resistance to these treatments and thereafter re-occur, typically around 6-8 months after resection. The team hypothesizes that GBM acquires resistance to one common chemotherapeutic, temozolomide (TMZ), through specific molecular mechanisms, and is using experimental evolution to attempt to better understand these mechanisms.

Illuminating evolutionary processes with synthetic biology

Jeff Barrick (UT), Scott Harrison (NCAT), and Rob Newman (NCAT) are **illuminating evolution in action with expanded genetic codes.** Evolution of the genetic code has remained poorly understood due to its nearly universal conservation in all living organisms and the difficulty of engineering changes in its properties. With advances in synthetic biology, it is now possible to create genetic codes that have been expanded by recoding a stop codon to one of many different non-canonical 21st amino acids. Furthermore, recent work has established that organisms evolved in the context of such a code will both adapt to and make use of the new amino acid. These results encourage the wholesale exploration of the properties of organisms evolved in the presence of expanded genetic codes. This team is probing the implications of this type of major evolutionary transition using the AVIDA artificial life system and laboratory evolution experiments carried out across a variety of biological scales. They are comparing the abilities of organisms and proteins to tolerate mutations to different non-canonical amino acids (or computational instructions) in expanded genetic codes. They will then assess how the chemical or computational properties of each expanded genetic code enable organisms to evolve new and useful traits. Finally they will determine what factors affect the propensity of newly

expanded codes to either collapse or become fixed in free-living organisms. Overall this work will further our understanding of the evolution of one of life's most fundamental properties.

James Bull (UT) and Scott Nuismer (UI) are working on **predicting the evolution of synthetic genomes** to develop **transmissible viral defense**. The goal of this project is to develop the concept of an infectious vaccine – a transmissible agent that protects the host against harmful agents such as lethal viruses. The work has a theoretical component and an empirical one. The original intent was to develop a synthetic system (using bacteria and phages) in which the vaccine was engineered to block infection by the lethal virus, but as the work progressed, the team realized the concept was so original that they should develop it more broadly. The empirical focus thus expanded beyond synthetic systems to include natural agents that could function as a vaccine against lethal viruses.

Andrew Ellington (UT), Eric Klavins (UW), and graduate students Chris Takahashi (UW) and Leandra Brettner (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). The Ellington group is developing an autoregulatory circuit based on T7 RNA polymerase (T7 RNAP) that will be used as a prototype for evolutionary optimization of synthetic circuits. Such an autoregulatory T7 RNAP circuit will work orthogonal to the host allowing for expression of metabolic/operons optimized for yield of the metabolic product. To increase the dynamic performance, they have identified two parameters – the ribosome binding site (RBS) and the T7 promoter – and have shown that both can be used to reliably tune the production of T7 RNAP and its downstream targets. The Klavins lab has developed an evolutionary model to describe the growth microbes in continuous culture which can subsequently be used for optimization of the synthetic metabolic pathways. 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.

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, cognition, communication, coordination, social dominance, and mate choice. 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**. Discrimination against members of other populations while breeding promotes reproductive isolation and thus speciation. Understanding the evolution of mate discrimination requires insight into its heritable (i.e., genetic) basis. This interdisciplinary group is approaching this issue using two very different systems: limnetic and benthic threespine sticklebacks (*Gasterosteus aculeatus* species complex) and Avida. They examined gene expression patterns in female sticklebacks making mate choice decisions, specifically by comparing females who reject heterospecific males to females who accept conspecific males. They also examined more generally how female gene expression is correlated with particular female and male behaviors. To parallel this work, the team also used Avida, a software platform that has populations of self-replicating and competing digital organisms that undergo mutation and thus can evolve. Using a modified version of Avida that includes male display and female mate choice, they studied populations adapting to two different environments to test hypotheses about the evolution of reproductive isolation during ecological speciation. Finally, the group's monthly discussions inspired MSU staff member Clifford Bohm to do related work regarding speciation, natural selection, and mate choice using Markov Network Brains (MNBs). MNBs are artificial brains composed of logic gates that connect sensor nodes, actuator nodes that control virtual bodies, and hidden nodes that allow for memory and processing. The MNBs are encoded by a genome that is subject to mutation and agents compete to reproduce, providing the conditions for evolution. Notably, they are distinct from Avidians and an independent system for study. Bohm has been using MNBs to conduct experiments analogous to the ones using Avidians; populations will evolve in allopatry and then be brought into secondary contact to test for evolution of reproductive isolation. This project leverages expertise and computational resources at MSU and UT Austin to give insight into the evolution and genetic architecture of reproductive isolation. In addition, it will add to our understanding of the genetic basis of behavior and decision-making.

UW graduate student Frazer Meacham, with Thomas Getty (MSU) and Ben Kerr (UW), is 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: (A) Can females use a male's attractiveness to gauge his likelihood of providing future parental care? And (B) if so, how does discretionary male care influence female preferences? The team has developed

mathematical models to investigate these questions. Their results demonstrate that (A) it is possible for a female to gauge whether a male will choose to help care for her offspring even though she can only observe his physical quality, and (B) that the availability of paternal care can cause females to be more willing to accept low quality males.

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 and 2) determine how mito-nuclear compatibility influences offspring number and performance. The team has used whole genome sequencing to characterize feral chicken population structure, and analyzed behavioral and morphological traits from field observations of their focal populations. Their results are shedding new light on the evolutionary interplay between the complex behaviors of animals, and the interacting genomes within (nearly) every animal cell.

Craig McGowan (UI), Phil McKinley (MSU), and postdoc Jared Moore (MSU) are **exploring the evolution of robust joint-level control**. This multidisciplinary project combines computational evolution, detailed neuromuscular models, and experiments with 3D-printed robotic joints in order to explore the evolution of robust joint-level control. In animals, joints are controlled by signals from the brain propagating through the somatic nervous system to groups of muscles, whose collective responses produce movement. Importantly, the behavior of a joint also depends on the composition and orientation of the constituent bones, tendons and muscles. This combination enables animals to maneuver through a wide range of uneven terrains at high speeds and with minimal conscious control. Yet, the relationship between intrinsic properties of joints and their control remains poorly understood. The primary goal of the project is to elucidate this relationship in order to (1) better understand the functional morphology of biological systems and (2) improve the design of engineered systems, including all-terrain autonomous robots and robotic prostheses. The team's basic approach is to evolve joint behaviors and morphological characteristics in 3D animats using an abstract neuromuscular model called digital muscles, then map the results into detailed models of both biological and robotic systems. In doing so, this project is intended to help to answer fundamental questions in biology and improve the design of engineered systems, including all-terrain autonomous robots and robotic prostheses.

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, it is still unknown how setal morphology and perch texture interact dictating how geckos use their adhesive pads in the wild. This team is using genetic algorithms, computed tomography, and dynamic finite element analyses 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.

Fred Dyer (MSU), Robert Heckendorn (UI), Terence Soule (UI), and Laura Grabowski (UTRGV) are studying the phenomenon of **landmark guidance in an integrated study in bees, Avida, and physical robots**. Many animals navigate using landmarks – features anchored to specific locations in the environment. Bees in particular are extremely adept at returning to specific locations in complex, dynamic environments and easily out-perform all but the most sophisticated robotic navigation systems using LIDAR, GPS, and similar advanced technology. Understanding bee navigation would both significantly increase our understanding of natural navigation and improve the navigational ability of lower cost robots. The team's goals are to identify strategies of landmark guidance in bees that could support flexible landmark guidance in computational systems (specifically Avida and COTSBots), and to draw upon the performance of the artificial systems to test hypotheses about how bees navigate. To focus the research, they address two ways of using landmarks that are observed in bees: (1) using a landmark as a beacon to maintain a straight path; (2) using the same landmark to pinpoint a specific goal location. Multiple models have been proposed to explain how bees do this; the models differ in their computational sophistication, and in the modularity of the control architecture. This group has planned experiments that will tease apart these hypotheses in bees, and will explore the nature of the control system evolved in artificial systems faced by similar navigational tasks.

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. This effect can be powerful but also perplexing, because it entails a reluctance or a complete refusal to exploit the only reward the animal knows about. To understand the evolution of this phenomenon, Dyer and Hintze hypothesized that it represents a shift from exploitation to exploration that is dependent on the costs or benefits of these options, as well as the agent's uncertainty about the availability of better options. Using a combination of digital evolution and behavioral experiments with nectar-feeding bees, they found that the expression of this phenomenon is heavily influenced by the following factors: (i) environmental fluctuations (which produce uncertainty); (ii) memory of recent past experience – without memory the agent simply tracks the environment; (iii) benefits of exploitation of the inferior option (arising from the urgency of energy demands); (iv) costs of search and exploration; (v) information-gathering constraints, especially regarding social influences on the capacity to discover alternative options.

Gerry Dozier (NCAT), James Foster (UI), and Bert Baumgaertner (UI) are bringing together software design and animal behavior in a study on **simulating signals and security**. A signaling game consists of world states, actions, and two players: senders and receivers. Senders send a message about the world state to receivers, and receivers engage in an action according to the signal they receive. This team will extend signaling games simulations that they have already developed by modeling how agents survive in a sufficiently complex changing environment by learning how to reuse signals they developed in less complex situations. This goal will be accomplished by implementing signaling games as agent-based models with a changing environment. At the same time, they will extend our existing coevolutionary artificial immune

system (CAIS) for active authentication, which is based on empirical usage data where users signal their authenticity to software by their behavior and the system acts by granting the appropriate level of access. The group will use results from simulations to tune and refine the CAIS system, and they will use the CAIS system as a source of inspiration for more sophisticated simulations.

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 Alex Jordan (UT postdoc, now a PI at Max Planck Institute for Ornithology Konstanz) combine social behavior of fish with digital evolution experiments to study **information flow through hierarchical social systems**. Understanding how individuals in collectives interact and influence each others' behavior is a central challenge in modern science and is essential for achieving progress in fields ranging from the dynamics of information exchange in digital systems, human societies and other social organisms. However, one aspect of social interaction that is commonly overlooked in studies of collective systems is that interacting nodes within social networks are often not of equal status – a hierarchy exists that affects the nature and frequency of interactions among individuals. Naïvely, one may predict that socially dominant individuals, which have the greatest number of network connections, are the best sources of social information and exert the greatest influence at the level of the group. Yet there are behavioral correlates of social dominance that may inhibit information flow. For example, this team shows that the best connected dominant males in a social fish, *Astatotilapia burtoni*, are the worst sources of social information, despite having the highest rate of individual learning. Unexpectedly, subordinate males in the network, who occupy peripheral positions in conventional network analyses, are the most effective agents of information transfer in their social groups. This project has shown that the interaction metrics conventionally measured in network analyses are poor predictors of information flow through social systems, and that a new paradigm is needed.

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**. Animal intelligence appears to have evolved as a cluster of domain-specific modules that allow individuals to solve specific types of ecological and social problems. However, many animals also possess general-purpose cognitive mechanisms allowing them to find innovative solutions to problems in multiple domains. This team is exploring the evolution

of domain-general intelligence. Although animal intelligence clearly includes both domain-specific and domain-general elements, the evolution of the latter, in particular, is very poorly understood. There is also currently substantial controversy in the literature regarding whether or not brain size is even predictive of cognitive abilities in multiple domains. This group has combinined the study of problem solving in spotted hyenas and other carnivores with modeling the evolution of neural networks *in silico*. Their goals are not only to test hypotheses suggesting variables that might facilitate or constrain convergence in the evolution of general intelligence, but also to assess behavioral flexibility in a comparative context and to inquire whether brain-size predicts problem-solving ability. The team is 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.

Evolution of mechanisms mediating complex behaviors

BEACON scientists are working with diverse systems on the evolution of the neurological, physiological, and epigenetic mechanisms and other targets of natural selection that mediate behavior.

Barbara Lundrigan, Laura Smale and 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 substantial change, not only in the neural systems that coordinate the temporal patterning of a multitude of behavioral and physiological functions, but also in the many associated features that support activity in a cold/dark night vs. a warm/bright day. This study explores 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, using evolvable Markov brains, to test hypotheses concerning the factors that (likely) influence the process of temporal niche transitions. These three projects will each inform and help guide the other, ultimately leading to a better understanding of how one complex suite of adaptations can evolve from another.

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. Fred Dyer, Ian Dworkin, and Charles Ofria (MSU), with graduate students Emily Dolson and Abhijna Parigi and postdoc Frank Bartlett, are investigating **the applicability of hidden markov models to decipher motivational states underlying complex behaviors**. The target of natural selection for behavior evolution is not just isolated actions, but extended sequence of behaviors driven by shifts in underlying motivational states. Hidden markov models (HMMs) utilize 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 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. This group's goals are to 1) extend and evaluate the interpretability of

HMMs for underlying motivational states in behavioral analysis using Avida, and 2) evaluate motivational states in biological systems (*Drosophila* and bees) where these can be manipulated via evolutionary or experimental manipulations.

Kay Holekamp (MSU), Arend Hintze (MSU), and Risto Miikkulainen (UT) are examining **trans-generational epigenetic inheritance in living and digital hyenas** and its implications for understanding the evolution of behavior. During the past decade, epigenetically-mediated developmental plasticity has come to represent a critical aspect of evolutionary developmental biology, and computer scientists have also recently started to appreciate the implications of epigenetics for machine learning and robotics. In both biological and computational systems, epigenetically-mediated developmental plasticity can bias evolution and enhance evolvability. In fluctuating environments, epigenetic modification can theoretically permit young mammals to enhance their fitness by adjusting their phenotypes to match the environment they will experience at independence. The team is combining field and lab-based study of wild spotted hyenas with evolution *in silico* of digital hyenas to test a hypothesis suggesting that epigenetic mechanisms match offspring phenotypes to current environmental conditions, and thereby permit crossing of fitness valleys imposed by fluctuating environments

Patric Vaelli (MSU graduate student) and Heather Eisthen (MSU) are working to understand **voltage-gated sodium channel evolution in a neurotoxic amphibian**. Electricity is the language of the nervous system, and voltage-gated sodium channels (Na_v channels) are primarily responsible for initiating electrical signals in nervous tissue. Consequently, a diverse array of neurotoxins targeting Na_v channels have emerged throughout animal evolution. Tetrodotoxin (TTX) blocks Na_v channels at nM concentrations and is found across the animal kingdom. Rough-skinned newts possess the highest concentrations of TTX in any animal due to asymmetrical selection for increasing toxicity in response to toxin-resistant snakes, resulting in a coevolutionary arms race in which extreme phenotypes evolve. However, it is not known how newts avoid self-toxicity of their own Na_v channels. Further, the physiological effects of TTX resistance in Na_v channels are largely uninvestigated. In the absence of snake predators, some populations of newts possess little or no TTX, suggesting that TTX toxicity is costly and that Na_v channel function may be compromised by TTX resistance. Vaelli and Eisthen are examining the evolution of TTX resistance in newt Na_v channels by sequencing the TTX binding regions of all six newt Na_v channel paralogs and characterizing novel mutations. They predict that all six paralogs will possess TTX resistance mutations. They will then use electrophysiological methods to characterize the effects of TTX resistance mutations on the biophysical properties of resistant channels. This research will expand upon the dense ecological literature to address the genetic and physiological mechanisms underlying adaptive evolution in a coevolutionary model system.

Danielle Whittaker (MSU), Kevin Theis (formerly MSU, now Wayne State University), and Thomas Getty (MSU) are studying the **evolutionary implications of sexual selection on socially transmissible phenotypes**. Symbiotic microbes contribute to their host animal's phenotypes in a variety of ways, and these phenotypes can in turn affect the host's fitness. For example, microbial communities resident in mammalian and avian scent glands contribute volatile compounds used as chemical signals, and these signals are then used by the host's conspecifics to evaluate the quality of potential mates or rivals. An individual's symbiotic microbial community is strongly influenced by their social partners – individuals that interact and have physical contact on a regular basis have more similar microbial communities. Continuing their work with a songbird, the dark-eyed junco (*Junco hyemalis*), this team is testing

the hypothesis that social behavior may influence the evolution of sexual selected traits in this population. Such behavior would continually update an individual's phenotype, but may do so in a predictable way depending on the species' social and mating system (e.g., socially and genetically monogamous species vs. cooperative breeders) and seasonally patterned social interactions (e.g., territorial male-female pairs during the summer vs. single-sex flocks in the winter). The team is examining whether social behavior predictably affects an individual's microbiome within and between species, how these changes affect an individual's chemical signaling phenotype, and the implications for sexual selection and parental investment theory.

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. Seventeen 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 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, sequencing samples along gradients of shifting bacterial communities will enable metagenomic assembled genomes (MAGs) that will give insights into metabolisms of specialized endemic and generalist cosmopolitan 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 in the lake. The contrasting metabolic repertoires may also play a crucial role in 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), with graduate students Carina Baskett and Alita Burmeister (MSU) and postdoc Luis Zaman (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.

In addition to studying how external factors influence biological diversity, BEACON researchers are also studying how community dynamics affect variation through horizontal gene transfer. UW postdoc Sylvie Estrela is working with Ben Kerr (UW), Eva Top (UI), Benjamin Ridenhour (UI) and UI postdocs Wesley Loftie-Eaton and Thibault Stalder to examine how **alternating selection promotes horizontal gene transfer**. Unlike eukaryotes, most prokaryotes exchange genes horizontally and can do so at a high frequency. Plasmid transfer via conjugation is a common mechanism of horizontal gene transfer in bacteria. It is still unclear, however, how conjugative plasmids persist in populations given the costs associated with conjugation. Given such costs, why are some genes found on conjugative plasmids rather than the chromosome? The team's preliminary results via mathematical modeling indicate that conjugative plasmids can be maintained in an environment with alternating selection. They are now testing this hypothesis experimentally using a biological system consisting of three players: an *E. coli* strain containing a conjugation-proficient plasmid, a conjugation-deficient plasmid, and a plasmid-free strain. They will compete these three strains in an environment that a) constantly selects for the plasmid-encoded gene (antibiotic present), b) constantly selects against the plasmid-encoded gene (antibiotic-free), and c) alternates with periodic switching between the antibiotic-present and antibiotic-free environments. This project will provide new insights into how and why conjugative plasmids persist. Given the critical role that plasmids play in the spread of antibiotic resistance genes, this work also has wider implications for human health by contributing to our understanding of the impact of antibiotic cycling on antibiotic resistance.

Wesley Loftie-Eaton (UI postdoc), Eva Top (UI), and John Mittler (UW) are investigating how **source-sink population dynamics facilitate plasmid host range evolution**. Horizontal gene transfer in microbial communities is facilitated by bacterial plasmids. Accessory genes carried by these plasmids can encode antibiotic resistance and other beneficial traits. Under continuous strong selection, it is easy to understand how plasmids persist and spread. However, in nature most plasmids do not encode genes with obvious host benefit, and even drug resistance plasmids are not continuously under antibiotic selection. Following theoretical source-sink evolution models, this team hypothesizes that genetic variation in the genome of a plasmid in a long-term host (source) can facilitate adaptation to a naïve host (sink) in the absence of strong external selective pressure. The group is testing this hypothesis with both experimentation and mathematical modeling. Identifying ecological conditions that facilitate evolution of plasmid host range under weak selection will ultimately help limit the spread of antibiotic resistance.

Coevolutionary dynamics of interacting species

Maitreya Dunham (UW) and Ian Dworkin (formerly MSU, now at McMaster University) 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 considerably within and between populations. How such variation is maintained, and the degree to which it is evolutionarily stable, is generally unclear. 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. Flies eat yeast in both laboratory and wild environments, and yeast may contribute to a variety of nutritional, behavioral, and other traits. In turn, there is some evidence that yeast may rely on this interaction as a means of spreading through environments, and potentially as a mode of outcrossing in the *Drosophila* gut. Thus the relationship is more complex than a simple predator-prey or parasite/host interaction. 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 her undergraduate students are investigating **the role of tradeoffs in mutualistic coevolution in the lab and in the real world.** In a previously funded BEACON project with Tracy Teal (MSU), they discovered that after hundreds of generations of evolution in the absence of sulfate, *D. vulgaris* lost its ability to respire sulfate. This evolutionary outcome occurred repeatedly when *D. vulgaris* evolved with a mutualistic partner, *Methanococcus maripaludis*. They competed mutants with deletions of genes for sulfate respiration against a wild-type *D. vulgaris* to test whether removal of these genes had a beneficial effect on fitness. Their results suggested that deletion of these genes was beneficial at low frequencies, but these results have not been entirely consistent across experiments. They also developed a relationship with our local wastewater treatment plant and some protocols for detecting sulfate reducing bacteria in wastewater treatment samples. Hillesland now plans to continue along both lines of investigation to test whether the tradeoffs observed in those competitions i) depend on a mutualistic partner and ii) affect the evolution of sulfate-reducers in anaerobic digestors, where quantities of sulfate are low and possible mutualistic partners are common.

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. Such questions are incredibly challenging to study with organic systems due to imperfections in the historical data and long generation times that preclude systematic study within a reasonable time frame. For this project,

the team is using digital evolution, a form of experimental evolution where organisms are self-replicating computer programs, to study questions surrounding major transitions in evolution.

