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## I. GENERAL INFORMATION

<table>
<thead>
<tr>
<th>Date submitted</th>
<th>October 31, 2018</th>
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</thead>
<tbody>
<tr>
<td>Reporting period</td>
<td>February 1, 2018 – January 31, 2019</td>
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**Name of the Center**  
**BEACON Center for the Study of Evolution in Action**

**Name of the Center Director**  
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**Center URL**  
**http://www.beacon-center.org**

### Participating Institutions

<table>
<thead>
<tr>
<th>Institution 1 Name</th>
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<tbody>
<tr>
<td><strong>North Carolina A&amp;T State University</strong></td>
</tr>
<tr>
<td>Contact Person</td>
</tr>
<tr>
<td>Joseph L. Graves, Jr.</td>
</tr>
<tr>
<td>Address</td>
</tr>
</tbody>
</table>
| Joint School of Nanoscience and Nanoengineering  
2907 East Gate City Blvd.  
Greensboro, NC, 27401 |
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| Email Address       |
| gravesjl@ncat.edu   |
| Role of Institution at Center | Member Institution |

<table>
<thead>
<tr>
<th>Institution 2 Name</th>
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<tbody>
<tr>
<td><strong>University of Idaho</strong></td>
</tr>
<tr>
<td>Contact Person</td>
</tr>
<tr>
<td>James Foster</td>
</tr>
<tr>
<td>Address</td>
</tr>
</tbody>
</table>
| Department of Biological Sciences  
Moscow, ID 83844-3051 |
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| Role of Institution at Center | Member Institution |

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<th>Institution 3 Name</th>
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<tr>
<td><strong>The University of Texas at Austin</strong></td>
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<tr>
<td>Contact Person</td>
</tr>
<tr>
<td>Risto Miikkulainen</td>
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<td>Address</td>
</tr>
</tbody>
</table>
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| risto@cs.utexas.edu  |
| Role of Institution at Center | Member Institution |

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<th>Institution 4 Name</th>
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<tr>
<td><strong>University of Washington</strong></td>
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<tr>
<td>Contact Person</td>
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<tr>
<td>Benjamin Kerr</td>
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<td>Address</td>
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</tbody>
</table>
| Department of Biology  
Box 351800  
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| Role of Institution at Center | Member Institution |
CONTEXT STATEMENT

OVERVIEW OF VISION AND GOALS

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

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

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

Our range of study systems and our focus on evolution in action allow us to explore fundamental issues in evolutionary theory. While science has come a long way in understanding evolutionary patterns and the history of life on earth, many important questions remain about the causal processes: How do complexity, diversity, and robustness arise in evolving systems? What conditions lead to the evolution of intelligent behaviors? How do ecological communities form? Why do multicellularity and other forms of cooperation evolve? How much do these processes
vary between species or across biological, computational and robotic systems? Answering these and related questions will allow our understanding of evolution to better inform other areas of biological investigation and augment the practical utility of evolutionary design in engineering and industry. A guiding precept of this Center is that we must perform controlled experiments on evolution as it happens to fully understand, predict, and control evolutionary dynamics. These concepts demand exploration by interdisciplinary teams, joining biologists with computer scientists and engineers to solve increasingly difficult real-world design and optimization problems.

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

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.

**BEACON Legacy**

As BEACON enters its final years of STC funding, we have been focusing more on documenting our successes and creating products with an eye towards stimulating and enabling future progress in interdisciplinary research on evolution in action.