Lauren Meyers and Rebecca Lewis (UT) are studying **factors that influence gut microbiota diversity and intestinal bacteria transmission dynamics in wild lemurs**. Primates exhibit diverse ecological and behavioral patterns, ranging from solitary foragers (many nocturnal lemurs and lorises) to several hundred individuals, as in the multi-level societies of chimpanzees and hamadryas baboons. Many diurnal primates live in social groups with individuals typically interacting frequently and intimately within their own group and rarely with individuals outside of their group. The resulting dynamic and hierarchical contact patterns constrain microbial transmission and fundamentally determine the fate of disease outbreaks. Several studies have demonstrated that heterogeneity in contact patterns influences pathogen transmission in wildlife populations. However, the effects of social contacts on the mammalian gut microbiome, and downstream impacts on host physiology and health, remain largely unexplored. The team's previous work in wild Verreaux's sifaka (*Propithecus verreauxi*) indicates that social relationships are an important determinant of gut microbiome composition in primate populations – social group membership and social network relationships predict both within-host diversity and between-host taxonomic variation in gut bacteria. They are now investigating the effects of social interactions, network structure, and proximity to other species on commensal bacteria transmission dynamics (1) within and between sifaka social groups, and (2) between animal populations inhabiting Kirindy Mitea National Park (KMNP), Madagascar. By applying network-based statistical models to rich behavioral and bacteriological data, this research will elucidate the impact of primate social behavior on susceptibility to bacteria, and identify factors that shape the gut microbiomes of individuals, social groups, and populations. Dynamic, data-driven models of microbial transmission within wild primate populations will provide a conceptual bridge between primate social behavior and gut microbial composition, and serve as a practical tool for assessing and reducing wildlife disease risk and addressing scientific hypotheses regarding the relationship between disease susceptibility and the evolution of sociality.

Evolution of communication, cooperation, and group problem solving

Chris Adami (MSU) and Claus Wilke (UT), with graduate students Masoud Mirmomeni (MSU) and Amir Shahmoradi (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 Adami (MSU) and Kay Holekamp (MSU) are applying game theory to hyena behavior to study **the evolutionary origins of despotic societal structures**. Hyenas live in despotic groups where the high-ranking females enjoy better access to food, are protected from aggression, and have more offspring than lower ranked females. This societal structure is blatantly unjust, but it appears that it is an evolutionarily stable adaptation. What are the selective pressures that make such an unjust societal structure possible? What ecological factors favor it? Can we learn something from the selective pressures that tell us something about unjust human societies and how to perhaps remedy these? These are all difficult questions and one might think altogether unanswerable. However, being able to study evolution in action might give us some insights. Evolutionary game theory is a framework that allows us to study the balance of costs and benefits. The plausible candidate theory (the Public Goods game) is inapplicable because the cooperative hunting reward is not a linear function of the investment (as in the PG game), but displays threshold behavior. Furthermore, the reward is not equally distributed to the hunters that participated in the game. This team proposes to modify the standard PG game to account for threshold behavior (the "collective hunting" game), and study the effect of unequal distribution of the kill. They will set the parameters of the game using the empirical data provided by the long-term hyena clan observation effort in the Mara desert of Kenya, yielding 27 years of data.

Chris Waters (MSU), Ben Kerr (UW), Ajai Dandekar (UW), and John Mittler (UW) are examining the **evolution of communication and cooperation in social systems**. Quorum sensing (QS) is the process by which bacteria use small chemical signals to communicate information about cell density. As bacterial populations increase, so to do molecular autoinducers which switch the population from a low- to high-cell density state. Many cooperative behaviors such as public good production are induced at high cell density, leading to the generally accepted idea that one function of QS is to control cooperation. This project integrated the research of four laboratories studying the evolution of QS systems in bacteria spanning from the wet-lab experimental approaches with *Vibrio harveyi* and *Pseudomonas aeruginosa* to mathematical computation.

Chris Waters and Charles Ofria, with graduate students Eric Bruger and Anya Vostinar (all MSU), are studying **the evolution of collaborative public goods production**, again focusing on quorum sensing. Bruger has studied the evolutionary factors underlying the stability of QS in the bioluminescent marine bacterium *Vibrio harveyi*. This bacterium is a model system to study QS as it induces bioluminescence at high-cell density in a QS-dependent fashion. Extracellular proteases, which function as public goods, are also induced by QS and allow *V. harveyi* to grow in a protein rich media. A mutant strain that is constitutively locked at high cell density is rapidly invaded by non-producing defectors, but the WT strain that is capable of communicating has much greater resistance to defector invasion. The goal of this project is to integrate studies of the evolution of QS in *V. harveyi* with the *in silico* Avida evolutionary platform, allowing the Ofria

and Waters research groups to explore if outcomes observed in either system are fundamentally applicable to one another.

Jeffrey Morris (former MSU, now U of Alabama), with Rich Lenski (MSU), Ben Kerr (UW), and Robert Newman (NCAT) 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. The team is testing the BQH using both wet lab (*E. coli*) and computational (Avida) experiments, and is working on developing 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) a biological (*Escherichia coli*) system, and 3) mathematical modeling. 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), they are using a strain of *E. coli* that has been engineered to switch between non-altruistic and altruistic states (SDAc cells), 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. For 3), a population-level ODE model will be used in conjunction with the "gro" modeling and simulation environment to systematically evaluate how stochasticity, parameter variation, cell density, and nutrient concentration affect the experimental system. Because altruism in the engineered *E. coli* results in cellulose degradation, an increase in altruistic suicide could have profound applied significance for biofuel production.

Brian Connelly (UW postdoc), Ben Kerr (UW), and Caroline Turner (MSU graduate student) are examining the **evolution of cooperation through niche construction feedback** using an agent-based model. Previous studies on the evolution of cooperation have have typically neglected one potentially major determinant of evolutionary outcomes: environmental change brought about by the organisms themselves. Yet through their metabolism, their interactions with others, and even through their deaths, organisms constantly modify their environment. These changes can produce evolutionary feedback loops in which environmental change alters selection, which, in turn, alters phenotypes and their corresponding effects on the environment. This project will reveal how environmental change brought about by organisms, or niche construction, affects the evolution of cooperation. The team will explore how selective feedbacks influence the evolution of cooperation as populations construct their environment, and then

widen their scope to include scenarios where the environment itself is biotic, such as when symbiont populations modify their host.

Charles Ofria (MSU), Luis Zaman (UW postdoc), and Anya Vostinar (MSU graduate student) are studying **conflict and cooperationg in the evolution of behavior-altering symbionts**. Symbionts are ubiquitous in nature, and many even thrive within humans. Some are mutualistic, helping their host as they help themselves, while others are parasitic. One extreme type of symbiont alters their host's behavior, effectively turning them into "zombies." Many examples of these zombification parasites exist, but there have been no direct empirical tests for how they evolve and only minimal quantitative theory. Further, while all known behavior-alterations are damaging to the host, they are also the most likely to be observed due to the unexpected behaviors they promote; there is no fundamental reason why behavior-altering symbionts cannot evolve to be commensalists or even mutualists given the proper selective conditions. As a simple example, symbionts that rely on a single host for a long period of time must maintain that host's health. This team is conducting experiments in two engineered systems (one digital [Avida], one biological [f1 chronic phage]) to determine the conditions under which populations of zombie parasites can stably co-exist with their hosts, as well as the factors that influence whether these populations will remain purely parasitic or evolve to become mutualistic.

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) evolution-based software engineering and robotics; and (3) using evolution for biotechnology and synthetic biology. Below we describe 16 projects currently funded in this thrust group.

Evolutionary algorithms

Bill Punch and graduate student Armand Burks (both MSU) are developing **techniques for improving genetic programming by utilizing lineage diversity**. Many studies have been conducted with the goal of understanding genetic diversity in genetic programming (GP). These studies have shown that GP populations often experience a rapid loss of genetic diversity, a phenomenon referred to as premature convergence, which tends to lead to poor search performance. Over the years, some sophisticated algorithms have been developed to maintain diversity in evolving populations and thus avoid premature convergence. However, by avoiding premature convergence, these algorithms can require more time to find a solution. This project explores novel techniques for maintaining diversity and avoiding premature convergence while still finding solutions in an efficient manner. This group has developed and compared new techniques for maintaining genetic diversity in GP while overcoming some of the shortcomings of current state-of-the-art algorithms, and are now expanding this research to conduct a more thorough analysis of their approach and its effects on the evolutionary process in GP.

Brian Goldman (MSU postdoc) and Arend Hintze (MSU) are working on **faster evolution of Markov Brains using P3 (the Parameter-less Population Pyramid)**. The Parameter-less Population Pyramid (P3) is an easy to apply method for performing fast and accurate evolution, developed by Goldman with Bill Punch (MSU) under a previously funded BEACON project, but it is currently limited to binary representations. Markov Brains are an expressive way of converting binary representations into classification and learning machines, but are typically evolved by an inefficient and hard to configure genetic algorithm. Successfully combining these technologies will create an accurate, fast, and easy to use tool with a wide range of real-world applications. The team seeks to combine these methods to evolve Markov Brains effectively, and ultimately to show that P3 in conjunction with Markov Brains can outperform deep learning.

Kalyanmoy Deb, Erik Goodman, Matt Ryerkerk, 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*. Such problems can be solved with traditional methods by assuming a fixed number of components; however, if the assumed number is incorrect the solution will be suboptimal. The problem could be solved several times to determine the optimal number of components, but this approach is inefficient and often impractical. An alternative is to use an algorithm that doesn't fix the number of components in a solution, instead allowing different solutions to use different numbers of components. Most optimization methods, including gradient-based approaches, are not readily applied. This project investigates the use of genetic algorithms, and possibly other evolutionary algorithms, in solving variable-dimensional problems. The population will contain solutions with a varying of number of components, where individual solutions may vary their own number of components via crossover or mutation, using variable-length genome. The team developed a variable-length genetic algorithm that successfully solves several engineering testbed problems. The group's most recent work has focused on adapting their newly developed single-objective selection operator, which has produced very strong results, for use in multi-objective problems.

Kalyanmoy Deb and Sandeep Kulkarni (MSU) are studying **multi-scenario optimization using evolutionary multi-criterion optimization for engineering problem solving**. In many engineering and computational optimization problems, a solution must be evaluated against a number of different scenarios. For example, in a structural optimization problem, a solution must usually be checked under a number of loading conditions arising from various considerations, such as from severe wind conditions providing lateral loads and from extreme vertical loads occurring from additional vehicular loads, heavy snow conditions, etc. In such problems, a solution is considered acceptable or feasible only if it performs in a satisfactory manner to not one but all specified scenarios. This research group developed a new evolutionary multi-objective optimization method for handling multiple scenarios successfully applied the method to test problems and also to two engineering design problems: three-bar truss and welded bean design problems.

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, the iris image acquisition process can be affected by nonideal factors such as illumination variations, noncooperation of persons, head rotations, gaze directions, and camera angles, resulting in noise that hampers the segmentation performance. 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. They have found that GEFE outperforms the traditional technique on all spectrum ranges. Next, they applied a parallel game theoretic approach to segment the wide spectral varieties of iris images, and found that their model maintains better recognition accuracy while reducing the overall surface area needed for recognition purposes.

John Deller and Erik Goodman (both MSU) are working on **evolutionary algorithms for enhanced ultra-wideband microwave imaging of breast cancer tumors**. BEACON researchers at MSU, with Meng Yao, BEACON Visiting Scientist and Professor of Engineering at East China Normal University (ECNU), are engaged in research to reduce the inherent risks of using x-ray for breast cancer screening. It is predicated on the development at ECNU of an ultra-wideband microwave transceiver with impedance-matching characteristics permitting unprecedented penetration of microwave energy into breast tissue. Many experts have considered microwave screening infeasible, but the potential benefits of this diagnostic modality are so great that research persists after three decades of disappointing results. While BEACON's research team has also been impeded by the very low signal/noise ratios in the microwave data collected by Yao and his team, they are developing a new generation of that technology that will allow for improvement in that ratio and ultimately, imaging that is clinically usable. This project is highly leveraged by the well-funded effort in Shanghai, and NSF Ph.D. fellowship at MSU, and a visiting postdoctoral researcher supported by Chinese funds. The group has made several breakthroughs in understanding difficult issues in the interpretation of scanning results.

In a related project, Chris Adami and Charles Ofria (MSU) are also working on **detecting and diagnosing breast cancer with evolutionary algorithms**. They are specifically focusing on evolving Markov and neural networks to classify regions of mammograms into normal vs. cancerous tissue types. While the initial focus is on breast cancer, the techniques they develop will likely translate to other types of cancer. Evolutionary algorithms are an ideal tool for cancer detection because of their ability to produce a population of disparate diagnosis strategies. These amount to many "digital second opinions" that can be used to inform radiologists' diagnoses. The team is focusing on 1) evolution of classification via active image exploration; 2) information-theory enhanced fitness functions; and 3) evolution of classifiers that can detect boundaries. These three developments will greatly improve automated image processing technology.

Evolution-based software & robotics engineering

Gerry Dozier (NCAT) and collaborators developed 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 successfully developed a Malware Cyber Attack Advisement Tool (MalwareCAAT) that will allow users to detect a malicious website before it can affect their system. Malware CAAT outperforms six of seven other online malware detection tools, and the group has filed a provisional patent application.

Erik Goodman (MSU), Erik Runkle (MSU), and international collaborators are working on **greenhouse optimization using evolutionary computation**. The overall goal is to develop greenhouse climate control strategies that balance maximizing of tomato fruit yield and minimizing of resource consumption for a new generation of greenhouses in China. The control system will use the concept of "compatible control," using ranges of allowable states rather than single target values. For this control system to be evolved correctly, the plant growth/yield model must work very robustly, so that unusual and poor growth conditions that would never be tested by a human greenhouse manager – but MIGHT be generated by a genetic algorithm – will not improperly be assigned high yields. This allows a genetic algorithm to explore the control space freely without generating unrealistic behaviors and results. Initial models of greenhouse environment and tomato crop were derived starting from published data, but these models had to be revised extensively in 2014-15. Runkle, an MSU expert in greenhouse management, has guided redevelopment of the model of the crop, greenhouse and its control system. Multiobjective evolutionary optimization of the compatible controller has begun, and the experimental greenhouse in Shanghai in which the controller is to be validated is being prepared to perform that validation in the next year.

Kalyanmoy Deb, Andrey Guber, and Alvin Smucker (all MSU) are working on a **precision irrigation system design for optimal water usage**. Water is vital for irrigation of crops but water is also scarce and today's food and cellulosic biomass producers must make a judicial use of water for irrigation. As the water availability and supply is different in different places, different crops require different amounts of water and nutrients during their growth. Thus, irrigation water supply for a healthy crop growth depends on quite many factors, such as soil type, moisture content in the soil, climatic conditions, crops to be grown, etc. Since water is precious and additional irrigation water supply is costly, farmers can be supported with sophisticated computational means of determining dynamic but optimal requirement of irrigation water. Retaining more water in plant root zones for longer periods of time is achievable with the new Subsurface Water Retention Technology (SWRT). MSU's membrane based water retention technology in which bowl-shaped troughs of impermeable membranes are placed at a certain depth below the soil surface in a systematic staggered manner has been shown to increase the productivity to 1.4 to 3.4-fold. The research team plans to find optimal shape and placement of membranes for minimum water usage and maximum nutrient presence for maximum crop growth by linking a numerical modelling software, HYDRUS-2D, and a multi-objective optimization algorithm, NSGA-II. MSU's HPCC computing system will be used to achieve a parallel implementation of the combined methodology. The project will demonstrate the usefulness of evolutionary algorithms in handling a multi-disciplinary, computationally expensive, and practical problem of utmost societal importance.

Terence Soule (UI), Robert Heckendorn (UI), Gerry Dozier (NCAT), Peter Fuerst (UI), and Deborah Stenkamp (UI) applied **genetic and evolutionary feature extraction for evolutionary robotics**. The time to process images remains a fundamental limitation for vision-based robotics. Robots must be able to detect, in real time, features such as roads, obstacles, signs, etc. In robots

using evolutionary (or other) learning algorithms, image processing competes with evolution for on-board resources. Image processing time can be reduced by only processing the regions of an image that are likely to be significant to the current task – for example, for road following, the area directly in front of the robot may be much more important than the top of the image. The important regions may also vary with robot morphology - e.g., a wider robot may need information from the edges of an image to avoid clipping obstacles. Thus, a robot must be able to learn which regions are important for a given task and its own morphology. Genetic and Evolutionary Feature Extraction (GEFE) is a technique that can be used to evolve the regions of interest. GEFE has been shown to effectively reduce the number of regions, and total number of pixels, processed in tasks including: face recognition, differentiating between male and female *Drosophila melanogaster*, identifying computer users by mouse movements and by their irises, and generating disposable feature extractors to foil replay attacks on biometric-based control. The project generated several proof-of-concept results, and the team will continue researching ways to improve this method of robot control.

Xiaobo Tan and Kalyanmoy Deb (both MSU) are working on **robust multi-objective evolutionary design of artificial lateral line systems in robotic fish** and **reliable detection of objects with a collection of artificial lateral lines**. The lateral line is an important hydrodynamic sensory system for fish and for many amphibians, and plays an essential role in various behaviors of these animals, such as prey/predator detection, schooling, station holding, obstacle avoidance, and rheotaxis. Inspired by the lateral line system, recent years have seen emerging interest in engineering artificial lateral lines as a new noiseless sensing modality for the navigation and control of underwater robots and vehicles. The goal of these projects is to explore the use of evolutionary computing in the multi-objective design of artificial lateral lines. Current specific goals of the current project include designing a 3D lateral line for a fixed dipole and a lateral line for a moving object.

Using evolution for biotechnology and synthetic biology

Chris Waters (MSU), Joseph Graves (NCAT), and Jeff Barrick (UT) are **applying evolution in action to understand the mechanisms of novel antimicrobial therapies**. Antimicrobial resistant is a growing health threat that has been recognized by the Federal Government of the United States as a key national health priority. Without the development of novel antimicrobial therapies, a number of infections will become untreatable. Moreover, many surgical procedures that rely on prophylactic antibiotic therapy become much more dangerous with the increased risk of nosocomial infections. The goal of this BEACON funded project is to use experimental evolution followed by whole genome sequencing (EERseq) to explore the development of resistance and the mechanism of unique antimicrobial agents. Understanding the mechanism of these agents, and how bacteria evolve resistance to their treatments, are key steps in the drug development process. This synergistic research team has initiated experiments focusing on bacterial biofilm infections (Waters lab) and silver nanoparticles that are effective at killing *E. coli* (Graves lab). Barrick is working with both labs on bacterial genome sequencing and bioinformatics analysis.

Chris Adami (MSU), Dukka KC (NCAT), and Claus Wilke (UT) are **improving contact map prediction combining correlated mutation information using evolutionary computation**. Contact map prediction is an important problem in protein structure prediction.

Contact maps, matrix representations of protein residue-residue contacts, provide an avenue for predicting protein 3D structure from sequence data. Various approaches have been developed for predicting these maps, however the prediction accuracy is not yet satisfactory. In this regard, to address the limitations of machine learning-based approaches, the team has recently developed an alternative approach using Markov Networks that can be evolved instead of trained. The group is currently working to improve the prediction accuracy of their Markov Network based contact prediction method, and to identify the mechanistic details of which features are contributing to the contacts.

Jeff Barrick (UT), Dukka KC (NCAT), and Scott Newman (NCAT) are studying **directed evolution of novel protein functions using expanded genetic codes**. The genetic code is nearly universally conserved. Consequently, little is known about how the chemical palette of the standard 20 amino acids (AAs) constrains evolution. For instance, can the genetic code be altered by ongoing evolution or human engineering, and what limits, if any, govern the side chain chemistries that can be used effectively? Likewise, can specific side chain chemistries be used to selectively alter the biochemical and/or biophysical properties of a protein and, if so, to what extent can computational biology be used to inform applied evolution experiments to optimize these properties? The team is exploring these questions using genetic codes that are synthetically expanded with 21st noncanonical amino acids (ncAAs). Specifically, they are testing the impact that expanding chemical space has on evolving two types of proteins with widespread applications in medicine and biotechnology: antimicrobial peptides and fluorescent proteins. The group hypothesizes that ncAAs will have distinct phenotypic effects relative to those of the standard AAs that make new and useful properties accessible to directed evolution experiments. In parallel, they will use the Rosetta molecular modeling software to understand how an expanded chemical space impacts the structure and function of the resultant proteins and to guide mutagenesis and library design strategies for applied evolution experiments aimed at optimizing the biochemical and biophysical properties of ncAA-containing proteins.

Ben Kerr (UW), Luis Zaman (UW postdoc), and Richard Lenski (MSU) are **harnessing water-in-oil emulsion technology to enhance product yield for biotechnology**. Metabolic byproducts from microorganisms are proving increasingly valuable in biotechnology, from the production of pharmaceuticals to biofuels. One major obstacle in the use of microorganisms in industry involves the difficulty in maximizing and maintaining the yield of desirable products. Part of the difficulty is that yield often trades off with growth rate; consequently, genetic variants that improve growth rate (and thereby decrease yield) will generally have a competitive advantage, at least under standard well-mixed culture conditions. The team is using oil-in-emulsion technology and experimental evolution to select for greater yield production in isolates from various time points of Lenski's long-term evolution experiment, which have shown increasing growth rate (and concomitantly decreased growth yield) over time. This approach offers the opportunity to explore the potential for evolutionary reversion to higher yield (and the accompanying genetic changes) from various states of rate adaptation. Also, as the oil emulsion system can be easily applied to industrial settings where microorganisms are necessarily propagated in large bioreactors, results from this experiment will be directly applicable to biotechnology. This project represents a unique opportunity to address a fundamental challenge in biotechnology while contributing to our understanding of evolutionary processes.

2b. Progress towards metrics listed above.

Integrative Research Goals

1. New research collaborations and proposals

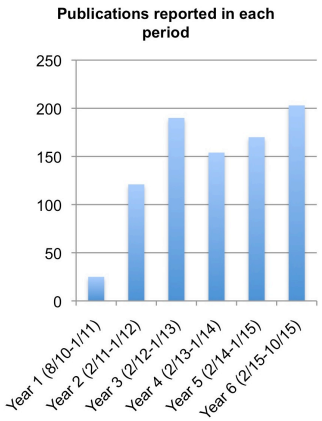
- Of the 67 projects currently underway, 33 are new projects and include new collaborations.
- 203 publications submitted this reporting period, of which about 49% are reported as multidisciplinary and 33% can be categorized as multi-institutional
- Many projects include funding for students/postdocs/faculty to travel between partner institutions.

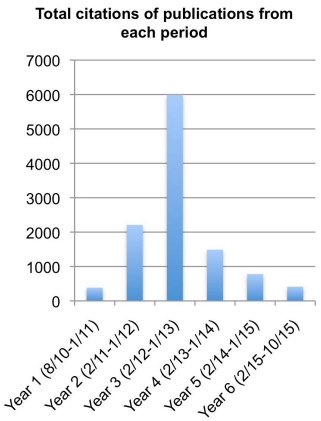
2. New paradigms for research in organic and digital domains

- Number of new sessions at scientific meetings or scientific meetings hosted at BEACON: None to report for this period.
- 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 72 proposals, and >$22M in external funding has been granted.

3. Increase in publications related to evolution in action

- Number of publications: 203 publications submitted by BEACONites to date in the current reporting period
- *Increase in BEACON publications and citations.* We used 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 graphs at right summarize the results as of October 2015. As one would expect, older publications have more citations, and we expect the citations of more recent publications to increase over time. Because Google Scholar does not index every publication in which BEACON work is published, these numbers are an underestimate of BEACON's impact.





- High visibility science journalism about BEACON research: Since our previous annual report, there have been 12 university press releases about BEACON research. Over 50 features on BEACON research appeared in the mainstream and online media since then, including high profile pieces in *New Scientist*, *The New York Times,* CBS, *Fox News*, *The*

Daily Mail, NPR, and two episodes of Science Channel's *Through the Wormhole with Morgan Freeman*.

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

- 4,508 downloads of Avida-ED in the current reporting period.
- It is no longer possible to track Avida downloads, as Github has removed that function. We will explore new methods of tracking Avida downloads for the next reporting period.
- over 3,600 visits to BEACON website monthly, where all resources are linked

Ethical Research Goal

1. Responsible Conduct of Research (RCR) training and scientific norms/virtues

- Robert Pennock and Michael O'Rourke have offered 4 Scientific Virtues workshops have been run at BEACON in the current reporting period, including a new module on Humility to Evidence.
- The very multi-disciplinary weekly Friday meetings have been going on continuously since October 29, 2010. 28 seminars were offered in the current reporting period.

Research Output Goals

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

- Number of publications submitted: 203 reported to BEACON February-October (goal is 150 per reporting period, February-January)
- Conference presentations: 189 reported (goal is 150)
- Grant proposals submitted: 72 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, and nearly achieved for publications. 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

- Fifth External Advisory Committee meeting was held August 2015.
- 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 2016. We will hold our project selection process for Year 6 (see explanation in VII. Management) in February 2016 in order to choose projects that will begin in August 2016. 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 that (1) evolution is a historical AND ongoing dynamic process; (2) evolutionary biology is a good example of how science works; and (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 (14 PhD's, 5 Master's, 2 Bachelor's). Of the PhD graduates, 71% are currently in postdoc positions, 7% are in faculty positions, and 7% are working in industry. Of 7 postdocs who left BEACON this year, 4 took faculty positions, 2 are now postdocs 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. 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). Despite these challenges *Computational Science for Evolutionary Biologists* CSE 801 currently has 12 students enrolled for Fall 2015 and *Evolutionary Biology for Non-life Scientists* has 5 students for F15. These numbers show an increase from last year.

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. We also regularly receive positive feedback and evaluations related to our outreach activities.

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. Arend Hintze; Evolutionary Biology for non-Life Scientists (ZOL 890) taught by Dr. Louise Mead; and Multidisciplinary Approaches to the Study of Evolution (CSE 891, Spring) taught by Drs. Charles Ofria, 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, Arend Hintze, Louise Mead, and Charles Ofria (MSU)

Intended Audience	Beginning graduate students
Approximate # of attendees	~25 per year

Computational Science for Evolutionary Biologists: 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 2015 class has 12 students.

Evolutionary Biology for Non-Life Scientists: ZOL 890-601 is currently being taught at MSU, with an enrollment of 5 students, and 1 student auditing. 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. The course is currently co-instructed by Dr. Louise Mead and Michael Wiser, a graduate student in Dr. Richard Lenski's lab. The opportunity to engage a senior graduate student as a co-instructor is an additional training opportunity provided to graduate students.

Multidisciplinary Approaches to the Study of Evolution: In Spring 2015, three students enrolled in the course, and 1 additional postdoctoral fellow 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. Many of these projects lead to publications.

Dr. Claudia Vergara of the Center for Engineering Education Research (CEER) has been evaluating the graduate courses. Given the low numbers of student during the past year, we held off on evaluation, aside from follow-up interviews with previous students. Increased numbers in the current year will allow us to continue with our overall evaluation. As we proceed with the next few years, we plan to follow-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	**A short-course in microbial metagenome analysis**
Led by	Ashley Shade and Tracy Teal (MSU)
Intended Audience	Graduate students, postdocs, and faculty
Approximate # of attendees	20-30

BEACON responded to the need for microbial metagenomic analysis training in eco-evolutionary research by supporting a ten-day, intensive short-course in how to analyze

microbial metagenomic data, from raw sequence handling to statistical analyses, co-taught by Ashley Shade and Tracy Teal. The short course provided training for, advanced graduate students, post-docs, faculty from both research and teaching institutions, and advanced researchers from government laboratories and industry.

The overarching educational objective was to provide computational, bioinformatics, and statistical training in how to analyze microbial metagenomic data, from raw sequence handling to statistical analyses. In support of this objective, the course included four specific aims: 1) Improve computing literacy by developing key skills; 2) Master state-of-the-science tools for microbial metagenome analyses; 3) Apply statistics and interpretation appropriate for sound experimental designs; 4) Demonstrate best practices for managing large datasets and for using computing resources.

The course was offered in 2014, with generous ad-hoc support from BEACON, and received overwhelmingly positive feedback, and again in June/July 2015 while the current BEACON project proposal was under review. Once awarded, funds were applied towards the expenses of the 2015 course. Data from our 2014 course evaluation shows that our educational strategy was effective at increasing skill level, confidence, and analysis sophistication among our participants. Our educational consultant, STEM ED, LLC is currently analyzing data from our 2015 course. In the mean time, co-PIs Shade and Teal have written a paper based on their experiences with the workshop to advise biologists in developing and managing computing workflows with an eye towards promoting reproducible results. (The paper has been accepted subject to minor revisions in PLoS Biology, and it acknowledges BEACON support). They also submitted a proposal (in autumn 2014) to the National Institutes of Health to support the workshop, which we recently learned was funded and which will support three more workshops (through 2018). A BEACON blog post was also created describing the workshop and its objectives.

Activity Name	**From the Classroom to the Lab: Undergraduate Research Education in Computational Evolution**
Led by	Claus Wilke and Art Covert (UT), Charles Ofria (MSU), Billie Swalla (UW) Scott Harrison (NCAT)
Intended Audience	Undergraduates
Approximate # of attendees	47

The Computational Evolution (CE) research stream at the University of Texas is a year-long inquiry-based class for undergraduate students. In this class, UT 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 for year IV of the stream is allowing us to focus on three new long term goals, in addition to our on-going research projects: (1) Assessing our 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, and (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.

During the 2014/15 academic year, 17 undergraduate sophomores participated in the stream doing research in the fall of 2014, and a new group of 30 freshmen participated in the spring of 2015. In addition, another 10 undergraduate students who had completed the stream in previous years returned as peer mentors and coached this year's students. Moreover, in the summer of 2015, three students from the UT-Austin FRI stream traveled to MSU to conduct research projects, and two students from NC A&T traveled to Austin for a summer research experience.

Unfortunately, in May 2015 our long-term project leader and research educator, Art Covert, left UT to take a job in industry, and therefore we have started to wind down the stream over the 2015 summer. Nevertheless, two undergraduates from the stream carried out research in the Wilke lab over the summer, and one continues to perform research this fall with BEACON support.

Activity Name	**BEACON REU/URA Field Experience at Kellogg Biological Station**
Led by	Kay Gross (MSU), Gregory Goins and Joseph L. Graves Jr. (NCAT)
Intended Audience	Undergraduate Students
Approximate # of attendees	7

The BEACON Field Research Experience project provided support for seven 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 Undergraduate Field Research program supports the educational goals of BEACON by increasing student 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. Goals included attracting a large and diverse applicant pool, especially students from underrepresented groups and BEACON partner institutions, to participate in the KBS undergraduate research program. The program also works to integrate research and educational experiences by including professional development and an introduction to career pathways in science. Finally, the program provides additional training for research mentors.

In 2015 we again attracted a diverse pool of applicants to the KBS URA and REU program and developed a partnership with the Drew program in CNS to increase participation of MSU students from under-represented groups in the KBS Undergraduate Research/Professional Experiences program. Although ~40% of the URAs in 2015 were from under-represented groups, none of these students were funded by BEACON. Of the seven URAs funded by BEACON, six were women. In addition, BEACON provided partial support for 3 REUs (most were funded by a NSF site grant and faculty supplements). These three students (all non-MSU) were all from under-represented groups: two African-American males and one East Asian Female. One of the students was from a BEACON partner school (NCAT). All of the REUs and URAs participated in a rigorous professional development program over the summer in addition

to their research and (for URAs) course work. The professional development included RCR training (5 hrs), career pathways, applying to graduate school and preparing cover letters/resumes. The program stressed science communication and included sessions on 'elevator speeches', blogging and preparing an effective poster. All BEACON supported students presented their research as posters at the Undergraduate Symposium at KBS; several also attended the BEACON Congress and will be presenting at UURAF in April 2016. Blog posts written by some of the URAs and REUs are being edited and will be posted to the BEACON website. We provided training in mentoring for the graduate students involved in this program as a formal seminar (PLB 809, sec 431) that met twice prior to and three times during the summer. Staff from the MSU Graduate School contributed to the training for mentors.

The resubmittal of our REU site proposal (August 2014) Ecological and Evolutionary Dynamics in a Changing World: A scaffolded undergraduate research experience was funded in April 2015. There were a total of 15 REUs at KBS this year, 3 with partial support from BEACON. We again used the NSF SALG (Student Assessment of their Learning Gains) form for our initial (post-summer) evaluation and have recently received the summary of that report. Overall the students rated their experience as positive/rewarding; there was some variation in how the professional development was assessed by the URAs (uniformly positive). We will be working with NSF and other field stations to evaluate how (or if) REU experiences at field stations differ from those on campus or other research institutions.

Activity Name	**BEACON REU Field Experience at Friday Harbor Labs**
Led by	Billie J. Swalla (UW)
Intended Audience	Undergraduates
Approximate # of attendees	15

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

The REU experience at FHL includes: (1) a mentored independent undergraduate research experience; (2) a minority role model who runs the program – Vikram Iyengar; (3) videoconference discussion of BEACON research projects each Friday at 12:30PM; (4) weekly professional development seminars (including RCR training), how to write an NSF Graduate Research Fellowship proposal, resume building, statistics and scientific ethics training; (5) a visit to Seattle to UW main campus to encourage students to apply for graduate school; (6) FHL research seminars throughout the summer; (7) student research presentations and final papers submitted at the end of the summer.

The program structure above accomplished the goals of this project by giving students an opportunity to conduct research on contemporary topics in evolution with BEACON faculty, but also be exposed to a variety of other BEACON projects at each of the participating BEACON partner institutions. Coinciding with this goal, students also learned common approaches and

methodology to study questions with modern genetic and genomic tools. In addition, the ability to recruit and collaborate with multiple BEACON partner institutions (MSU, UW, and NCAT) increased REU diversity, and gave the REUs a cross-disciplinary and cross-institutional research experience.

This program was only funded in August of 2015, so full student participation will not happen until summer 2016.

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 continue to coordinate 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, Tomomi Suwa (MSU)
Intended Audience	Undergraduate pre-service teachers
Approximate # of attendees	5

Several decades of research have shown that beginning teachers need to develop a deep understanding of science and pedagogy to engage their students in authentic science learning experiences. Most science education programs require that pre-service science teachers take a substantial number of science content courses to expose them to a breadth of scientific content. However, these courses are typically taught as large lectures and labs that provide few opportunities to learn or understand science practice. As an alternative, we provided five pre-service teachers with an integrated, field-based research and educational experience at the Kellogg Biological Station (KBS) that combined coursework in ecology with biweekly seminars on how ecological processes lead to evolutionary change. The students also developed a research project in collaboration with in-service teachers, faculty and graduate students, designed to demonstrate evolution in action. By being in residence at KBS, these pre-service teachers were part of a 'living and learning community' that exposed them to the various ways ecological and evolutionary research is done. We expect that this exposure to authentic science will give them experiences and access to resources that will prepare them to teach evolution – and science – more effectively.

A central goal of this project is to provides students aspiring to be teachers the opportunity to participate in an authentic science experience that will increase their understanding of research and science so they are better prepared to teach evolution. Over summer 2015 we worked with five MSU undergraduates aspiring to be middle and high school biology teachers. Their program at KBS included a short course titled "Teaching Evolution" designed to increase their understanding of evolution in action and deepen their understanding of science. Three of the five students took a 5-week Ecology course. All students participated in weekly seminars/discussions on fundamentals of evolution and participated in several inquiry-focused research activities. They also worked with mentor teachers to develop curriculum that demonstrated evolution in action. These products were shared with other teachers at the KBS K-12 Partnership Institute.

To evaluate the impact of this program on students understanding of science and preparation for teaching, the students and mentor teachers were interviewed at the beginning and end of the program. Further evaluation will be done in the coming year when the students are enrolled in a teaching methods class. This will provide a measure of the impact of a field station and research experience on the students approach to teaching and future success as classroom science teachers. The students participating in this program had both an authentic science research experience and developed skills in communicating what they had learned by creating and presenting a poster at the KBS Undergraduate Symposium, creating blogs that are posted on the "Teaching Evolution in Action" website (https://sites.google.com/a/msu.edu/teachingevolutioninaction/), and organizing two professional development sessions in collaboration with their mentor teachers for the KBS K-12 Partnership Summer Institute. These experiences focused on addressing misconceptions of evolution and developing hands-on activities to help teachers better understand models and how to incorporate them into the classroom to help students understand evolution.

Activity Name	**Are Students Losing the Thread? Interweaving Evolution and Molecular Biology in the Classroom**
Led by	Ben Kerr, Peter Conlin, Katie Dickenson, Hannah Jordt, Scott Freeman (UW); Sarah Eddy (UT)
Intended Audience	Undergraduates

Approximate # of attendees	100s

The University of Washington Department of Biology has support from the Howard Hughes Medical Institute (HHMI) to develop, test, and implement – at large scale – an authentic research experience for students in the introductory course series for majors. The experience will be based on experimental evolution in *Escherichia coli*, using a suite of antibiotics, phages, and/or abiotic conditions as environmental challenges. During the first course in the year-long series, students will design an experiment, perform serial transfers of cultures in the environment they design, perform fitness assays, and communicate their results to peers. With support from BEACON, this experience will be extended to the second course in the series, which introduces molecular genetics. Specifically, the BEACON team will develop, test, and implement protocols that will allow students to explore the molecular basis of adaptation – via sequencing studies, protein-binding assays, and other techniques – so they can understand the nature of the arrows in the genotype → phenotype → fitness relationship of their evolved vs. ancestral populations. To our knowledge, this will be the first course-based authentic research experience based on experimental evolution, and the first that allows students to explore the links between genotypes, phenotypes, and fitness.

The project is designed in three phases as follows. Phase I: design development and piloting with small student groups. Phase II: assessing changes in student conceptual understanding, scientific skills, and affect, via a "matched sections" comparison of students who complete the authentic research experience vs. traditional labs. Phase III: given evidence of efficacy in Phase II, implementing at scale (up to 1150 students per quarter). Our goals in the first year of BEACON funding are to support Phase I by: (1) developing molecular protocols to support student use of PCR, Sanger sequencing, minimum inhibitory concentration assays, protein visualization, enzyme kinetics, RT-PCR, next-generation sequencing, and other techniques; (2) developing educational modules to support students in understanding and analyzing the data that they are generating; (3) developing assessment tools to support the experiments planned for Phase II.

Dr. Joya Mukerji has been hired as Research Scientist in charge of the entire project; Research Scientist Katie Dickinson has been engaged to assist Dr. Mukerji in developing protocols; and graduate students Peter Conlin and Hannah Jordt have committed to assist with developing protocols and educational modules. All of the key players are in place. Mukerji has held a large series of informational meetings designed to raise the project's visibility and get feedback from stakeholders in the department, university, and BEACON community. Mukerji, Dickinson, and Kerr have developed detailed project plans and timelines—developing important project management tools—drafted a preliminary week-by-week plan of instruction for the course, and made important progress on analyzing space and new versus existing equipment needs. Mukerji, Freeman, and colleague Dr. Greg Podgorski have completed a survey of the existing literature on conceptual, skills, and affect assessments, and developed a preliminary guide to developing the assessment used in Phase II. The remainder of this academic year we be used to test existing protocols, draft educational modules (worksheets, jigsaw exercises using sources in the primary literature, quizzes/self-tests, etc.) to support just-in-time student learning, and draft and finalize learning goals for the course.

Activity Name	Avida-ED – Continued development, assessment, and instructor training
Led by	Robert Pennock, Jim Smith, Louise Mead, Amy Lark, Wendy Johnson, Michael Wiser, Cory Cohn (MSU)
Intended Audience	Undergraduate biology students and instructors
Approximate # of attendees	1000s

This is a continuation of the current Avida-ED Curriculum Development and Assessment Study to extend the study with a reviewer-requested controlled experiment to strengthen our bid for external funding.

Our major research aim for this study was to determine how well Avida-ED helps students achieve two key learning objectives for this course pertaining to the origin and spread of a mutation in a population under both neutrality and selection. The first is that students 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 is that students will be able to explain 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. We need a quasi-controlled experiment to substantiate what we have previously found in pre-post test studies.

We conducted a controlled experiment in two sections of LB 145: Introductory Cell and Molecular Biology in spring semester 2014, one teaching some evolutionary concepts using Avida-ED and one teaching the same material without it. The main data collection and preliminary analysis was completed by the end of the summer of 2014, showing a significant gain in student learning in the Avida-ED classroom for the core evolutionary concepts we investigated.

In the fall semester 2014 we incorporated Avida-ED more deeply into LB145 and collected data again, though this time without a control group. We developed a lab book with a series of exercises and plan to revise and extend this for use in planned faculty development workshops. A paper that describes Avida-ED implementation in these courses is now in preparation and we expect to submit it by December 2015.

The study results strengthened our bid for external funding and we have now procured 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	BEACON TEACHER REVOLUTION: Teachers Researching Evolution
Led by	Louise Mead, Richard Lenski, Jeff Connor, Jen Lau, Elena Litchman, Robert Pennock, and Kara Haas (MSU)
Intended Audience	K-12 Educators

Approximate # of attendees	7

The BEACON TEACHER REVOLUTION Program (TEACHERs Researching EVOLUTION) provided seven teachers with a summer research experience in a mentored lab or field situation while simultaneously offering a professional development experience that identified effective ways to integrate their research experience and science practices into their classroom. Teachers carried out original research, under the guidance of MSU scientists and graduate student mentors. The program built on successful, evidence-based, programs that show research experiences positively impact the teachers as well as their students. Feedback from participating teachers reinforced these results.

Participating faculty included Drs. Jeff Connor, Jen Lau, and Elena Litchman at Kellogg Biological Station and Dr. Richard Lenski on MSU main campus. The seven participating teachers came from the following schools: Dewitt High School, St. Johns High School, Delton Kellogg High School, Thornapple Kellogg Schools, Lawton Community Schools, and Kalamazoo Area Mathematics and Science Center.

Goals of the program included giving teachers research opportunities, for example, teachers joining the Lenski lab gained learned basic microbial methods including sterile technique; identified several possible microbial evolution-in-action projects of interest to them and their students and chose one to try; and simplified and trouble-shot the methods, costs, and time suitable for their HS labs. Other teachers gained experience working on quantitative traits in Arabidopsis plants, investigating how increased temperatures change multiple mutualistic interactions between partridge pea, rhizobia, and ants, as well as collecting data that their respective students can analyze in classes. In many cases these are being developed as Data Nuggets.

In addition to joining research labs, all teachers met weekly with BEACON faculty. The goal of these meetings was to (1) create a community of teachers doing research; (2) discuss different ways of integrating these research experiences into the K12 classroom; (3) identify ways of communicating the benefits of these experiences to other teachers. As a result of the final goal, these teachers plan to attend the Michigan Science Teachers Association annual conference in winter 2016 to present on their experiences and two teachers will be attending the National Association of Biology Teachers annual professional development conference in November 2015 with support from BEACON.

Teachers also participated in a symposium at BEACON Congress, highlighting both their research experience and the implications of the experience for their teaching. We are continuing to work with these teachers, developing a website that will highlight the program, their research experiences, and materials developed from their time in the labs. Statements below summarize how these experiences impact their teaching and classrooms.