Charles Ofria (MSU) has taken the lead on synthesizing concepts within evolution in action by writing a series of synthesis papers. The BEACON Center has had notable success bringing together biologists, computer scientists, and others interested in studying questions related to the topic of evolution in action. A major component of this success has been in facilitating communication among people in these different fields by working through issues where language, concepts, background, and even research goals might differ, but questions still revolve around evolution as a dynamic process. His team is helping extend this multidisciplinary interaction beyond BEACON by developing synthesis papers that will be the start of
a series, each focusing on a core concept within evolution in action. These papers will explore the similarities and differences in how each concept is used, highlighting not just the profound distinctions, but also the subtle nuances that could derail a research project if left unnoticed. They have begun with the concepts of “fitness” and “diversity” - fundamental concepts in both biology and evolutionary computation. As they develop these initial synthesis papers, they are also refining the process for producing the papers. The team will produce a common paper structure and process to turn this into a consistent paper series that will highlight the BEACON legacy. Key to each of these papers is that they provide a conceptual gateway into the relevant concepts, and allow domain experts on either side to understand the depth of each field, how they relate, and what open questions are of particular interest. In the synthesis paper on fitness they are highlighting that the concept of fitness is central to all forms of evolution that involve selection, and yet has important distinctions in different fields. In biology, fitness is a measured quantity intended to reflect the survival potential of a species, typically based on the number of offspring an individual is expected to produce, while in evolutionary computation fitness is assigned by a “fitness function” that measures the quality of a prospective solution and is used to determine how many offspring that individual should be a parent to. They are highlighting these distinctions, and discussing how concepts translate well between fields and where differences in the meanings of fitness can frequently lead to misunderstandings. In the synthesis paper on diversity they are exploring the drivers and effects of diversity as they are studied in fields ranging from ecology to evolutionary computation. Diversity matters to each of these fields, but for differing reasons, which lead them to ask different questions. For example, many ecologists research the effects of diversity on ecosystem functioning, evolutionary biologists focus more on the origins of natural diversity, and evolutionary computation researchers study how to increase diversity to produce more varied solutions. The manuscript includes a meaningful breakdown of how diversity concepts are used, separating them into the target of the measure (a region, a species, etc.), the trait of the organisms (e.g., a phenotypic trait or their genomes), and the metric being used (e.g., Shannon diversity, richness, etc.). The team ran a successful workshop at the 2018 BEACON congress and has recruited a large number of interested authors across the fields. In both of these cases the team has been fleshing out the writing process, and are now testing what they believe will be an effective set of rules for collaborative writing.

The 2018 BEACON Congress included an extra day in celebration of Director Erik Goodman’s upcoming 75th birthday and featured 20 talks on evolution in action, many of which were presentations by notable scholars of evolutionary computation including John Koza, Stephanie Forrest, Darrell Whitley, and Maggie Epstein. Wolfgang Banzhaf, MSU’s John R. Koza Professor in Genetic Programming and a very active member of BEACON, has taken the lead on producing and editing a “Festschrift” volume in honor of the occasion, to be published by Springer next year. The volume will be titled Evolution in Action: Past, Present, and Future and will include original research, reviews, and a variety of essays. 34 chapters have been submitted and are under review, including a number of chapters reflecting specifically on BEACON’s contributions to science, including intellectual contributions, leadership & management style, and methods of increasing and maintaining diversity.

Perhaps the most important legacy that BEACON will leave is our impact on the people who have participated in BEACON work and, in turn, their impact on future generations of scientists. 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. This year, the team produced a study of alumni who completed PhDs and postdocs at BEACON. They found that the overwhelming majority rated their experience quite highly, and valued the interdisciplinary community and research. The majority of participants indicated that BEACON has impacted their thinking and their participation in interdisciplinary research. More specifically, BEACON alumni believed participation in BEACON improved their ability to make connections between different fields and disciplines, and improved their ability to look across disciplinary boundaries and consider other perspectives. In terms of career preparation, alumni believe their programs prepared them well for their careers and value interdisciplinary research.

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.
<table>
<thead>
<tr>
<th>GOAL</th>
<th>METRICS</th>
<th>PROGRESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>New research collaborations and proposals</td>
<td>Number of interdisciplinary/multi-institutional research projects and publications</td>
<td>55 projects currently underway, 1348 publications reported to date (122 submitted in the current reporting period)</td>
</tr>
<tr>
<td>New paradigms for research in organic and digital domains</td>
<td>Number of new sessions at scientific meetings or scientific meetings hosted at BEACON</td>
<td>None to report in this period</td>
</tr>
<tr>
<td></td>
<td>Number of new journals and societies</td>
<td>None to report yet</td>
</tr>
<tr>
<td></td>
<td>New or increased funding for biocomputational research</td>
<td>BEACON researchers submitted 36 proposals for external funding concerning evolution in action, and &gt;$13M in external funding was granted</td>
</tr>
<tr>
<td>Increase in publications related to evolution in action</td>
<td>Number of BEACON faculty participants writing such publications and the number of citations of their work.</td>
<td>BEACON publications are continuing at a high rate every year.</td>
</tr>
<tr>
<td></td>
<td>High visibility science journalism about BEACON research</td>
<td>7 press releases and &gt;15 media pieces since previous annual report, including pieces on several print journalism outlets</td>
</tr>
<tr>
<td>Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution</td>
<td>Number of requests for information</td>
<td>Avida-ED accessed 20,441 times in past year</td>
</tr>
<tr>
<td>Ethical Research Goal</td>
<td>Number of RCR training opportunities provided</td>
<td>4 Scientific Virtues sessions offered at BEACON seminars and BEACON Congress</td>
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<tr>
<td>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</td>
<td>Number of BEACONites who attended RCR training sessions offered by BEACON</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Number of BEACON seminars offered</td>
<td>22 BEACON seminars have been offered since Feb 1, 2018.</td>
</tr>
</tbody>
</table>
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 | 122 publications submitted, 132 conference or other presentations, 36 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 focused on basic research and group according to natural levels of organization (genomes, behavior among individuals, and community-level dynamics) and a fourth, added in 2014, focusing on evolutionary applications. 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 in which 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) adaptation in action; (2) effects of genetic interactions on evolution, including epigenetics and gene regulatory networks; (3) evolution of complexity; and (4) development of new tools for studying evolution in action. A total of 17 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 7 projects reported are studying (1) effects of brain function on social behavior; (2) the evolution of communication, in both acoustic and chemical modalities; and (3) theoretical and practical applications of intelligence.