"I now know what opportunities lie ahead for my students and I have the confidence to prepare them for those opportunities. … Going through the authentic process of experimental design is one that all science teachers should experience" Fred Hingst

"In fact, it's the first time I have been in a program focused on content that is specific to what I teach. Much of my graduate work was in education techniques and curriculum development. My experience has inspired me to transform my classroom into a place where

science is experienced and understood rather than a place where science in just known." Rich Schultz

"Having had the opportunity to work in a biology lab has been quite different than prior RET jobs where I have worked on curriculum research and development. I see how much data is needed to make conclusions about evolution and how standardized protocols are important." Marcia Angle

"I hope to be able to bring my experiences back to my teaching practice, not by growing and counting stamens with my class, but instead showing how data (and lots of it) is necessary to evaluate the ongoing process of evolution." Cheryl Hach

"Having first-hand knowledge of how scientific research actually happens changed the way I run my investigations. My experimental design template reflects what I've learned. My investigations are now more rigorous, thorough, and fun!" Shaun Davis

"My research experience in the Litchman Lab has made my teaching job more invigorating, exciting, inquiry based, and data driven. The techniques and protocols that I learned in the Litchman Lab gave me experience to be confident in my abilities to use probeware, collect data, and guide students in telling the story of that data as well as leading them to to run their own inquiry experiments. … I have been able to develop my own experiments to be used in the classroom." Connie High

Activity Name	**Taking Data Nuggets to a National Level**
Led by	Melissa Kjelvik, Louise Mead, Elizabeth Schutheis, and Anya Vostinar (MSU)
Intended Audience	K-12
Approximate # of attendees	1000s

Trust in scientific theories, such as evolution, is correlated with an understanding of the data and methods used to support them. An understanding of evolution depends on a student's analytical and quantitative skill set. Without an understanding of the quantitative data used to support the theory of evolution, such as measures of natural selection or long-term datasets of genetic change, students cannot fully embrace or support evolution as a unifying theory in biology and a lens through which we can view all of the living world. Once students have the tools to understand scientific principles, such as the evolutionary process, we predict their attitudes about science will shift and a career in science will seem more attainable and exciting. Our goals for the second year of funding for the Data Nuggets project included bringing this educational tool to the national level where it can promote BEACON goals and address the needs of the current K-16 education reform.

Our goals for the second year included developing a nationally recognized K-16 educational resource that builds students' quantitative skills, demonstrates the process and nature of science, and promotes an understanding of evolution. In order to develop and disseminate Data Nuggets as a national-level educational tool, BEACON funds supported Elizabeth Schultheis and Melissa Kjelvik to organize and run the first of a series of working groups sponsored by NIMBioS where group participants identified skills necessary for progression towards quantitative literacy and discuss the role of Data Nuggets in acquiring these skills. As a product of this endeavor, we

shared our findings on our Data Nugget and NIMBioS websites, detailing our discussion on the quantitative skills necessary to accomplish current national learning objectives within biology and evolution and present a call-to-action for science educators to increase data use in their classrooms. These discussions will play into our future work with Data Nuggets.

While the original Data Nugget structure was designed to accommodate and supplement instruction at the K-12 level, we 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 we added more flexibility to the K-12 resources, and made sure that Data Nuggets aligned with the quantitative skills required for undergraduates. We discussed extension possibilities during the NIMBioS working group, and brought these ideas together on our website. Working with Tammy Long we were also awarded a Year 5 BEACON grant to integrate Data Nuggets into an undergraduate course at MSU.

Finally, our most substantial accomplishment was being awarded a 4-year NSF DRK-12 to continue our work on Data Nuggets. Working in partnership with Biological Sciences Curriculum Study (BSCS), we will develop, administer, and publish findings on our assessment of Data Nugget efficacy.

Activity Name	**Data on Data Nuggets: Assessing the efficacy of an innovative science education resource to build a foundation for future support**
Led by	Tammy Long, Louise Souther Mead, Melissa Kjelvik, Elizabeth Hart Schultheis, Joelyn de Lima (MSU)
Intended Audience	Undergraduate students
Approximate # of attendees	100s to 1000s

Data Nuggets are short worksheets, based on real data, designed to help students learn to defend claims from evidence. Initial plans for this grant included (1) developing assessment instruments and carrying out preliminary efficacy traits at the 6-12 grade level; (2) developing and testing Data Nuggets for use in undergraduate biology classes, specifically to explore how DNs can be used to evaluate student learning about biological systems. We received an award from NSF in July from the DRK12 program, that is now providing the funding for a more comprehensive efficacy study, in collaboration BSCS (Biological Science Consortium Study), carried out across California, Michigan, and Colorado over the next four years. Given this new development, we have reframed the BEACON proposal to focus on goal two, specifically developing and testing Data Nuggets in undergraduate biology classrooms.

The objectives of this goal include implementing new DN strategies and organization that facilitates their use at the undergraduate level. Specifically, we will expand on our current organization scheme to align DNs with calls for undergraduate biology education reform, following Vision and Change (AAAS, 2011). As active members of QUBES (Quantitative Undergraduate Biology Education Synthesis - https://qubeshub.org/) , we have learned of the BioSquare assessment currently under development, that we believe could provide an excellent set of questions we can use to evaluate the efficacy of DNs at the undergraduate level. We will also be planning our second NIMBioS working group that will allow us to focus on these next

tasks – identifying next steps for implementation in UG classes, how to assess, how can these tools be used to chart student systems thinking?

To date, to meet these goals we have hired a graduate student (Joelyn de Lima) who is a new graduate student in Plant Biology, working with Tammy Long. Joelyn will be working with the DN team on the UG implementation portion of the project. We also anticipate that Alexa Warwick, a postdoc who will be joining the BEACON team in January will have a significant role in this project as it moves forward. The core Data Nugget team met September 24-25th to discuss the K12 research, and the next steps for the NIMBioS working group. We anticipate regular meetings with the UG team to begin in the next couple of weeks, at which point we will begin to identify learning goals for use of Data Nuggets in UG classrooms, and how to structure the research to be most informative.

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). We encourage graduate students to take the lead in these activities, and additional papers are currently in preparation (Weigel et al; Mead et al., Cohn et al.) BEACON members also routinely bring their research to general public audiences, through programs such as Darwin Discovery Day at Michigan State University, participation in the Darwin Day Roadshow, as well as science nights at local schools, and national venues like the US Science and Engineering Festival. Our database lists 95 Education and Outreach activities, distributed across the following audiences:

Audience	People in attendance	Number of events
K-12 students and teachers	10-50	52
General public	50-1000s	25
Undergraduates	50-150	8
Faculty and graduate students	30	7
Conference attendees	100s	2

We highlight a few of these programs below.

The **MSU Museum exhibit team** is coalescing their collective experience in informal and K-12 education, science, exhibit creation, digital media, and professional design and fabrication to create a second phase of exhibits in the museum's **Evolution in Action (EiA) gallery**. New exhibit components will be designed to blend seamlessly with Phase One components, “Introduction to BEACON” and “50,000.” “Hyenas Rule” - the longest running exhibit in the gallery, will be replaced by “Of Mice and Scorpions” (working title), featuring the research of Drs. Ashlee and Matt Rowe. The exhibit will inspire exploration via state of the art, museum tested, interactive technology, a venue to “talk” to BEACON scientists, and an evolution hub that will create a solid foundation for visitor understanding of basic evolution processes and concepts.

The 5E Learning model (Engage, Explore, Explain, Elaborate, Evaluate) will guide the creative process. Formative and summative evaluation measures will assess achievement of visitor learning goals as well as provide feedback regarding how visitors learn science in museum settings. The goals of this BEACON project are as follows: (1) replace "Hyenas Rule" in the EiA Gallery with an exhibit featuring Drs. Ashlee Rowe and Matt Rowe's work on Venom Evolution, (2) create and install an evolution hub in the EiA Gallery, and (3) create a visitor interactive station that connects the EiA Gallery with other natural science galleries in the Museum and provides the basis for interest and inquiry in evolution. To date, we have created drafts of the evolution hub's content. We have contracted with the company Museum Explorer to design and build a prototype of this hub, which will be installed in the gallery this fall for formative evaluation (December 2015 to January 2016). The hub design will be finalized by April 2016. We have started to develop content for the venom evolution exhibit. Exhibit ideas will be discussed and storyboarded at an in-person meeting among project participants this October or November. The venom evolution design will be finalized by April 2016.

Sapling Learning, an education company, has adapted Laura Crothers' and Ammon Thompson's ***Treethinking* game** for use on mobile devices. We are partnering with Sapling to install the game in the interactive station. Analytics will be coded in the game in order to evaluate learning gains as visitors interact with the game's levels. The interactive station design will be finalized by April 2016. The Museum's new "Exhibition Technology Specialist" has joined the project to advise on the interactive technology components and on assessment of the evolution hub prototype. Our target exhibit launch date is July 27, 2016.

BEACON has collaborated with **NESCent** to organize the **Evolution Symposium at the National Association of Biology Teachers annual professional development conference**. On November 14, 2014 the symposium featured 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*. In November 2015 we will showcase a new organization to the Evolution Symposium, featuring a BEACON scientist followed by a Data Nugget workshop highlighting data collected by the featured scientist.

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 continues as 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. 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.

To date, 96 BEACONites have reported receiving a degree or completing a postdoc, and their placements are summarized in the table below.

	Masters	PhD	Postdoc
Graduate School	8 (36%)		
Postdoc		31 (51%)	2 (15%)
Faculty Position		14 (23%)	8 (62%)
Industry	8 (36%)	8 (13%)	3 (23%)
Government	2 (9%)	1 (2%)	
K-12 Education	2 (9%)	3 (5%)	
Unknown	2 (9%)	4 (6%)	
Total # graduates	22	61	13

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. submitted; Smith 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.
- BEACON students and faculty continue to participate in numerous workshops and presentations, bringing our evolution education materials to classrooms across the country.

3. Increased interest in STEM careers

- We continue to think creatively about how to further engage young students in STEM careers. With this goal in mind, we will be using supplemental funds for our Luminary Scholars program, in collaboration with a number of faculty from underrepresented minority institutions.

2f. Educational plans for next reporting period

We will continue to develop, test, and review all 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 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 bureaucracies to join a consortium. 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 several additional industrial collaborators.
	Number of joint grant proposals submitted with industrial partners	At least 3 proposals have been submitted, and others are 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 plans are continuing to

		develop for another spinoff 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 types of interactions

Newly Initiated KT Activities

Metron: As of December 2014, a non-disclosure agreement was fully executed between MSU and Metron, where initially the focus is on specific collaboration between Philip McKinley, Betty Cheng, and Metron. During 2015, Cheng and McKinley have continued to explore collaborative investigations with members of Metron.

Tri-level Supply Chain Management Decisions: Led by Profs. Kalyanmoy Deb and Erik Goodman. This project is funded by Midland Research Institute for Value Chain Creation (MRIVCC), an institute founded by Dow Chemical Company, Dow Corning, and Michigan State University. The project links three levels of decision making activities in a supply chain management problem together and optimizes for multiple objectives involving cost and tardiness. The levels include bi-annual strategic decisions, quarterly tactical decisions, and weekly operational decisions for addressing the same supply chain management problem but focusing at appropriate entities in the supply chain. Uncertainties in the decision parameters will be considered. This project will be executed with Dow Chemical.

Ford-MSU Alliance Framework: Members from MSU College of Engineering and Business Connect worked with Ford research members to establish this new alliance between MSU and Ford. A key benefit of this alliance is facilitated access between MSU faculty and Ford researchers and engineers to work on collaborative research. Betty Cheng (as a member of BEACON at MSU) submitted a proposal in response to the request for proposals. As of November 2015, her proposal had made it through two stages of review within Ford. Her proposal addressed the use of evolutionary computing techniques to address uncertainty and feature interaction detection for powertrain features in multicore environments.

Hyundai: Led by Betty Cheng (MSU). Cheng submitted a proposal describing the use of evolutionary computation-based techniques to address automotive security for V2V and V2I communication. The proposal is pending as of October 2015.

Toyota: Led by Betty Cheng (MSU). Cheng submitted a proposal describing the use of evolutionary computation-based techniques to address safety concerns for onboard autonomous systems in the context of environmental and system uncertainty. The proposal is pending as of October 2015.

Continuing KT Activities

Ship Design: Led by Kalyanmoy Deb (MSU) with funding from the Office of Naval Research (ONR), the project entitled "Development of a Knowledge-Informed Tradespace for Resilient Systems (KITRS)" was completed in early 2015. Deb developed a reliability-based ship design methodology from given uncertain data and the use of a knowledge-based management tool. This collaboration was between MSU and University of New Orleans.

Optimal Casings and Covers for Electronic Equipment: Led by Kalyanmoy Deb (MSU). This project started in 2014 and is continuing in 2015, where 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 equipment to satisfy various 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."

Protein evolution: Led by Andy Ellington (UT Austin). The Ellington lab uses directed evolution methods to improve a variety of enzymes and proteins. Recently, they have made great strides in developing novel polymerases, including high-temperature reverse transcriptases with proofreading activities, which should be of interest to industry. They are beginning to engage corporate partners on licensing these polymerase variants. In addition, they have developed novel methods to evolve neural receptors in yeast, which should again have corporate impact into the future. These efforts have already resulted in a prestigious R21 BRAIN award [1R21EY026442-01]

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 have worked together with the Ford contacts and have created software models that can be analyzed for various properties.

WISDOM Project: An approach to solving "wicked" problems using many-objective optimization, multi-criterion decision-making tools, and visualization of high-dimensionality data.

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: In 2014-15, the MSU team was in negotiations with the CEO of Living PlanIT, Mr. Steve Lewis, for support to continue their research and eventually to collaborate in producing 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, in May, 2014, BEACON hired Dr. Chikumbo as a Research Associate Professor at Michigan State University. Individual and institutional non-disclosure agreements with Living PlanIT were negotiated and signed, enabling next steps that were anticipated in the near future. In October, 2014, 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. Instead, in April, 2015, Living PlanIT hired Dr. Chikumbo as its Chief Data Scientist, a new position, and is no longer expressing interest in further collaboration with BEACON. The work in BEACON on developing tools for addressing "wicked" problems, including many-objective optimization and visualization of solutions in many-objective spaces, continues, including research on high-dimensional data visualization by a graduate student and continuation of land use planning application by a visitor from ETH Zürich, but with no further involvement of Living PlanIT.

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.

Secure Designs: Led by Gerry Dozier (NCAT). Dozier continues to interact with Secure Designs, Inc., including university visit and NCAT demonstration of their MalwareCAAT. Dozier also jointly submitted a proposal ($500k) that was unfortunately not funded.

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. The research investigations have concluded and she is writing up the final report and bundling the corresponding prototype software and documentation for BAE.

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. Cheng, along with her PhD students are making good progress in developing a technique to automatically detect n-way feature interactions.

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 ***US patent*, "Gliding robotic fish navigation and propulsion,"** has been filed. The gliding robotic fish technology integrates key advantages of robotic fish with those of underwater gliders, and it 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 (including prototype improvement) of this technology, and a longer-term goal is to launch a start-up company. 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 BEACON 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. 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, including utilizing their novel polymerases for POC diagnostic applications. 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 the near future 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 continue to receive 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, iPlant Collaborative , National Earth Observatory Network (NEON) and Data Carpentry.

Narrative: BEACON received a $200K supplemental grant to address cyberinfrastructure across multiple NSF centers. Led by C. Titus Brown, the project brought together people from SESYNC, NESCent, iDigBio, iPlant, NEON and BEACON, to establish course objectives and develop materials for Reproducible Research workshops and a new kind of workshop patterned loosely on Software Carpentry workshops, called Data Carpentry. Funding has supported a hackathon to develop materials for a Genomics-focused Data Carpentry workshop and the subsequent piloting of that workshop and a hackathon to develop lessons for a Reproducible Research workshop and four Reproducible Research workshops. Instructors who developed and taught the material were from NESCent (Hilmar Lapp and Karen Cranston), BEACON (Tracy Teal), iDigBio (Deb Paul, Matt Collins and Francois Michonneau), SESYNC (Mike Smorul and Mary Shelley), NEON (Leah Wasser), iPlant (Jason Williams) and multiple other universities. There have been over 80 contributors to lesson development and teaching efforts. All materials developed are CC-BY and have been used in workshops as well as adapted by others for use in their own workshops or courses. Funding also supported Tracy Teal (of BEACON) to lead continuing efforts on Data Carpentry, and the resulting non-profit organization has recently

received a grant from the Moore Foundation Data-Driven Discovery initiative, administered through BEACON.

Activity: BEACON External Faculty Affiliate Program

Organizations/people involved: University of California Irvine/Adriana Briscoe, Yale University/Paul Turner, University of Texas Rio Grande Valley/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, and he continues to be active in BEACON. In 2014, we appointed our third Affiliate, Dr. Laura Grabowski of the University of Texas Rio Grande Valley (formerly University of Texas Pan American, now merged with UT Brownsville). 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. She will take on a prominent role in our recently awarded Supplement for the BEACON Luminaries program. While her Faculty Affiliate guaranteed funding will run out in 2016, she and the earlier-appointed faculty affiliates remain full members of BEACON and can apply for budget requests just as the faculty members at BEACON partner universities do.

BEACON expects to run the last External Faculty Affiliate competition in 2015-16, with funding to extend until 2018. That will be the last year of the program, as the two-year funding guarantee would otherwise extend into the period in which NSF funding is being phased down.

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. The first meeting was held January 6-9th, 2015 and a second meeting is in the planning stages. We also submitted a DRK12 grant proposal to NSF to work with the Biological Sciences Curriculum Studies (BSCS) group in Colorado. The proposal was funded in June and we are beginning our 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. This collaboration also involves both Detroit and Flint school districts, in addition to community members that include Friends of Parkside and the Charles Wright Museum in Detroit.

Visiting researchers during this reporting period: Professor Lihong Xu (Tongji University), Haiqiang Nie (Tongji University), Leilei Cao (Tongji University), Professor Meng Yao (East China Normal University), Prof. Hailin Liu (Guangdong University of Technology), Jonas Schwaab (ETH Zürich), Mohamed Abouhawwash (Mansoura University, Egypt), Xin Li (Wuhan University, China), Berna Kiraz (Marmara University, Turkey), Tolga Altinoz (Ankara University, Turkey), Marde Helbig (University of Pretoria, South Africa), Gregorio Toscano (CINVESTAV, Mexico), Shahryar Rahnamayan (University of Ontario Institute of Technology, Canada), Julian Blank (University of Magdeburg, Germany).

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

Visiting speakers: BEACON has hosted a number of visiting speakers in 2015, 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. Many of these speakers were co-hosted by other MSU departments and gave multiple talks, which allowed us to share travel costs. This year's co-hosts were the Ecology, Evolutionary Biology, and Behavior program, the Department of Entomology, and the Department of Electrical and Computer Engineering. This year's visitors included:

- Howard Rundle, University of Ottawa
- Thomas Williams, University of Dayton
- James Nieh, University of California San Diego
- John P. Masly, University of Oklahoma
- Chris Faulk, University of Minnesota
- Jeremy Fox, University of Calgary
- Matt McHenry, University of California Irvine

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. 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 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

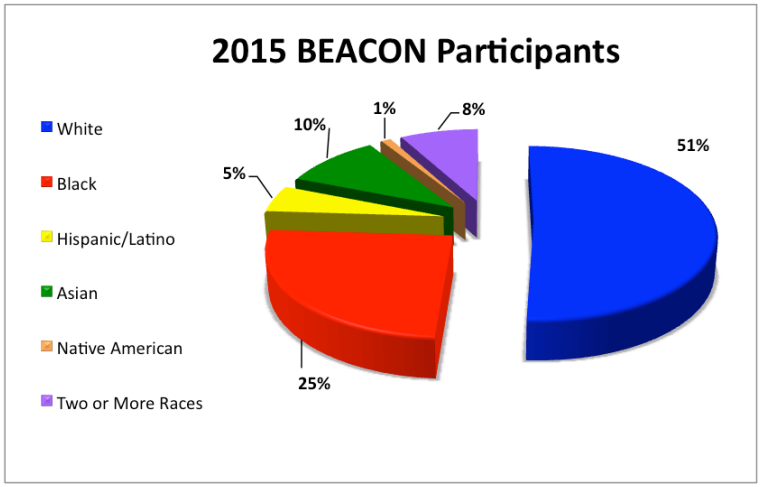
BEACON has effectively institutionalized its two overarching diversity goals: 1) ensure diversity is represented as an inclusive and connecting thread through all aspects of BEACON, and 2) exceed national norms for diversity at all levels in the Center. In the original 2010 proposal, section *4.e Diversity 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 continues to competitively strive towards being the most diverse, world-class scientific research center in the United States. 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

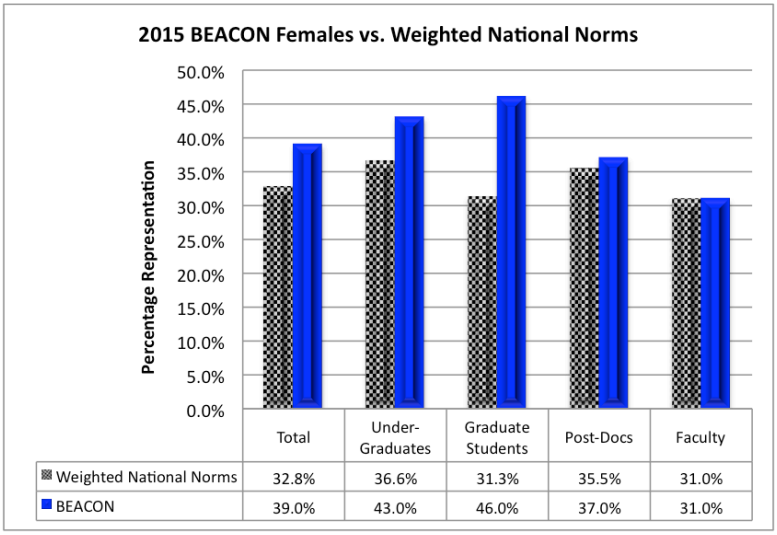
BEACON has established baseline data for diversity measures and created mechanisms to ensure its accuracy. We have collected comparative data on the numbers (and percentages) of undergraduate and graduate students, post-docs, and faculty participants from diverse demographic groups, including women, 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, 25% Black, 10% Asian, 5% Hispanic/Latino, 1% Native American, and 8% 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 33.4% of BEACON participants are self-reporting as URMs, which is 9.2% above the National Norm for URM. This is also an impressive 61% 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 16% (16 of 98) of BEACON participant graduate students are



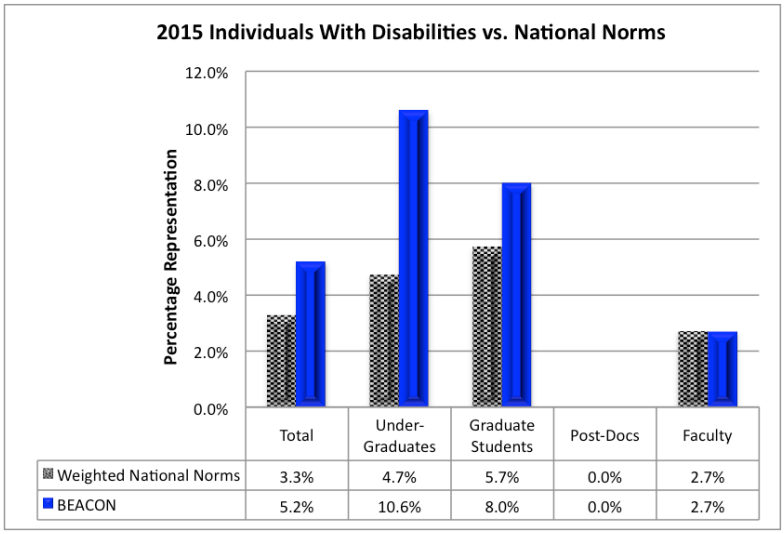
URM's, as are 63% (42 of 67) of the undergraduates (principally REU students); and at partner school NCA&T, which has 72% URM graduate students, and across the entire consortium, where 21% (12 of 58) of the post-docs are URMs. Successful and inclusive effort has been given to increasing the number of URM post-docs and to exploration of support mechanisms for URMs in post-bachelors research opportunities.

Women: BEACON's effort to increase overall female participation across all levels is now accomplished: currently 38.8% of BEACON participants are female versus the National Norms of 32.8%. In comparison to the prior annual report, the number of female post-docs has risen from 32.0% (2014) to 37% (2015), which also surpasses the national norm of 35.5%; and the number of female faculty has risen from 29.4% (2014) to 31.9% (2015), which also surpasses the national norm of 31.0%.



Working collaboratively, BEACON members recruited graduate students from across its partner schools, coordinated with faculty advisors at Minority Serving Institutions (MSI) and networked with other NSF STC's to create robust and diverse post-doc candidate pools from which to hire. The increase in the number of female post-docs within the last two years is a positive response to our collective efforts. BEACON has recruited new BEACON members among current faculty at BEACON partner schools to collaborate on research, teach classes, submit grants, and/or write publications related to its mission. Finally, the percentage of 2015 female undergrads is 43%, which also surpasses the national norms of 36.6%.

Individuals with Disabilities: Currently 5.2% of BEACON participants self-report as having a disability, which greatly exceeds the National Norms at 3.3%. BEACON is working hard to establish itself as a best-practice model for increasing adaptive learning strategies in STEM education, and as a result the learning environments are enriched and inclusive of all participants.



However, many individuals with disabilities state that they underreport their status due to 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. While we are pleased that more individuals have self-reported, we acknowledge that our participant numbers are still underreported and our efforts continue.

1c. Problems encountered

While our stretch goal of surpassing the national norms for females across BEACON has been reached, the subsequent goal (which may prove harder) will be to maintain these numbers by ensuring an environment that supports and advances female participation throughout BEACON and the STEM community at-large.

Individuals with disabilities are a priority within our strategic efforts; and to address the above-stated challenges, BEACON has 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 a newly created webpage (release date TBA), with opportunities to blog on the issues around disabilities. At our recent 2015 BEACON Congress, a workshop was presented at the Graduate and Post-doc Retreat addressing strategies and techniques for adaptive labs and classrooms. Once the website is launched, the graduate students and post-docs from across the consortium will submit content. This also includes creating a repository of best practices and adaptive software in an effort to provide scalable models and tools. When all activities are launched, BEACON will administer an assessment to evaluate and measure success.

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 a 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 recognize it is difficult to effect cultural change; therefore, we will continue to diligently support the unique needs of minorities, females and individuals with disabilities. Importantly, addressing activities that enhance and support diversity is an important part of BEACON's internal budget request process, and of reporting for funded projects.

Across the BEACON 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 2015, forty-five (45) internally funded research projects and educational activities were in operation across the five partner schools and two field sites. A closer examination of the participants on these projects revealed the following:

Regarding PIs and co-PIs, 43.6% of all projects had one or more women listed and 12.7% had URMs listed. While some individuals are listed on more than one project, the aggregate shows there is diverse PI or co-PI leadership on 47.4% of all internal BEACON projects.

The 45 projects listed include 114 URM participants, including 63 undergraduate students (including summer REU students), 32 graduate students, 11 faculty and 8 post-docs. Again, please note that some individuals are listed on more than one project; however, this shows that there is broad URM diversity across all levels and disciplines of our research efforts. Additionally, there are one or more women listed on 87.2% of the funded projects. As stated before, some individuals are listed on more than one project; regardless, women are becoming increasingly more visible across BEACON's research teams and education/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 a permanent member of BEACON. This grant has a two-year overlapping funding cycle, which currently supports 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 Rio Grande Valley. Sixty-six percent of past and current awardees are women, and 66% are URMs. All have remained BEACON members.

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 who will serve as research mentors. The successful applicants help foster collaborations among faculty and disciplines, and serve as a professional model for pre-doctoral trainees. We currently support four Fellows, including two women (50%) and two URMS (50%), thanks in part to successful leveraging of funds for some of the positions. While one of our Fellows is completing her two-year award, BEACON is thrilled to report that two additional post-docs were recently hired; both are females and one is a URM. Therefore, in 2016 BEACON will have five Fellows, three (60%) are females and three (60%) are URMs

BEACON Day @ NCAT: Dr. Gerry Dozier (NCAT) will host the annual **BEACON Day** in spring 2016, highlighting the accomplishments and partnerships between the BEACON consortium and the NCA&T community. On an annual basis, this event introduces and educates NCA&T faculty and administration about BEACON, provides a forum for discussion of BEACON research across the consortium, provides an opportunity for faculty across the consortium to come to NCA&T and discuss possible research collaborations, and provides a showcase for getting NCA&T students excited about research at BEACON institutions or other universities. One highlight is 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 & dry labs, computer/simulations, field experiences, and/or a combination.

REU PARTICIPANTS						FUNDING MODEL		
YEAR	*TOTAL*	*URMs*		*FEMALES*		*BEACON $*	*LEVERAGED $*	*TOTAL $*
2015	49	36	73%	29	59%	$117,640	$105,600	$223,240
2014	63	43	68%	33	52%	$105,171	$190,736	$295,907
2013	73	46	63%	38	52%	$106,400	$243,079	$349,479
2012	67	41	61%	25	37%	$133,820	$295,040	$428,860
2011	17	17	100%	8	47%	$28,500	$82,000	$110,500
TOTAL	**269**	**183**	**68%**	**133**	**49%**	**$491,531**	**$916,455**	**$1,407,986**

Over the past five summers, BEACON has served 269 undergraduate students (freshman to 5th-year seniors) and spent $1,407,986 by leveraging funding from several sources. The average cost per 2015 participant was $7,498 (housing/meals - $2,698; travel/baggage - $800; stipend - $4,000). The 2015 summer's total program costs were $223,240, reflecting 53% BEACON funds and 47% leveraged funds from other sources. For every $1 dollar spent, BEACON has consistently blended/braided/matched approximately $2 dollars from external sources. To date, nine (63%) of the graduating seniors with BEACON REU experience are now enrolled in graduate programs at BEACON universities; and an additional six students are enrolled in STEM graduate programs at non-BEACON schools.

In most cases, graduate students or postdocs in the REU student's research laboratory directly mentor the REU students. A distinguishing feature of BEACON's summer research program is that before the REU program begins, and in regular meetings during the summer, all mentors received **formal training in mentoring** from BEACON's Diversity Director, who is available to both mentors and mentees over the course of the summer to help solve problems that arise, 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. By emphasizing the benefits of this professional mentoring experience to the MENTORS, we hope to increase their attention to the task and their professional satisfaction with the results.

In May 2015, Dr. Brown Clarke provided a formal mentoring training session for forty-seven (47) graduate student and postdoc mentors. This training has become so popular that it has expanded to other non-BEACON summer research programs at MSU. 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 weekly reports are reviewed and approved by the research mentor before being submitted to the program director, who reads

each form and follows 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. The evaluation process – using pre, mid & post surveys and focus group interviews – found that 92% of interns reported a significant increase in research skills and confidence, and 89% reported positive working relationships with their research mentors. Feedback surveys from the research mentors indicate that they were 94% satisfied with the productivity of their interns and with the success of the formal mentoring program. Making the mentoring activity a much more recognized, higher-visibility activity clearly is having a positive effect.

In an effort to expand capacity, multiple grants have been submitted to external funding sources. Drs. Eisthen & Lonstein successfully secured a NSF REU site grant for their program called Integrative Biology of Social Behavior (IBSB). This funding is for three years (2013-2015) to support ten neuroscience undergraduates in the summer. The cohort consisted of ten interns, 50% (5) were ethnic minorities, and 50% (5) were female.

BEACON's Dr. Kay Gross, Director of Kellogg Biological Station, successfully submitted and was awarded a NSF REU Site grant for 2015-2017. The competitiveness of their proposal came from the previous four years of successful summer research programming, partially funded from BEACON's internal budget request process. This new (external) grant funding will support ten (10) REU students starting in summer, 2016.

Additionally, MSU BEACON submitted and was awarded an NSF supplemental funding grant to support the Luminary Scholars Research Program. This is an intensive undergraduate research program that will, when paired with other funding, support approximately eight URM students each year to come to MSU for the summer research opportunities, then return to their minority-serving institutions (MSI) and continue their undergraduate research for up to 10-hours per week during the academic year, under the guidance of an identified faculty members at the home institutions in collaboration with BEACON faculty.

Finally, BEACON was successful in securing another $47,00 from the MSU Office of the Provost – Undergraduate Education Office to support year-round research opportunities for 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 130 girls grade 6th -8th providing math and science experiences. BEACON also funded **citizen science day activities** and ***Darwin Day Road Show*** at various urban & rural classrooms and museums.

Outside of BEACON: Chair of the BEACON Diversity Committee Dr. Percy Pierre and Diversity Director Judi Brown Clarke are co-PIs on the Alfred P. Sloan Foundation & National Action Council for Minorities in Engineering grant funded July 2014-July 2017. Dr. Brown Clarke remains an external advisory committee member on the state of Nevada's 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. This committee meets bi-annually, and the next meeting is to be held on March 13th -15th, 2016.

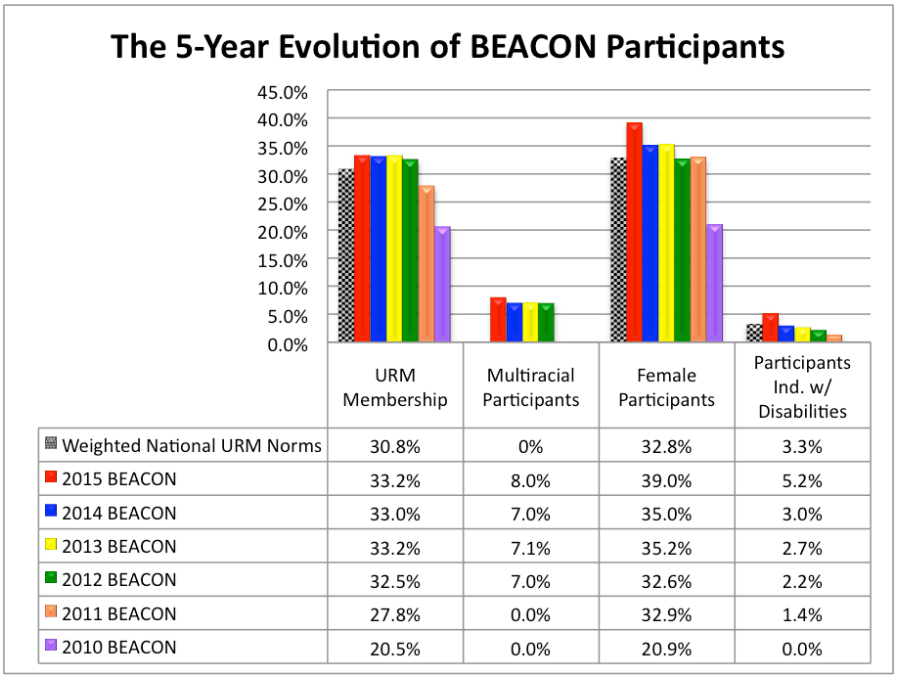
Dr. Brown Clarke is an advisory board member for the Society for the Study of Evolution's (SSE) Diversity in STEM Careers, which meets at Duke University on October 22-23, 2015. She continues as an advisory board member for the Research Education Program to Increase Diversity in Health Researchers (REPID) in the MSU College of Human Medicine, an advisory board member for the W.K. Kellogg Biological Station Advisory Committee, an advisory board member for Director's Research Scholar at the MSU National Superconducting Cyclotron Laboratory (NSCL), and a board member for the NSCL-Joint Institute for Nuclear Astrophysics (JINA). She was the keynote speaker for the National Organization of Black Chemist and Chemical Engineers (NOBCChE) Annual Meeting on September 27, 2015 in Orlando, Florida; and a session speaker at the Grace Hopper Annual Conference: Celebrating Women in Computing on October 14, 2015 in Houston Texas.

Finally, BEACON members – Education Director Louise Mead, NCA&T faculty member Joe Graves, post-doc Frank Forcino, and Dr. Brown Clarke – published "Factors influencing the career pursuit of underrepresented minorities with an interest in biology", *Evolution: Education and Outreach* 8 6 [10.1186/s12052-015-0034-7].

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 Brown Clarke and the Chair of the Diversity Steering Committee, Dr. Percy Pierre. 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" within our strategic efforts, no longer requiring annual requests to continue. 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 sustained pipeline for recruitment and interdisciplinary 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.



	URM Membership	Multiracial Participants	Female Participants	Participants Ind. w/ Disabilities
Weighted National URM Norms	30.8%	0%	32.8%	3.3%
2015 BEACON	33.2%	8.0%	39.0%	5.2%
2014 BEACON	33.0%	7.0%	35.0%	3.0%
2013 BEACON	33.2%	7.1%	35.2%	2.7%
2012 BEACON	32.5%	7.0%	32.6%	2.2%
2011 BEACON	27.8%	0.0%	32.9%	1.4%
2010 BEACON	20.5%	0.0%	20.9%	0.0%

2c. Progress towards goals

To summarize our diversity statistics:

- *URMs*: BEACON participants are: 51% White, 25% Black, 10% Asian, 5% Hispanic/Latino, 1% Native American, and 8% two or more races/ethnicities. Currently 39% of BEACON participants are self-reporting as URMs, which is above the National Norm (31.0%) for URM.
- *Women*: BEACON successfully surpassed female participation (39.1%) across all levels in the consortium, which is above the National Norm of 32.8%.
- *Individuals with Disabilities*: Currently 5.2% of our participants self-reported as having a disability, which exceeds the National Norm (3.3%).

With the involvement of 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 is charged with increasing URM PhD 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 NCA&T launched a PhD program last fall and three former BEACON REU students have been admitted. This effort was greatly assisted by collaborations between NCA&T faculty and their BEACON computer science colleagues. Collectively, BEACON is 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 in engineering.
- 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 URMs, females and individuals with disabilities.

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. In the previous reporting period we added a fourth research thrust group, which has been a successful change. We have had a couple of personnel changes in the organization chart, specifically in the areas of Multidisciplinary Training and the Diversity Steering Committee. Going forward, we plan to make some minor adjustments to the center's approach to peer review in our annual project selection process.

Thrust Group Reorganization. In the previous reporting period, we changed Evolutionary Applications from a cross-cutting theme to its own research thrust group, as projects in that theme were difficult to fit into any one of the three thrust groups, and as a result were not getting the attention they deserved when discussing BEACON research. The new thrust group was intended to draw together work previously distributed among the other thrust groups that is relevant to addressing real-world problems, be they computational or biological. This shift has been successful so far, with 9 projects funded in this thrust group in 2015.

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 and a smaller number of BEACON postdocs and senior Ph.D. students. 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.

An issue about the budget request review process that has come up via direct feedback and also through the organizational evaluation (described in more detail below) concerns the nature of the feedback that some members have received. The review process is anonymous, like all grant proposal reviews, but BEACON is a comparatively small group of peers. Occasionally, reviewers make non-constructive and sometimes even offensive comments in their reviews. This behavior can lead to a loss of trust in BEACON and the budget request process, and negative feelings towards the recipient's peers within the center. Some of these comments appear to have been made by graduate students who are newer to the practice of peer review and may perceive a need for "proving" their expertise through criticism. Moving forward, we plan to address the culture of our internal review process, instructing reviewers to focus on providing helpful feedback and enabling scientific progress, rather than competitiveness. BEACON has always focused on collaborative science, and our aim is to insure this spirit of teamwork and cooperation throughout all of our operations.

Personnel changes. As described above, there have been some changes to the Multidisciplinary Training leadership. Titus Brown and Ian Dworkin have both left MSU, and Louise Mead and Arend Hintze have taken over this role. Additionally, it was determined that the Diversity Steering Committee was not operating quite as effectively across our institutions as it could be. Instead of designated Diversity Coordinators at each institution, the Partner Leads will now nominate appropriate interested individuals to carry out diversity-related activities appropriate to their institution, but will also remain engaged themselves as members of the Diversity Steering Committee. Our updated Organizational Chart (Appendix B) reflects these changes.

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.

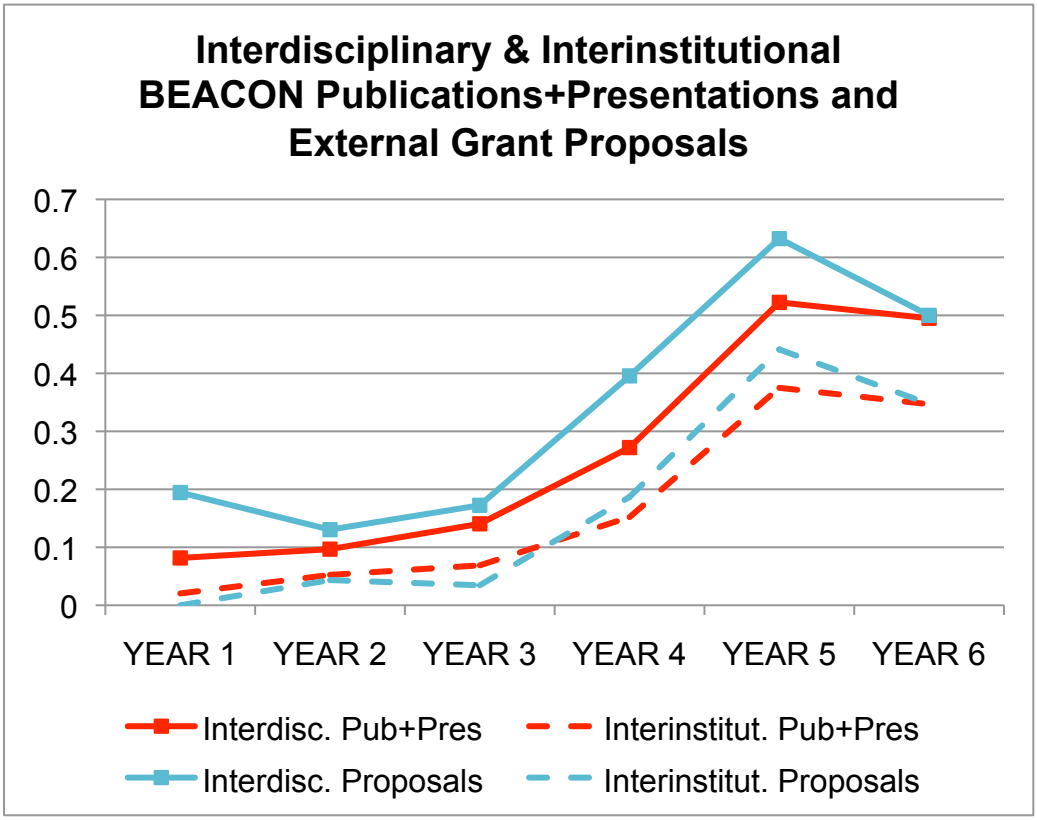
Management Goals		
GOAL	**METRICS**	**PROGRESS**
Increase in cross-disciplinary research and education	Number of paper/conference submissions by BEACON authors	50% of publications and 49% of presentations reported as interdisciplinary
	Number of students enrolled in cross-disciplinary courses	20+ in semester-long courses, plus hundreds in workshops

		on computational science for biologists
	Number of funding proposals submitted	36 of 72 grant proposals submitted (50%) reported as interdisciplinary; 25 of 72 (35%) inter-institutional
Increase in cross-institutional research and education	Number of paper/conference submissions	37% of all publications and 33% of presentations reported to be cross-institutional
	Number of new courses and workshops	New Data Carpentry, EDAMAME workshops
	Number of students in cross-institutional courses	This year only MSU students participated in semester-long BEACON courses, though the courses were available to students at the partner institutions. Hundreds participated in workshops on computational science for biologists
Increase in new funding sources (cross-disciplinary and cross-institutional)	Number of submissions	BEACON researchers submitted 72 proposals for external funding concerning evolution in action, and >$22M in external funding was granted
	Award dollars	BEACONites have been awarded over $22M from outside BEACON in this funding period (~$17M for cross-disciplinary proposals, compared to last year's $9M), far exceeding goal of $5M/year
Effective support of Center operations by Management team	Survey for participants about management team	2015 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	BEACON's 5-year renewal proposal was approved and funded.
	Number of public mentions	Over 40 tweets, retweets,

	made by NSF about BEACON	favorites, and mentions by @NSF_BIO Twitter account; at least one piece on NSF media (Science 360 Radio)

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 increased steadily during BEACON's first five years, with a much sharper increase of interdisciplinary publications between Years 3 and 5. The past year shows that this rate has plateaued, and about 50% of current BEACON outputs are self-reported as interdisciplinary and about 35% as interinstitutional. This plateauing is not unexpected and is at a level viewed as very acceptable by BEACON management.