**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) host-parasite evolutionary dynamics; (2) competition and niche construction; (3) microbiome evolution; and (4) evolution of antibiotic and antimicrobial resistance. Nine 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, and this Thrust Group is 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 applications for (1) biotechnology; (2) agriculture; and (3) healthcare and forensics; as well as (4) development of evolutionary computation methods. Twelve projects are currently funded in this thrust group.

**Education**

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

<table>
<thead>
<tr>
<th>Education Goals</th>
<th>METRICS</th>
<th>PROGRESS</th>
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<tbody>
<tr>
<td>Multidisciplinary Ph.D. graduates and post-docs placed in faculty positions at rates approaching averages across engineering, computer science, and biology</td>
<td>Fraction of BEACON graduate students and post-docs receiving offers of faculty positions</td>
<td>Among BEACON’s alumni to date: 16/118 (14%) PhDs and 17/35 (49%) postdocs are now in faculty positions. 64 (54%) of BEACON PhD graduates went on to postdoctoral positions.</td>
</tr>
<tr>
<td>Increased public literacy in</td>
<td>Development of educational</td>
<td>Testing, presentation, and</td>
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</table>
### Recent science education reform recognizes that students learn better when information is organized around major unifying concepts (National Research Council, 2012), and all recent science education reform places evolution as a core idea within the biological sciences (Brewer and Smith, 2011; College Board, 2011). Yet, evolution is summarily rejected by nearly half of the general public living in the United States (Miller et al. 2005). Across all BEACON, our educational projects aim to use BEACON research demonstrating evolution in action to reveal the power of evolution, showing (1) evolution is a historical AND ongoing dynamic process; (2) evolutionary biology is a good example of how science works; (3) evolutionary processes can help us solve complex biological and engineering problems.

### Internal Education Activities.**  
BEACON has instituted, and continues to offer, a series of courses specifically designed to train graduate students across disciplines. We continue to discuss and evaluate the effectiveness of our educational programs. Our graduate training courses create unique inter-institutional challenges such as different academic calendars (for example UW is on a quarter system whereas MSU is on a semester system). During the Spring 2018 semester we were able to offer Research Methods, however, we were unable to offer **Computational Science for Evolutionary Biologists** CSE 801 during the Fall 2018, the establishment of the new CMSE department resulted in changes to current faculty commitments. There were four students either enrolled or auditing **Evolutionary Biology for Non-life Scientists** during the Fall 2018 semester. There does seem to be a fair degree of fluctuation year to year, due to the varying numbers of new graduate students associated with BEACON.

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

<table>
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<tr>
<th>Increased interest in STEM careers in both academia and industry</th>
<th>The creation of programs that provide for the sustainability of students interested in STEM</th>
<th>Programs like the Luminaries Scholars and URA program at KBS assist in these areas.</th>
</tr>
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<tbody>
<tr>
<td>Communication of the diversity of careers associated with STEM disciplines</td>
<td>Participation in diverse careers workshops, and tracking our own students.</td>
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both KBS and FHL, projects to engage with K-12 biology education, and science communication workshops. We continued to provide research experiences for in-service teachers in the BEACON TEACHER REVOLUTION program. BEACON continues to participate/organize community outreach efforts, including 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 museum exhibits at MSU, the Darwin Day Roadshow, and outreach events co-sponsored by the Society for the Study of Evolution, the American Society of Naturalists, and the Society of Systematic Biology. 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.

Knowledge Transfer

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

<table>
<thead>
<tr>
<th>Knowledge Transfer Goals</th>
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<tbody>
<tr>
<td><strong>GOAL</strong></td>
</tr>
<tr>
<td>New collaborative research with industry partners</td>
</tr>
<tr>
<td>Number of joint grant proposals submitted with industrial partners</td>
</tr>
<tr>
<td>Description</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>Number of publications submitted that arise from industry-provided challenge problems and data</td>
</tr>
<tr>
<td>Receiving industry-provided challenge problems and data with feedback</td>
</tr>
<tr>
<td>Spinoffs formed</td>
</tr>
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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.