Education: The BEACON interdisciplinary graduate courses have continued, as described in section III: Education, and have served about 20 students this year. In addition, major efforts by C. Titus Brown, Tracy Teal, and collaborators at SESYNC, NESCent, iDigBio, iPlant, NEON and BEACON established course objectives and developed materials for Reproducible Research workshops and a new kind of workshop patterned loosely on Software Carpentry workshops, called Data Carpentry. Funding has supported a hackathon to develop materials for a Genomics-focused Data Carpentry workshop and the subsequent piloting of that workshop and a hackathon

to develop lessons for a Reproducible Research workshop and four Reproducible Research workshops. Instructors who developed and taught the material were from NESCent (Hilmar Lapp and Karen Cranston), BEACON (Tracy Teal), iDigBio (Deb Paul, Matt Collins and Francois Michonneau), SESYNC (Mike Smorul and Mary Shelley), NEON (Leah Wasser), iPlant (Jason Williams) and multiple other universities. There have been over 80 contributors to lesson development and teaching efforts. All materials developed are CC-BY and have been used in workshops as well as adapted by others for use in their own workshops or courses. An intensive, 10-day 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), organized and taught by Ashley Shade, a new BEACON faculty member, along with several postdoctoral and graduate teaching assistants. This workshop followed up and improved upon last year's first, one-week EDAMAME course. Recently, Shade was awarded support by the National Institutes of Health to offer this workshop each summer for an additional three years.

Funding sources: BEACON researchers reported submitting 72 grant proposals for well over $35M during this reporting period, 36 (50%) of which are interdisciplinary, and 25 (35%) of which are interinstitutional. Of these, 32 have been funded so far (17 [53%] interdisciplinary and 13 [41%] inter-institutional) for a total of over $22M in external funds, from NSF, NIH, DARPA, the Office of Naval Research, and private foundations including the Gordon and Betty Moore Foundation, the Simons Foundation, the Welch Foundation, the Fred Gloeckner Foundation, the Andrew W. Mellon Foundation, and the Alfred P. Sloan Foundation. 19 submitted proposals were declined, and no decision has yet been reported for another 21 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. In Spring 2015, Farrell-Cole and Amey conducted a survey of BEACON faculty, postdocs, and graduate students. The questions were closely aligned with the previous survey conducted in 2013, to allow for comparison across time. The questions centered on (1) how well BEACON is meeting its mission statement, (2) satisfaction with BEACON leadership and management, as well as the climate among colleagues, (3) impressions of BEACON's impact in research, education, and outreach. All sections included open-ended questions where respondents could identify issues that concerned or interested them. The survey revealed that overall satisfaction with BEACON leadership and management is still quite high. Climate and respect among BEACON colleagues is very highly rated, particularly within institutions. We were very pleased to see that the perception of BEACON as "a catalyst for the creation of new research" has increased very favorably over 2013. Areas of focus for the year ahead include continuing efforts to socialize new members of BEACON – and keep more senior members engaged, and assuring a culture of respect and constructive feedback in the budget request review process (addressed above).

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. 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. MSU has appointed Dr. Wolfgang Banzhaf, currently at Memorial University of Newfoundland, to fill this chair, beginning August 2016. Banzhaf is one of the co-authors of *Genetic Programming: An Introduction*, a classic text in the field, as well as the sole author of *Linear Genetic Programming*, which provided a new basis to view genetic programming, extending the original work of Koza to new domains. In addition, Banzhaf served as the founding editor of the journal Genetic Programming and Evolvable Machines. He currently chairs the Association for Computing Machinery's Special Interest Group on Genetic and Evolutionary Computation (SIGEVO). At MSU, Banzhaf's primary appointment will be in the Department of Computer Science and Engineering, and through BEACON he will be interacting with many other researchers from many disciplines.

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. We recently upgraded our videoconferencing equipment and software, with great results (details of new system below, under Videocommunications Systems).

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 annual 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 has now become standard. Beginning with the 2012 Congress, we began holding a Student/Postdoc Retreat day on the day before the main Congress. Topics covered at the Retreat, 2012-2015, included communicating science to the public (led by Danielle Whittaker), engaging the public (led by John Besley), 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), biases in academia (led by Ann Marie Ryan), and a roundtable on avoiding burnout. At the 2013 Congress, we also introduced a networking event that gave

students and postdocs an opportunity to meet and interact with faculty members that they might not normally talk to. This event was very popular and successful, and was repeated in 2015.

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, 431 "likes" as of 10/23/15, an increase of 18% since the last annual report) and Twitter (@BEACON_Center, 874 followers as of 10/23/15, an increase of 58%). 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. We also encourage live-tweeting at the BEACON Congress, which worked very well in 2015 and greatly increased BEACON's visibility in scientific social media circles. These social media feeds 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) and a software bridge hosted by Acano. 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 Skype, Google Hangouts, or Acano. A Canon Vixia camera and Vidiu encoder are available for live-streaming events via Youtube, Livestream, or other web video services.

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

In 2015, there were no changes to 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 fifth meeting of BEACON's External Advisory Board was held August 19, 2015, 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

The only major change to any of the outcomes or metrics in our Strategic Implementation Plan is in the Ethics Plan section. In previous versions of our Strategic Implementation Plan, we stated that BEACON would track the *percent completion of department- and university-specific RCR training requirements by participants*, to ensure that all participants complete training requirements. This tracking has proven to be extremely difficult to implement successfully, as each university, department, and program has their own requirements, their own tracking systems, and their own timelines. That is, although all the units require annual compliance of their students and postdocs, there is no single time of year when compliance can be checked across all the units. We had also stated that we would track the resulting *change in frequency of ethics violations*. As of October 2015, zero ethics violations by BEACON members have been reported. As a result, we are shifting our goal and our action items in this Optimal Outcome to focus on providing RCR training opportunities to BEACON members, rather than attempting to track external activities. We will now track the *number of RCR training opportunities provided* and the *number of people who attend BEACON RCR trainings.*

In 2013, Co-PI Pennock gave a series of presentations on the scientific virtues and their relationship to Responsible Conduct of Research (RCR) at the regular BEACON group meetings. These served as a pilot test of the virtues-based approach to RCR training that he is developing. Dr. Pennock and Toolbox project leader Dr. Michael O'Rourke are collaborating to develop and test Toolbox-style models that focus on the virtues that are central to the scientific character. In 2013, 2014, and 2015, they put on several workshops focusing on curiosity, the purpose of science, honesty, courage, and humility to evidence for BEACON Congresses and Friday seminars. We continue to collect data from these workshops to improve our curriculum and to see how participants view this approach. In 2014 Pennock received a new $1 million Templeton Foundation grant to fund a national study of exemplary scientists to see how well this new ethical approach matches the values scientists actually hold. These projects aim to transform the way we think about and teach RCR.

VIII. CENTER-WIDE OUTPUTS AND ISSUES

1a. Center publications

Peer-Reviewed Publications

1. Adami C 2015. Information-theoretic considerations concerning the origin of life *Origin of Life and Evolution of the Biospheres*. 45: 9439.
2. Adami C 2015. Robots with Instincts *Nature*. 521: 426-427. doi:10.1038/521426a
3. Adami C 2015. The Engine of Complexity: Evolution as Computation by John E. Mayfield *Quarterly Review Biology*. 90: 90-91. 10.1086/679929
4. Adami C 2015. What is Information? *Phil. Trans. Roy. Soc. A*. 347
5. Ahrari A, Lei H, Sharif M, Deb K, Tan X 2015. Design optimization of an artificial lateral line system incorporating flow and sensor uncertainties *Engineering Optimization*.
6. Ahrari A, Aidi Sharif M, Lei H, Deb K, Tan X 2015. Design Optimization of Artificial Lateral Line System under Uncertain Conditions *IEEE Congress on Evolutionary Computation* 1807-1814. 10.1109/CEC.2015.7257106
7. Atwell JW, Cardoso GC, Whittaker DJ, Price TD, Ketterson ED 2015. Hormonal, behavioral and life-history traits exhibit correlated shifts in relation to population establishment in a novel environment *The American Naturalist*. 184: E147-E160.
8. Bahceci E, Miikkulainen R 2015. Evolving Strategies for Social Innovation Games *Proceedings of the Genetic and Evolutionary Computation Conference*.
9. Bazaz Behbahani S, Tan X 2015. Design and modeling of flexible passive rowing joints for robotic fish pectoral fins *IEEE Transactions on Robotics*.
10. Bazaz Behbahani S 2015. Dynamic modeling of robotic fish caudal fin with electrorheological fluid-enabled tunable stiffness *GECCO Proceedings of the 2015 Annual Conference on Genetic and Evolutionary Computation*.
11. Beck D, Foster JA 2015. Machine learning classifiers provide insight into the relationship between microbial communities and bacterial vaginosis *Biomedical Data Mining and Analysis*. 8: 23.
12. Benson-Amram S, Dantzer B, Stricker G, Swanson EM, Holekamp KE. 2015. Brain size predicts problem-solving ability in mammalian carnivores. *PNAS*. Submitted.
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16. Braylan A, Miikkulainen R 2015. A Neural Network Approach to Model Learning for Stochastic Discrete Environments *IJCAI Workshop on General Intelligence in Game-Playing Agents (GIGA'15)*.
17. Burks A, Punch W 2015. An Efficient Structural Diversity Technique for Genetic Programming. *GECCO 15 Proceedings of the 2015 Annual Conference on Genetic and Evolutionary Computation* 991-998. http://dx.doi.org/10.1145/2739480.2754649

18. Burmeister A 2015. Horizontal Gene Transfer *Evolution, Medicine, and Public Health*. DOI 201510.1093
19. Cannon JT, Kocot KM, Waits DS, Weese DA, Swalla BJ, Santos SR, Halanych KM 2014 Phylogenomic resolution of the hemichordate and echinoderm clade *Current Biology*. 24: 1-6.
20. Chapman S, KC D 2015. The PFP and ESG protein function prediction methods in 2014: effect of database updates and ensemble approaches *GigaScience*. DOI 10.1186/s13742-015-0083-4
21. Clark AJ, McKinley PK, Tan X 2015. Evolutionary Multiobjective Design of a Small Robotic Fish with a Compliant Fin *Bioinspiration & Biomimetics*. Submitted.
22. Clifford JW, Adami C 2015. Discovery and Information-theoretic Characterization of Transcription Factor Binding Sites that Act Cooperatively *Physical Biology*. 12: 056004. 10.1088/1478-3975/12/5/056004
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172. Waters C et al 2015. The Cyclic Di-GMP Phosphodiesterase Gene Rv1357c/BCG1419c Affects BCG Pellicle Production and In Vivo Maintenance *IUBMB Life*. 67: 129-138.
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176. Weigel EG, Testa N, Peer A, Garnett SC 2015. It's All About Context: Sexual Signaling Loss in Digital Organisms. *Ecology and Evolution*.
177. Weigel EG, Tinghitella R, Boughman J 2015. No evidence for adjustment of maternal investment under alternative mate availability regimes *J Fish Biology*. Submitted.
178. Wiser M, Lenski R 2015. A comparison of methods to measure fitness in *Escherichia coli PLOS ONE*. 10: e0126210. 10.1371/journal.pone.0126210
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181. Yan J, Deller JR 2015. NARMAX Model Identification Using a Set-theoretic Evolutionary Approach *Signal Processing*. Submitted.
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Nonlinear System Identification *17th IFAC Symposium on System Identification 2015*.
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185. Zhao Z-G, Liu Z-J, Conner JK. 2015. Plasticity of floral sex allocation within inflorescences of the hermaphrodite *Aconitum gymnandrum Journal of Plant Ecology* 8: 130-135.
186. Zhbannikov I, Foster JA 2015. MetaAmp: Analysis high-throughput microbial amplicon sequence data with multiple markers *Bioinformatics*. 31: 1830-1832. 10.1093/bioinformatics/btv049
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Book Chapters

1. Adami C, LaBar T 2015. From Entropy to Information: Biased Typewriters and the Origin of Life. *From Matter to Life: Information and Causality*, eds. SI Walker, PCW Davis, and G Ellis. In press.
2. Atwell JW, Whittaker DJ, Price TD, Ketterson ED 2015. Shifts in hormonal, morphological, and behavioral traits in a novel environment: comparing recently diverged Junco populations. *Snowbird: Integrative Biology and Evolutionary Diversity in the Junco*, eds. ED Ketterson and JW Atwell. In press.
3. Baskett CA, Schemske D 2015. Evolution and Genetics of Mutualism. *Mutualism*, ed. JL Bronstein. Pp. 77-92.
4. Conlin P 2015. Trade-offs drive the evolution of increased complexity in nascent multicellular digital organisms *Multicellularity: Origins and Evolution*, eds. KJ Niklas and SA Newman. Pp. 131-147.
5. Conner J 2015. Artificial Selection. *Encyclopedia of Evolutionary Biology*, ed. RM Kliman. In press.
6. Gandomi AH 2015. Boundary Constraint Handling Affection on Slope Stability Analysis. *Engineering and Applied Sciences Optimization*, eds. N Lagaros and M Papadrakakis. Pp. 341-358.
7. Gandomi AH 2015. Reactive Power and Voltage Control Based on Mesh Adaptive Direct Search Algorithm. *Engineering and Applied Sciences Optimization*, eds. N Lagaros and M Papadrakakis. Pp. 217-231.
8. Harris RM, Hofmann HA 2015. Brain Evolution, Development, and Plasticity. *Handbook of Evolutionary Neuroscience*. In press.
9. Holekamp KE, Jones S, Strauss E 2015. Ecology of African Carrion. *Carrion Ecology, Evolution, and Their Applications*, eds. ME Benbow and JK Tomberlin. Pp. 459-489.
10. Smalla K, Jechalke S, Top E 2015. Plasmid detection, characterization, and ecology. *Plasmids – Biology and Impact in Biotechnology and Discovery*, eds. ME Tolmasky and JC Alonso. PLAS-0038-2014.

11. Stenkamp D 2015. Development of the Vertebrate Eye and Retina. *Progress in Molecular Biology and Translational Science volume 134, Molecular Biology of Eye Disease*, eds. F Hejtmancik and JM Nickerson. Pp. 397-414.
12. Theis KR, Schmidt T, Holekamp KE, Wagner A, Venkataraman A 2015. Age-related variation in the scent pouch bacterial communities of striped hyenas (*Hyaena hyaena*). *Chemical Signals in Vertebrates 13,* eds. BA Schulte, TE Goodwin, and MH Ferkin.
13. Top E, Ridenhour B 2015. Plasmid driven evolution of bacteria. *Encyclopedia of Evolutionary Biology*, ed RM Kliman. In press.
14. Whittaker DJ, Gerlach NM 2015. Mate choice in dark-eyed juncos using visual, acoustic, and chemical cues. *Snowbird: Integrative Biology and Evolutionary Diversity in the Junco*, eds. ED Ketterson and JW Atwell. In press.
15. Whittaker DJ, Theis KR 2015. Bacterial communities associated with junco preen glands: ramifications for chemical signaling. *Chemical Signals in Vertebrates 13,* eds. BA Schulte, TE Goodwin, and MH Ferkin.

1b. Conference presentations

Talks

1. Adami, Chris. Life in the Universe: From Entropy to Information. American Physical Society April Meeting. Baltimore, MD.
2. Adami, Chris. The Evolutionary Path Towards Sentient Robots. American Physical Society March Meeting. San Antonio, TX.
3. Adami, Chris. Exploring the Evolution of Behavior and Intelligence. Gordon Conference: Molecular Mechanisms of Evolution. Stonehill College, Easton, MA.
4. Adami, Chris. Universal Biosignatures for Life Detection. Second ELSI Symposium: Origin and Evolution of Life-Earth Systems. University of Tokyo, Japan.
5. Barrick, Jeffrey. Reinforcing synthetic biology against evolution. 5th International Conference on Biomolecular Engineering. Lost Pines, TX.
6. Barrick, Jeffrey. Reinforcing synthetic biology against evolutionary failure. Biochemical and Biomolecular Engineering XIX. Puerto Vallarta, Mexico.
7. Barrick, Jeffrey. Chance and metabolic necessity on the road to an evolutionary innovation. Gordon Research Conference: Molecular Mechanisms in Evolution. Easton, MA.
8. Baskett, Carina. Higher herbivory rates in lower-latitude populations of pokeweed (*Phytolacca americana*). Ecological Society of America. Baltimore, MD.
9. Blount, Zachary; Weatherspoon, Kiyana; Rowles, Maia; Quandt, Erik. Ecological Divergence and Incipient Speciation in an Experimental Population of *E. coli*. Gordon Research Conference on Speciation. Ventura, CA.
10. Brown Clarke, Judi. Social Justice Through Science: Disrupting Power. National Organization of Black Chemist and Chemical Engineers (NOBCChE). Orlando, FL.
11. Brown Clarke, Judi. Ensuring High-Performance Research with a Formal Mentoring Plan. NSCL-Joint Institute for Nuclear Astrophysics (JINA) Annual Frontiers Meeting. East Lansing, MI.
12. Brown Clarke, Judi. Student Opportunity Lab: Undergraduate Research Opportunities & Successfully Applying to Grad School. Grace Hopper Annual Conference: Celebrating Women in Computing, Houston, TX.

13. Bruger, Eric; Mead, Louise. Assessing the impact of digital evolution software on student understanding of the origin of variation during evolution. Future Academic Scholars in Teaching (FAST) Symposium. MSU, East Lansing, MI.
14. Bruger, Eric; Waters, Chris. Quorum sensing stabilizes cooperation against cheating in *Vibrio harveyi*. Microbial Population Biology (GRS) Gordon Research Seminar. Andover, NH.
15. Burmeister, Alita. A honeypot model of host-virus interactions. Gordon Research Conference on Microbial Population Biology. Andover, NH.
16. Burmeister, Alita. A honeypot model of host-virus interactions. Gordon Research Seminar on Microbial Population Biology. Andover, NH.
17. Burmeister, Alita. Do populations reach peaks? Comparing multiple methods of calculating fitness. Midwest Ecology and Evolution Conference. Bloomington, IN.
18. Clark, Anthony. Enhancing a Model-Free Adaptive Controller through Evolutionary Computation. GECCO 2015. New York, NY.
19. Conlin, Peter; Kerr, Ben. Origin and consequences of fitness decoupling during the evolutionary transition to multicellularity. Astrobiology Science Conference 2015. Chicago, IL.
20. Conner, Jeffrey. Data archiving: The view from Evolution. NSF/AIBS Workshop on Publishing Biological Data. Washington, DC.
21. Conner, Jeffrey; Perez, Sam; Royer, Anne. Mechanisms of trait loss: ongoing elimination of short stamens in a selfing plant. Society for the Study of Evolution (SSE) Annual meeting. Guarujá, Brazil.
22. Dolson, Emily; Vostinar, Anya; Wiser, Michael; Ofria, Charles. Understanding Complexity Barriers in Evolving Systems. Open Ended Evolution Workshop at European Conference on Artificial Life. York, UK.
23. Dunham, Maitreya. Transposable elements contribute to rapid adaptation in interspecific hybrids. Society for Industrial Microbiology and Biotechnology. Philadelphia, PA.
24. Eisthen, Heather; Theis, Kevin. Have microbes influenced the evolution of nervous system and behaviour? Homology and Convergence in Nervous System Evolution. Buckinghamshire, UK.
25. Estrela, Sylvie. Microbial interdependencies through loss of metabolic functions. Yosemite Symbiosis Workshop. Yosemite National Park, CA.
26. Foster, James. Combining bacterial fingerprints: A new algorithm. National meeting of the American Chemical Society. Pocatello, ID.
27. Foster, James. Combining bacterial fingerprints: A new algorithm. Origins and Benefits of Biologically-Active Components of Human Milk. Big Sky, MT.
28. Goodman, Erik. A Tale of an EC Startup: From GALOPPS Freeware to a Commercial Product. GECCO-2015, EC in Practice Track. Madrid, Spain.
29. Goodman, Erik. Organizational Structure and Transparency in a Multi-Faceted Center. NSF STC Directors' Meeting. Honolulu, HI.
30. Goodman, Erik; Teal, Tracy. Roles for STCs and Bio Centers in the Face of Big Data. NSF STC Directors' Meeting. Honolulu, HI.
31. Gupta, Aditi. DiffPath: Finding Differentially Expressed Biological Pathways. Great Lakes Bioinformatics Conference 2015. Purdue University, West Lafayette, IN.
32. Hagey, Travis. 3D Imaging of the Gecko Adhesive System for Finite Element Simulations. Society of Integrative and Comparative Biology. West Palm Beach, FL.

33. Hagey, Travis; Harmon, Luke; Uyeda, Josef. Tempo and Mode of Performance Evolution Across Independent Origins. Evolution 2015. Guarujá, Brazil.
34. Holekamp, Kay. The Evolution of Problem Solving Abilities in Mammalian Carnivores. Convergent minds: Investigating the Evolution of Cognitive Complexity in Nature. Boston, MA.
35. Hope, Elyse. Adaptive evolution in yeast reveals many genetic pathways to biofilm formation. Society for Industrial Microbiology and Biotechnology. Philadelphia, PA.
36. Hope, Elyse; Miller, Aaron; Dunham, Maitreya. Adaptive evolution in yeast reveals many genetic pathways to biofilm formation. Society for Industrial Microbiology and Biotechnology Annual Meeting and Exhibition. Philadelphia, PA.
37. Jack, Chandra. Herbivore Preference: Native vs Invasive Plants. Evolution 2015. Guarujá, Brazil.
38. Johnson, Wendy. Engineering in the Science Classroom: You CAN Do It. Michigan Science Teachers Association Conference. Grand Rapids, MI.
39. Keagy, Jason; Hofmann, Hans; Boughman, Jenny. Transcriptomics of female mate discrimination in recently diverged species of threespine sticklebacks. Animal Behavior Society Meeting. University of Alaska, Anchorage, AK.
40. Keagy, Jason; Hofmann, Hans; Boughman, Jenny. Transcriptomics of female mate discrimination in recently diverged species of threespine sticklebacks. Eigth International Conference on Stickleback Behavior and Evolution. Stony Brook University, Stony Brook, NY.
41. Krieg, Cara. Listening to what females have to say: female song characteristics may communicate information to rival house wrens. Animal Behavior Society Conference. University of Alaska, Anchorage, AK.
42. Krieg, Cara; Getty, Thomas. Aggressive mothers have larger offspring: a reproductive benefit to intrasexual aggression in female house wrens. Indiana University Animal Behavior Conference. Indiana University, Bloomington, IN.
43. La Rosa, Raffica; Conner, Jeffrey. Testing Bateman: selection on floral traits through male and female fitness in two milkweed species. Society for the Study of Evolution Annual Meeting. Guarujá, Brazil.
44. LaBar, Thomas; Adami, Chris. Exploring the likelihood of chance emergence of self-replication in a digital system. Astrobiology Science Conference 2015. Chicago, IL.
45. LaBar, Thomas; Adami, Chris; Hintze, Arend. Does Self-Replication Imply Evolvability? European Conference on Artificial Life 2015. York, UK.
46. Lehman, Kenna; Holekamp, Kay; Montgomery, Tracy. Investigating Group Signatures in Whoops, the Long Distance Calls of the Spotted Hyena. ABS 2015, Anchorage, AK.
47. Lehman, Kenna; Montgomery, Tracy; Holekamp, Kay. Communication and Cooperation in Spotted Hyenas (*Crocuta crocuta*). International Ethological Congress. Cairns, Australia.
48. Lenski, Richard. Experimental Evolution: Evolution in Action in Bacteria and Avida. 1st Avida-ED Active LENS Train-the-Trainers Workshop. Michigan State University, East Lansing, MI.
49. Lenski, Richard. Time travel in experimental evolution. Forecasting Evolution. Lisbon, Portugal.
50. Lenski, Richard. Phenotypic and Genomic Evolution During a 60,000 Generation Experiment. German Association for General and Applied Microbiology. Marburg, Germany.

51. Lenski, Richard. Time Travel in Experimental Evolution. Microbial Evolution: theory, simulation and experiment. University of Leuven, Belgium.
52. Lenski, Richard. Dynamics of Phenotypic and Genomic Evolution during a 60,000 Generation Experiment with *E. coli*. Two2Many: A Systems View of Biology. Weizmann Institute of Science, Rehovot, Israel.
53. Lewin, Nora; Holekamp, Kay. Early-life IGF-1 concentrations predict boldness in spotted hyenas. Annual Meeting of the Animal Behavior Society. Anchorage, AK.
54. Loftie-Eaton, Wesley; Ponciano, Jose; Top, Eva. Rapid evolution of plasmid permissiveness in Pseudomonas. Gordon Research Conference on Microbial Population Biology. Andover, NH.
55. Luttrell, Shawn; Swalla, Billie. Hemichordate Nervous System Evolution and Regeneration. Northwest Developmental Biology Conference. Friday Harbor Laboratories, Friday Harbor, WA.
56. Macias-Muñoz, Aide; Briscoe, Adriana. Transcriptome-wide differential gene expression between seasonal forms and sexes of *Bicyclus anynana* butterfly eyes. Evolution 2015. Guarujá, Brazil.
57. McGowan, Craig. Bouncing without springs. 7th International Symposium on Adaptive Motion of Animals and Machines. Cambridge, MA.
58. McGowan, Craig; Shine, Catherine; Kami, Cole. The effects of speed and incline on hopping mechanics in kangaroo rats. Northwest Biomechanics Symposium. Seattle, WA.
59. Mead, Louise; Johnson, Wendy; Pennock, Robert; Smith, Jim; Wiser, Michael. Contextual gains in student understanding of evolution after inquiry-based exercises with digital organisms. Evolution 2015. Guarujá, Brazil.
60. Miikkulainen, Risto. Evolving Neural Networks. 2015 IEEE Conference on Computational Intelligence and Games. Tainan, Taiwan.
61. Miikkulainen, Risto. Tutorial on Neuroevolution Reinforcement Learning. AAAI-2015. Austin, TX.
62. Miikkulainen, Risto. Deep Reinforcement Learning through Neuroevolution. Deep Learning Workshop, INNS Conference on Big Data. San Francisco, CA.
63. Miikkulainen, Risto. Tutorial on Evolving Neural Networks. Genetic and Evolutionary Computation Conference. Madrid, Spain.
64. Mirmomeni, Masoud; Hintze, Arend; Adami, Chris. Evolution of Super-Reciprocity in Noisy Iterated Games. American Physical Society March Meeting. San Antonio, TX.
65. Mirmomeni, Masoud; Hintze, Arend; Adami, Chris. Collective hunting game: A game-theoretic framework to model hyena hunting patterns. Society of Mathematical Biology Annual Meeting. Atlanta, GA.
66. Mirmomeni, Masoud; Hintze, Arend; Adami, Chris. A Game-theoretic Framework To Model Hyena Hunting Patterns. Society of Mathematical Biology Annual Meeting. Atlanta, GA.
67. Mishler, Dennis. UT Austin 2015 iGEM Synthetic Biology Team: Breaking is Bad. iGEM World Jamboree. Boston, MA.
68. Morris, James Jeffrey; Papoulis, Spiridon; Zaman, Luis; Lenski, Richard. Rapid Speciation Through Black Queen Gene Loss in Bacteria and Digital Organisms. Astrobiology Science Conference. Chicago, IL.
69. Pennock, Robert. Professional Ethics Report. Socially Relevant Philosophy of/in Science and Environment (SRPoiSE) conference. Detroit, MI.

70. Rowe, Matthew. Why Are So Many College Graduates Anti-Vaxxers? Improving Gen-Ed Science Courses by Focusing on the Process of Science. National Center for Case Study Teaching in Science Annual Conference. Buffalo, NY.
71. Rowe, Matthew. Using Cases to Engage the Science-Phobic Student While Correcting Their Pseudoscientific Thinking. National Center for Case Study Teaching in Science Annual Conference. Buffalo, NY.
72. Rowles, Maia; Blount, Zachary; Wright, Jacob; Lenski, Richard. Phenotype and fitness value of a novel trait-conferring mutation vary with genetic background in *E. coli*. American Society for Microbiology 115th General Meeting. New Orleans, LA.
73. Schultheis, Elizabeth. Increase your broader impacts with Data Nuggets. Long Term Ecological Research All Scientists Meeting. Estes Park, CO.
74. Shade, Ashley. Exploring the consequences of rare taxa for microbial community stability. Gordon Conference Microbial Populations. Andover, NH.
75. Smith, James; Pennock, Robert; Mead, Louise; Johnson, Wendy; Lark, Amy. Avida-ED: An artificial life platform for teaching evolutionary principles and the nature of science. American Society for Microbiology Conference for Undergraduate Educators. Austin, TX.
76. Smith, James; Pennock, Robert; Mead, Louise; Wiser, Michael; Johnson, Wendy; Lark, Amy. Avida-ED: An artificial life platform for teaching evolutionary principles and the nature of science. HHMI/BioQUEST/SCN Conference. Harvey Mudd College, Claremont, CA.
77. Smith, James; Pennock, Robert; Mead, Louise; Wiser, Michael; Johnson, Wendy; Lark, Amy. Avida-ED: An artificial life platform for teaching evolutionary principles and the nature of science. The Western Conference for Science Education. London, ON.
78. Theis, Kevin. Have microbes influenced the evolution of nervous system and behaviour? Homology and Convergence in Nervous System Evolution. Buckinghamshire, UK.
79. Top, Eva. Rapid Evolution of multi-drug resistance plasmids: no general patterns? Western Regional IDeA Conference. Coeur d'Alene, ID.
80. Turner, Caroline; Lenski, Richard. Evolution of *E. coli* stoichiometry under carbon and nitrogen limitation. Conference on Biological Stoichiometry 2015. Trent University, Peterborough, ON.
81. Turner, Julie; Holekamp, Kay. Effects of Early Social Bonds on Adult Fitness in Free-living Spotted Hyenas (*Crocuta crocuta*). Animal Behavior Society. Anchorage, AK.
82. Walker, Allison. Thumbs Up! for Evolution. Life Discovery. San Jose, CA.
83. Waters, Chris. Can you hear me now? Quorum sensing stabilizes cooperation in *Vibrio harveyi*. Organismality Symposium. Washington University, St. Louis, MO.
84. Weigel, Emily; Mead, Louise; McElhinny, Teresa. Curriculum Interplay: What Putting Genetics Courses First Can Show Us About How Students Understand Evolution. 2nd Life Discovery - Doing Science Education Conference. San José State University, San José, CA.
85. Whittaker, Danielle. Chemical Communication in Songbirds: Signal Content, Production, and Inheritance. Third Congress of the Latin American Association of Chemical Ecology (ALAEQ). Bogota, Colombia.
86. Whittaker, Danielle; Theis, Kevin. Love is in the air: Influence of mating behavior on avian pairmates' odor-producing microbes. Animal Behavior Society. Anchorage, AK.
87. Wilburn, Paul; Shade, Ashley; Litchman, Elena. Microbial survey of Lake Baikal: insights and limitations of taxonomic, network-based and functional analyses. Second EMBO Conference on Aquatic Microbial Ecology. Uppsala, Sweden.

88. Wilburn, Paul; Shade, Ashley; Teal, Tracy; Litchman, Elena. Microbial survey of Lake Baikal: insights and limitations of taxonomic and network-based functional analyses. Association for the Sciences of Limnology and Oceanography. Granada, Spain.
89. Wiser, Michael; Lenski, Richard; Ofria, Charles. Comparing fitness trajectories in long-term evolution experiments in microbes and digital organisms. Evolution 2015. Guarujá, Brazil.
90. Young, Rebecca. How to be monogamous: Comparative transcriptomics across vertebrate brains reveals conserved themes despite independent behavioral evolution. Big Data in Biology Symposium. Austin, TX.

Posters

1. Blount, Zachary; Weatherspoon, Kiyana; Rowles, Maia; Quandt, Erik. Ecological Divergence and Incipient Speciation in an Experimental Population of *E. coli*. Gordon Research Conference on Speciation. Ventura, CA.
2. Blount, Zachary; Weatherspoon, Kiyana; Rowles, Maia; Wright, Jacob; Lenski, Richard. Two Tales of a Key Innovation. Gordon Research Conference on Microbial Population Biology. Andover, NH.
3. Blount, Zachary; Weatherspoon, Kiyana; Rowles, Maia; Wright, Jacob; Lenski, Richard. Two Tales of a Key Innovation. Gordon Research Seminar on Microbial Population Biology. Andover, NH.
4. Brooker, Sarah; Williams, Janet; Davenport, Kimberly; Foster, James; McGuire, Michelle; McGuire, Mark. Has evolution of human milk sugars responded to a biocultural sweet tooth? FASEB Origins and Benefits of Biologically-Active Components of Human Milk. Big Sky, MT.
5. Bruger, Eric; Waters, Chris. Quorum sensing in *Vibrio harveyi* provides resistance to social cheating. Microbial Population Biology (GRS) Gordon Research Seminar. Andover, NH.
6. Burmeister, Alita; Lenski, Richard; Smith, James J. Integration of evolution into an undergraduate microbial genetics laboratory course: student perceptions and explanations of microbial evolution. Center for the Integration of Research, Teaching, and Learning Forum. College Station, TX.
7. Conlin, Peter; Kerr, Ben. Pleiotropic effects of compensatory evolution in rifampicin resistant *Escherichia coli*. Gordon Research Conference - Microbial Population Biology. Andover, NH.
8. Estrela, Sylvie; Morris, James Jeffrey; Klavins, Eric; Kerr, Ben. The drivers and constraints of microbial interdependencies in spatially structured communities. Gordon Research Conference- Microbial Population Biology. Andover, NH.
9. Friel, Colleen; Friesen, Maren. Resource trade in the legume/rhizobia mutualism. Plant Biology 2015. Minneapolis, MN.
10. Gering, Eben; Getty, Thomas. Post-invasive evolution in Kauai's feral chickens. Gordon Conference: Speciation. Ventura, CA.
11. Glenney, Carrie; Lenski, Richard; Kerr, Ben. Reversing Rate Adaptation with Water-in-Oil Emulsions. Gordon Microbial Population Biology. Andover, NH.
12. Gupta, Aditi; Adami, Chris. Changes In Epistatic Interactions In Long-Term Evolution of HIV-1 Protease. Gordon Research Conference: Molecular Mechanisms in Evolution. Stonehill College, Easton, MA.
13. Hagey, Travis. Novel Imaging Techniques of the Gecko Adhesive System. Advanced Structural and Chemical Imaging (ASCI) Symposium. Pullman, WA.

14. Harrison, Scott. Evolutionary Modeling of Pathogen Mutation Rates. Bio-IT World Conference & Expo. Boston, MA.
15. Hillesland, Kristina. Limited Evidence that byproduct mutualists adapt specifically to their local population within 1000 generations of evolution. Gordon conference on Microbial Population Biology. Andover NH.
16. Jack, Chandra; Friesen, Maren. Comparison of herbivore response to naive and co-evolved *Medicago* polymorphs. European Society of Evolutionary Biology. Lausanne, Switzerland.
17. Johnson, Wendy. The Effects of Avida-ED on Students' Explanations of Evolution. CREATE for STEM Mini-Conference. Michigan State University, MI.
18. Keagy, Jason; Martinez, Jonathan; Hofmann, Hans; Boughman, Jenny. Transcriptomics of female mate discrimination in recently diverged species of threespine sticklebacks. Indiana University Animal Behavior Conference. Indiana University, Bloomington, IN.
19. Krieg, Cara. Eggs-pressing condition: what do house wren eggs say about the female? Fisheries and Wildlife GSO Symposium. Michigan State University, MI.
20. Krieg, Cara. Listening to what females have to say: female song characteristics may communicate information to rival house wrens. Midwest Ecology and Evolution Conference. Indiana University, IN.
21. LaBar, Thomas; Adami, Chris. Population Size Determines the Evolution of Phenotypic Complexity at High Mutation Rates. Gordon Research Conference: Molecular Mechanisms of Evolution. Easton, MA.
22. Martinez, Jonathan; Keagy, Jason; Wurst, Benjamin; Boughman, Jenny. The role of rearing environment on the spatial cognitive ability of two sympatric species of threespine stickleback. Indiana University Animal Behavior Conference. Indiana University, Bloomington, IN.
23. Mead, Louise; Johnson, Wendy; Lark, Amy; Smith, Jim; Wiser, Michael; Pennock, Robert T. Using Evolution in Action to Address Students' Naive Conceptions. Gordon Conference on Undergraduate Biology Education Research. Bates College, Lewiston, ME.
24. Schultheis, Elizabeth. Data Nuggets: An Avenue for Broader Impacts and Increasing K-16 Student Quantitative Literacy. Long-Term Ecological Research All Scientists Meeting. Estes Park, CO.
25. Soto, William; Waters, Chris. Quorum Sensing and Central Metabolism in *Vibrio harveyi* and *Vibrio cholerae*. Gordon Conference Microbial Population Reseach Symposium. Andover, NH.
26. Tajkarimi, Mehrdad; Hung, Albert; Harrison, Scott; Barrick, Jeffrey; Graves, Joseph L Jr. Single cell force spectroscopy analysis for *Acinetobacter baylyi* mutation aggregation. Biophysical Society. Baltimore, MD.
27. Turner, Caroline; Blount, Zachary; Mitchell, Daniel; Lenski, Richard. Evolution of Stable Coexistence in Response to a Key Innovation in a Long-term Evolution Experiment with *E. coli*. American Society for Microbiology 115th General Meeting. New Orleans, LA.
28. Waters, Chris. Cyclic di-GMP: A regulatory maestro that orchestrates bacterial biofilm formation and motility. Department of Microbiology invited speaker. Northwestern University Medical School, IL.
29. Weatherspoon, Kiyana; Blount, Zachary; Wright, Jacob; Lenski, Richard. Evidence of Self-Cross-feeding in Niche Specialization in an Experimental Population of *E. coli*. American Society for Microbiology 115th General Meeting. New Orleans, LA.

30. Weigel, Emily; Boughman, Jenny. Doing the right thing, the right amount: Male investment and reproductive success in the threespine stickleback (*Gasterosteus aculeatus*). Southeastern Ecology and Evolution Conference. University of Georgia, GA.
31. Weigel, Emily. #SciStuChat. ComSciCon. Microsoft New England Research & Development Center, Cambridge, MA.
32. Wiser, Michael; Lenski, Richard; Charles Ofria. Comparing fitness trajectories in long-term evolution experiments in microbes and digital organisms. Gordon Research Conference Microbial Population Biology. Andover, NH.

1c. Other dissemination activities

1. Adami, Chris. A New Path Towards Intelligent Machines. Artificial Intelligence Seminar Series. Information Sciences Institute, Univ. Southern California, CA.
2. Adami, Chris. A New Path Towards Intelligent Machines. MSU Cognitive Science Forum. MSU, East Lansing, MI.
3. Adami, Chris. A New Path Towards Intelligent Machines. Physics and Astronomy Colloquium. St. Mary's University, Halifax.
4. Adami, Chris. A New Path Towards Intelligent Machines. Stanford Complexity Group. Stanford University, CA.
5. Burmeister, Alita. Evolution and ecology in experimental communities of bacteria and phage. Presented at the EEBB Program Colloquium, MMG Bad Bug Club Seminar, and as an invited speaker at the MMG Undergraduate Microbiology Club, all at MSU. East Lansing, MI.
6. Conner, Jeffrey. Mechanisms of adaptive evolution in a conserved trait. University of New Mexico, NM.
7. Conner, Jeffrey. Mechanisms of adaptive evolution in a conserved trait. Michigan State University Department of Plant Biology. East Lansing, MI.
8. Dyer, Fred. Evolution of behavioral and cognitive search in nectar-feeding bees. Seminar to Indiana University Cognitive Science Program. Bloomington, IN.
9. Eisthen, Heather. Tainted love: Evolution of Pheromonal Communication in Salamanders. Department of Biology, Washington University in St. Louis. St. Louis, MO.
10. Foster, James; Baumgaertner, Bert. Introduction to Signaling Theory. Greensboro, NC
11. Harris, Rayna; Hofmann, Hans. White Paper: Integrative Neuroscience. NSF Data Science Workshop. Seattle, WA.
12. Hofmann, Hans. Distinguished Public Lecture, Center for Integrative Animal Behavior.
13. Hofmann, Hans. Dept. of Biology, New York University. New York, NY.
14. Hofmann, Hans. Dept. of Biology, Columbia University. New York, NY.
15. Hofmann, Hans. Dept. of Biology, Reed College. Portland, OR.
16. Hofmann, Hans. Max-Planck-Institute for Brain Research. Frankfurt am Main, Germany.
17. Hofmann, Hans. Dept. of Neurobiology & Behavior, Stony Brook University. Stony Brook, NY.
18. Hofmann, Hans. Invited Speaker/Symposium Organizer, Animal Behavior Society Annual Meeting. Anchorage, AK.
19. Hofmann, Hans. Instituto Gulbenkian de Ciéncia, Lisbon, Portugal.
20. Hofmann, Hans. Confederated Depts. of Biology, Rutgers University/NJIT. NJ.

21. Hofmann, Hans. Invited Speaker, James Goodson Memorial Symposium, IU Animal Behavior Conference, Indiana University, Bloomington, IN.
22. Hofmann, Hans. Invited Speaker, 12th Annual National Academies Keck Futures Initiative conference, Collective Behavior: From Cells to Societies, Irvine, CA.
23. Keagy, Jason. Studying cognitive evolution using bird nerds and speciating sticklebacks. Marsico Scholar Presentation. University of Denver, Denver, CO.
24. Kjelvik, Melissa. The Past, Present, and Future of Data Nuggets. KBS K-12 Summer Institute. Kellogg Biological Station, Hickory Corners, MI.
25. Kjelvik, Melissa. Data Nuggets: Bringing real scientific data into the classroom. Kellogg Biological Station, Hickory Corners, MI.
26. Lenski, Richard. Dynamics of Phenotypic and Genomic Evolution in a Long-Term Evolution Experiment with *E. coli*. Workshop on the Dynamics of Microbial Ecology and Evolution. Simons Foundation, New York, NY.
27. Lenski, Richard. Time Travel in Experimental Evolution. Darwin Day Public Lecture. University of Calgary, Canada.
28. Lenski, Richard. Time Travel in Experimental Evolution. Frances Diebold Symposium. Kalamazoo College, MI.
29. Lenski, Richard. Time Travel in Experimental Evolution: Phenotypic and Genomic Dynamics Across 60,000 Generations. Technion University, Haifa, Israel.
30. Lenski, Richard. Time Travel in Experimental Evolution: Phenotypic and Genomic Dynamics Across 50,000 Generations. Duke University, NC.
31. Lenski, Richard. Time Travel in Experimental Evolution: Phenotypic and Genomic Dynamics. University of British Columbia, Canada.
32. Lenski, Richard. Dynamics of Phenotypic and Genomic Evolution in a 60,000-Generation Experiment with *E. coli*. Scripps Research Institute, San Diego, CA.
33. Lenski, Richard. Dynamics of Phenotypic and Genomic Evolution in a 60,000-Generation Experiment with *E. coli*. University of California, Davis, CA.
34. Lenski, Richard. Dynamics of Phenotypic and Genomic Evolution in a 60,000-Generation Experiment with *E. coli*. Emory University, Atlanta, GA.
35. Luttrell, Shawn; Swalla, Billie. Hemichordate Nervous System Evolution and Regeneration. Marine Biology Course. Misaki Marine Biological Station, University of Tokyo, Japan.
36. Mead, Louise. Teaching Evolution. URIT program at KBS. Kellogg Biology Station, Hickory Corners, MI.
37. Miikkulainen, Risto. Evolving Neural Networks. Machine Learning Summer School. Austin, TX.
38. Miikkulainen, Risto. IEEE CIS Distinguished Lecture Program: Computational Intelligence in Games. Fort Worth CIS Chapter. Fort Worth, TX.
39. Morris, James Jeffrey. The Invisible Hand of the Black Queen: Reductive Evolution in the Ocean and Elsewhere. Kennesaw State University Biology Seminar, Kennesaw, GA.
40. Morris, James Jeffrey. The Invisible Hand of the Black Queen: Reductive Evolution in the Ocean and Elsewhere. Dauphin Island Sea Lab Seminar Series, Dauphin Island, AL.
41. Morris, James Jeffrey. The Invisible Hand of the Black Queen: Reductive Evolution in the Ocean and Elsewhere. University of Southern California Oceanography Department Seminar Series, Los Angeles, CA.

42. Pennock, Robert. Curiosity and Scientific Integrity: Creationism, Responsible Conduct of Research and the Moral Structure of Science. American Association for the Advancement of Science. Washington, DC.
43. Pennock, Robert. Teaching Evolution and Scientific Practices using Avida-ED. Biology department Sidwell Friends School. Washington, DC.
44. Pennock, Robert. Learning Like a Scientist: Thoughts on Teaching Evolution, the Nature of Science, and the Scientific Virtues. National Science Foundation. Washington, DC.
45. Pennock, Robert. Teaching Evolution and Scientific Practices using Avida-ED. Project 2061. American Association for the Advancement of Science. Washington, DC.
46. Pennock, Robert; Mead, Louise; Smith, Jim; Wiser, Michael; Ofria, Charles; Lenski, Richard; Blackwood, Diane; Johnson, Wendy. Active LENS Workshop. Active LENS Workshop. Michigan State University, East Lansing, MI.
47. Pennock, Robert; Mead, Louise; Wiser, Michael; Blackwood, Diane; Smith, Jim. Avida ED Workshop. Avida ED Workshop. Michigan State University, East Lansing, MI.
48. Pitchers, William. The Highs & Lows of Multivariate GWAS. Genetics Seminar series. U. of Wisconsin, Madison, WI.
49. Pitchers, William. Why are Wings Wing-shaped? Evolutionary Genetics of wing morphology in Drosophila Melanogaster. U. of Minnesota, St. Paul, MN.
50. Ribeck, Noah. The effects of epistasis and ecology on the rate of adaptive evolution. CUNY Brooklyn Biology Dept. weekly seminar. Brooklyn, NY.
51. Ribeck, Noah. The effects of epistasis and ecology on the rate of adaptive evolution. Oregon State University Integrative Biology Dept. weekly seminar. Corvallis, OR.
52. Schultheis, Elizabeth. Data Nuggets: Bringing real scientific data into the classroom to unearth students' quantitative and inquiry abilities. UC-Denver, CO.
53. Schultheis, Elizabeth. Data Nuggets: Increase your broader impacts while improving science education. Kellogg Biological Station, Hickory Corners, MI.
54. Smale, Laura. Temporal niche transitions. NSW Department of Primary Industries & Invasive Animal CRC, Coffs Harbor, Australia.
55. Stenkamp, Deborah. Seeing Double: Regulation of Expression of Tandemly-Duplicated Opsin Genes in the Zebrafish. Invited Seminar Visit. National Eye Institute, Bethesda, MD.
56. Stenkamp, Deborah. Evolution and Development of Color Vision. University of Idaho Interdisciplinary Colloquium. Moscow, ID.
57. Top, Eva. Rapidly evolving persistence and host range of drug resistance plasmids. Eastern Washington University. Cheney, WA.
58. Top, Eva. Increased persistence and expanded host range of antibiotic resistance plasmids. University of Washington, Department of Microbiology. Seattle, WA.
59. Vaelli, Patric; Theis, Kevin; Eisthen, Heather. Tetrodotoxin toxicity in rough-skinned newts: metaorganismal evolution in a predator-prey arms race? Early Career Scientists Symposium. University of Michigan, Ann Arbor, MI.
60. Vaelli, Patric; Theis, Kevin; Eisthen, Heather. The evolution of tetrodotoxin toxicity in salamanders. Ecology, Evolutionary Biology, and Behavior Colloquium. Michigan State University, East Lansing, MI.
61. Waters, Chris. Identifying Novel Molecules that Enhance Antibiotic Eradication of Bacterial Biofilm Formation. Drug Development Seminar Series. MSU, East Lansing, MI.

62. Waters, Chris. Cyclic di-GMP: A regulatory maestro that orchestrates bacterial biofilm formation and motility. Department of Microbiology. University of Washington, Seattle, WA.
63. Waters, Chris. Cyclic di-GMP: A regulatory maestro that orchestrates bacterial biofilm formation and motility. Departmental Seminar. University of Iowa, Department of Microbiology, Iowa City, IA.
64. Weigel, Emily. Hot or not? Just Try. TEDxMSU. Michigan State University, East Lansing, MI.
65. Weigel, Emily; Gall, Andrew; DeNieu, Michael. Oh, Behave! Behavior as an interaction between genes and the environment. National Association of Biology Teachers. Cleveland, OH.
66. Wiser, Michael. Fitness changes over 50,000 generations of evolution. Bad Bug Club. Michigan State University, East Lansing, MI.
67. Wiser, Michael. Long-term dynamics of adaptation in asexual populations. University of Memphis, Department of Biology Seminar Series. Memphis, TN.

2. Awards and Honors

	Recipient	Award Name and Sponsor	Date	Award Type
1	Carina Baskett	Dr. Marvin Hensley Endowed Fellowship, Michigan State University	2015	Fellowship
2	Armand Burks; William Punch	Engineering Graduate Research Symposium Poster Session - Honorable Mention	2015	Scientific
3	Alita Burmeister	Edith Hsiung and Margaret Everett Kimball Award, MSU Dept of Microbiology & Molecular Genetics	2015	Scientific
4	Alita Burmeister	EEBB Distinguished Student Speaker, MSU EEBB Graduate Program	2015	Scientific
5	Kalyanmoy Deb	Eminent Engineer Award, Tripura State Centre for the Institution of Engineers (India)	2015	Scientific
6	Kalyanmoy Deb	Honorary Life Member, Soft Computing Research Society	2015	Scientific
7	Bijoy Desai	Outstanding PhD Thesis, Biochemistry Trust of Urbana	2015	Scientific
8	Emily Louise Dolson; Charles Ofria	Honorable Mention at College of Engineering Graduate Research Symposium Poster Session, MSU CSE Department	2015	Scientific
9	Blair Fleet	GAANN (Graduate Assistance in Areas of National Need) Fellowship, United States Department of Education	2015	Fellowship
10	Alexander Fodor; Billie J. Swalla	Lambert Fellowship, Friday Harbor Labs, University of Washington	2015	Fellowship
11	Alexander; Billie J. Swalla	Sargent Award, University of Washington	2015	Scientific
12	James Arthur Foster	College of Science Distinguished Faculty Award, University of Idaho	2015	Scientific
13	James Arthur Foster	Faculty Excellence in Interdisplinary Activities, University of Idaho	2015	Scientific
14	Brian W Goldman; William Punch	Nominated Best Paper GA Track, GECCO	2015	Scientific

15	Hans A. Hofmann	College of Natural Sciences Excellence in Teaching Award, University of Texas at Austin	2014	Education
16	Kay E. Holekamp	Elected as Member, American Academy of Arts & Sciences	2015	Scientific
17	Elyse Hope	Society for Industrial Microbiology and Biotechnology's Diversity Travel Award	2015	Scientific
19	Chandra Jack	NextProf Workshop, University of Michigan	2015	Other
20	Zachary Laubach	Ecology, Evolutionary Biology and Behavior Program Summer Fellowship, MSU	2015	Fellowship
21	Kenna Lehmann	MSU EEBB Travel Fellowship	2015	Fellowship
22	Kenna Lehmann	MSU Graduate School Travel Fellowship	2015	Scientific
23	Kenna Lehmann	MSU International Studies and Programs Travel Fellowship	2015	Fellowship
24	Dacia Leon	Robert D. Watkins Graduate Research Fellowship, American Society for Microbiology	2015	Fellowship
25	Shawn M. Luttrell	E.S. Morse Institute Junior Fellow, University of Washington	2015	Fellowship
26	Risto Miikkulainen	Distinguished Lecturer, IEEE Computational Intelligence Society	2015-2017	Scientific
27	Sam Perez	Ford Foundation Fellowship	2015-2018	Fellowship
28	Sam Perez	MSU College of Natural Science Summer Continuation Fellowship	2015	Fellowship
29	Jacob Schrum; Risto Miikkulainen	Best Paper Award in the Digital Entertainment and Arts track, GECCO	2015	Scientific
30	Alvin Smucker	Innovator of the Year, MSU	2015	Scientific
31	William Soto	Carl Storm Fellowship, Gordon Conference	2015	Fellowship
32	Joshua Sukeena	University of Idaho College of Science Poster Presentation Award	2014	Scientific
33	Billie J. Swalla	Outstanding Diversity Commitment Award - Honorable Mention, UW College of the Environment	2015	Scientific
34	Chris Waters	MSU College of Natural Science, Teacher-Scholar Award	2015	Education-Related
35	Emily Grace Weigel	MSU College of Natural Science Dissertation Continuation Fellowship	2015	Scientific
36	Emily Grace Weigel	All-MSU Excellence-in-Teaching Award	2015	Education-Related
37	Holly Wichman	100 Inspiring Women in STEM, Insight into Diversity Magazine	2015	Other

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

	Student Name	**Degree**	**Years to Degree**	**Placement**
1	Jacob Bayless da Costa	Bachelors	2	Postbac researcher at UW
2	Mairin Chesney	Bachelors	5	Google
3	Rodney Pickett	M.S.	2	Civilian Employee, U.S. Navy
4	Nate Ward	M.S.	2	Software developer at SwipeSense

5	Jayandra Pokharel	M.S.		Software Developer at Univ of Minnesota
6	Charnee Pearson-Starling	M.S.	2.5	Medical Research Policy Admin
7	Kevin Hall	M.S.		K-12 Educator
8	Amy Lark	Ph.D.		Assistant Prof, Michigan Technological University
9	Jianxun Wang	Ph.D.	5	Apple Inc.
10	Anne Royer	Ph.D.		Postdoc at Willamette Univ
11	Brian W Goldman	Ph.D.	3	Postdoc at MSU
12	Randal S Olson	Ph.D.	4	Postdoc at U of Pennsylvania
13	Masoud Mirmomeni	Ph.D.	6	Postdoc at U of Michigan
14	Caroline Turner	Ph.D.		Postdoc at University of Pittsburgh Medical School
15	Jared Moore	Ph.D.		Postdoctoral Researcher at BEACON
16	Hong Lei	Ph.D.	6	Postdoc at MSU
17	Elizabeth Schultheis	Ph.D.		Postdoc at MSU
18	Melissa Kjelvik	Ph.D.		Postdoc at MSU
19	Jacob William Clifford	Ph.D.	8	Unknown
20	Raffica La Rosa	Ph.D.	9	Unknown

4a. General outputs of knowledge transfer activities

1. Provisional US patent filed for Gliding Robotic Fish (Xiaobo Tan, MSU).
2. Provisional US patent filed for Malware Cyber Analysis & Advisement Tool (MalwareCAAT) (Gerry Dozier & Henry Williams, NCAT).

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	Metron	Company	1818 Library Street, Suite 600 Reston, VA 20190		KT	N
3	Continental Automotive GmbH	Company	Vahrenwalder Straße 9 30165 Hanover Germany		KT	N
4	BAE Systems	Company			KT	N
5	General Motors	Company	PO Box 33170 Detroit, MI 48232-5170		KT	N
6	Dow Chemical Company	Company	S Saginaw Rd, Midland, MI 48640		KT	N
7	Secure Designs, Inc.	Company	301 N Elm St #201, Greensboro, NC 27401		KT	N
8	NASA	Federal Agency	Public Communications Office NASA Headquarters Suite 5K39 Washington, DC 20546-000		KT	N
9	University of Texas Rio Grande Valley	Other (Academic)	1201 West University Dr. Edinburg, TX 78539	Laura Grabowski	Research, Education, Diversity	Y
10	Yale University	Other (Academic)	New Haven, CT 06520	Paul Turner	Research, Education, Diversity	Y
11	University of California, Irvine	Other (Academic)	Irvine, CA 92697	Adriana Briscoe	Research, Education, Diversity	Y
12	NESCent	Other	2024 W. Main Street Suite A200 Durham, NC 27705-4667	Karen Cranston	Research, Education	Y
13	SESYNC	Other	1 Park Place Suite 300 Annapolis, MD 21401	Mary Shelley	Research, Education	Y
14	iPlant	Other	Thomas W. Keating Building 1657 East Helen Street Tucson, Az 85721	Stephen Goff	Research, Education	N
15	iDigBio	Other	105 NW 16th Street Gainesville, FL 32611		Research, Education	N
16	National Association of Biology Teachers	Other	1313 Dolley Madison Blvd, Suite 402, McLean, VA 22101		Education	N

7. Summary table

1	The number of participating institutions (all academic institutions that participate in activities at the Center) This value should match the number of institutions listed in Section I, Item 1 of the report plus other additional academic institutions that participate in Center activities as listed in the table above.	8
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	$800,000
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)	364

8. Media publicity

Press Releases

- 10/21/15: Data Nuggets are golden: MSU receives $1 million grant to study science education project
- 8/19/15: Forgotten sex signals
- 8/12/15: Computer scientists find mass extinctions can accelerate evolution
- 8/12/15: UI receives $22.5 Million to continue study of evolution in action
- 7/17/15: MSU's BEACON Center nets $22.5M grant to continue evolution research
- 7/15/15: Undergraduate researchers present at annual symposium
- 6/8/15: MSU hires nation's first endowed chair in genetic programming
- 5/11/15: Tortoise approach works best – even for evolution
- 3/12/15: Social status has impact on overall health of mammals
- 2/5/15: Settling for 'Mr. or Ms. Right Now' better than waiting for 'Mr. or Ms. Right'
- 12/16/14: Stay complex, my friends
- 10/30/14: Teaching evolution in action

Media Coverage

- 10/21/15: Fox 47 News: Data Nuggets are golden: MSU receives $1 million grant to study science education project
- 8/20/15: Futurity: Can species survive if sex signals are lost?
- 8/19/15: Science World Report: Sex signals of animals not always passed on from generation to generation
- 8/19/15: ScienceDaily: Forgotten sex signals
- 8/15/15: International Business Times: Simulated mass extinctions speed up robotic evolution in a new experiment
- 8/14/15: io9: Robot simulations show mass extinctions may accelerate evolution
- 8/13/15: Futurity: Mass extinction kicks off robot evolution
- 8/12/15: (e) Science News: Computer scientists find mass extinctions can accelerate evolution
- 8/12/15: ScienceDaily: Computer scientists find mass extinctions can accelerate evolution
- 8/12/15: Phys.Org: Computer scientists find mass extinctions can accelerate evolution
- 7/30/15: UT professor puts computer game research in context of "Pixels"
- 7/30/15: BBC Earth: How do we know that evolution is really happening?
- 7/23/15: 538.com: Stop trying to be creative
- 7/22/15: Lansing State Journal: MSU gets $22.5M to continue evolution research, education
- 7/22/15: CBS Detroit: MSU gets $22.5M to continue evolution research, education
- 7/22/15: WDET: Michigan State University is receiving $22.5M to study evolution [AUDIO]
- 7/22/15: The Detroit News: MSU gets $22.5M to continue evolution research
- 7/13/15: Austin American Statesman: Ask any robot: Future of humans and AI will be complicated
- 7/10/15: WKAR: MSU Pres on tuition hike, new discrimination office, future challenges
- 6/19/15: New Scientist: Cradle of creation: Evolution shapes up new ecosystem in the lab
- 6/4/15: NSF Science 360 Radio: Explorers of the brain

- 5/27/15: Science Channel's Through the Wormhole with Morgan Freeman: Are Aliens Inside Us?
- 5/15/15: Science Channel's Through the Wormhole with Morgan Freeman: Evolution is Like Poker
- 5/13/15: Futurity: Evolving E. coli follow 'tortoise-hare' pattern
- 5/10/15: The Telegraph: 6000-citation feat by 4 Indian researchers
- 5/10/15: Current Science: Indian paper crosses 5000+ citations mark [PDF]
- 5/3/15: Business Insider on MSN.com: Here's how humans are going to find alien life
- 4/6/15: New York Times: In Hawaii, Chickens Gone Wild
- 3/14/15: MSU researcher using Darwinian principles to create human-like robots
- 3/14/15: The Charlotte Observer: …Social status affects wild animals' health
- 3/13/15: The Daily Mail: Social status boosts health and fertility – even in HYENAS: Privileged females in a clan live longer and have more pups
- 3/13/15: Futurity: Hyenas at top of social ladder live longer
- 3/12/15: Counsel & Heal: Longevity predicted by social status in mammals
- 3/12/15: Science World Report: Overall health of mammals impacted by social status, study says
- 3/12/15: Phys Org: Social status has impact on overall health of mammals
- 3/12/15: Nature World News: Higher social status means healthier lives… for wild animals
- 3/11/15: New Scientist: Chance: The importance of randomness in evolution
- 3/6/15: Dick Jones Communications: Is 'Chappie' our future?
- 3/3/15: Engineering & Technology Magazine: Darwinian evolution to help develop human-like brains
- 3/3/15: Before It's News: Scientists continue path of Darwinian evolution for robots
- 3/2/15: Phys.Org: Evolving Robot Brains
- 2/12/15: Fox News: Waiting for Mr. Right may be an evolutionary wrong
- 2/12/15: The Onion: Study: Settling for adequate partner better than waiting for soulmate [Satire]
- 2/11/15: NPR: Mr. Right vs. Mr. Right Now [AUDIO]
- 2/9/15: Kansas City Star: Hey valentine: Maybe you should settle for Mr. or Miss Right Now
- 2/2/15: Kurzweil: Accelerating Intelligence: How complex environments push brain evolution
- 12/26/14: Futurity: Computer programs 'mutate' to outlast viruses
- 11/5/14: MSU Grad Factor: Alita Burmeister, Going Viral [VIDEO]

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 2014-15, each funded primarily by the visitor's host institution or a grant from their government. During the reporting period, two of Prof. Xu's students (Haiqiang Nie and Leilei Cao) spent time as visiting scholars in BEACON. The project in which they are involved is the Greenhouse Control project. Profs. Goodman and Erik Runkle (MSU) and grad student José Llera are visiting China in November, 2015, to continue that collaboration with the project's many members in China.

To facilitate continuation of the extensive collaboration going on between Dr. Goodman and Prof. Zhun Fan (Shantou University) 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. Dr. Goodman is visiting Shantou University in November, 2015. Prof. Hailin Liu, Guangdong University of Techology, a collaborator on the project, is a visiting scholar at BEACON from May, 2015 through June, 2016.

Ongoing work on using Multi-objective Evolutionary Optimization for solution of land use problems is continuing, with Mr. Jonas Schwaab joining BEACON as a visiting scholar from ETH Zürich from October, 2015 through August, 2016. He will collaborate with Profs. Deb and Goodman and their graduate students on this work.

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.

Prof. Deb is also extensively working with foreign collaborators in the area of evolutionary multi-criterion optimization and their applications. The following visiting students from abroad spent a considerable amount of time with Prof. Deb to progress their doctoral/master's thesis work funded by their own university/government:

1. Mr. Mohamed Abouhawwash (Mansoura University, Egypt): 2 years (September 2013 to October 2015), likely to defend PhD thesis in December 2015
2. Mr. Xin Li (Wuhan University, China): 1 year (November 2014 to October 2015), likely to defend PhD thesis in January 2016
3. Mr. Tolga Altinoz (Ankara University, Turkey): 10 months (September 2014 to August 2015), expected to defend PhD thesis in December 2015
4. Mr. Julian Blank (University of Magdeburg, Germany): 6 months (August 2015 to Jaunary 2016), expected to defend master's thesis in April 2016

The following post-doctoral researchers visited MSU on a grant from their own university and worked with Prof. Deb on evolutionary dynamic optimization, parallel evolutionary methods, visualization and opposition-based optimization methods:

1. Ms. Berna Kiraz (Marmara University, Turkey): 1 year (August 2014 to July 2015)
2. Ms. Marde Helbig (University of Pretoria, South Africa): 1 week in August 2015
3. Mr. Gregorio Toscano (CINVESTAV, Mexico): 1 year (August 2015 to July 2016) in collaboration with Prof. Goodman
4. Associate Prof. Shahryar Rahnamayan (University of Ontario Institute of Technology, Canada): 2 years (August 2014 to July 2016)

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)