Many companies are currently working with BEACON, including Siemens, Ford Motor Company, Continental Automotive, Hyundai MOBIS, BAE Systems, General Motors, StoneAge Robotics, and Polymorphic Games.

**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.

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

So successful has been the operation of the Data Carpentry not-for-profit organization under the leadership of BEACON’s Dr. Tracy Teal that the organization sponsoring the Software Carpentry workshops has decided to merge with the Data Carpentry organization under Dr. Teal’s leadership. This new combined organization represents a large contribution to the national infrastructure for preparing biologists to use computational resources in support of their research and teaching, and is a direct result of BEACON’s sponsorship, NSF’s supplement to BEACON, and BEACON’s leadership of the effort. That organization continues to operate very successfully as of the time of this report, and represents a self-sustaining part of BEACON’s legacy.

Our BEACON Faculty Affiliates program maintains members at University of California at Irvine and Yale University and has successfully engaged students and postdocs at these institutions.

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. This accomplishment transcends the cursory goals of increasing the number of diverse participants and demonstrates a strategic and thoughtful culture that demonstrates diversity within its research opportunities, grant submissions, broader impacts efforts, educational outreach activities, formal mentoring training/support, fellowships, and direct student support funds. To summarize our diversity statistics:

- **URMs**: BEACON participants are: 53% White, 24% Black, 10% Asian, 5% Hispanic/Latino, 1% Native American, and 7% two or more races/ethnicities. 37% of BEACON participants are self-reporting as URMs, which is 20.1% above the National Norm (30.8%).

- **Women**: BEACON’s strategic efforts to increase overall female participation across all levels has resulted in the fact that 43% of BEACON participants are female, which is 31.1% higher than the National Norms of 32.8%. The number of female faculty is 39%, which also surpasses the national norm of 31.0% by 25.8%.

- **Individuals with Disabilities**: Currently 6.4% of BEACON participants self-reported as having a disability, which exceeds the National Norms (3.3%) by 93.9%. By demonstrating a commitment to being an inclusive and welcoming consortium, BEACON has increased its undergraduates reporting disabilities to 7.1%, which is a 51% increase over the National Norm (4.7%); graduates has increased to 8.2%, which is a 43.8% increase over the National Norm (5.7%), post-docs (where National Norm data is unavailable) maintained at the level of 2%, and faculty (2.7%) are above the National Norm (2.17%).

Individuals with disabilities are a continued priority within our strategic efforts. To address the previous stated challenge of under-reporting, BEACON continues to enhance the Disability
Action Plan, which is tasked to establish a climate of safe, inclusive, and adaptive environments for individuals with disabilities to thrive.

BEACON supports a number of diversity initiatives that strive to create and support research and education opportunities for women, underrepresented minorities, and individuals with disabilities at the undergraduate, graduate, postdoc, and K-12 levels. BEACON has recently updated its diversity webpage, with opportunities to creating a repository of best practices on subjects such as broader impacts, adaptive software, scalable models and tools, diversity of careers, summer REU opportunities, diversity articles, and the Native American/Alaskan Native Initiative (NAANI).

Management

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

<table>
<thead>
<tr>
<th>Management Goals</th>
<th>GOAL</th>
<th>METRICS</th>
<th>PROGRESS</th>
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</thead>
<tbody>
<tr>
<td>Increase in cross-disciplinary research and education</td>
<td>Number of paper/conference submissions by BEACON authors</td>
<td>41% of publications and 48% of presentations reported as interdisciplinary</td>
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<tr>
<td></td>
<td>Number of students enrolled in cross-disciplinary courses</td>
<td>12 in semester-long courses, plus hundreds in workshops on computational science for biologists</td>
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<tr>
<td></td>
<td>Number of funding proposals submitted</td>
<td>24 of 36 grant proposals submitted (67%) reported as interdisciplinary; 11 of 36 (31%) inter-institutional</td>
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<tr>
<td>Increase in cross-institutional research and education</td>
<td>Number of paper/conference submissions</td>
<td>33% of all publications and 38% of presentations reported to be cross-institutional</td>
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<td></td>
<td>Number of new courses and workshops</td>
<td>As discussed in Education section, many Data Carpentry workshops were offered to a national audience in the reporting period, plus one EDAMAME (Explorations in Data Analyses for Metagenomic Advances in Microbial Ecology) workshop.</td>
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<tr>
<td></td>
<td>Number of students in cross-institutional courses</td>
<td>In 2018, there were 12 MSU students enrolled in semester-long BEACON courses. Some BEACON partners offered</td>
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<tr>
<td>Increase in new funding sources (cross-disciplinary and cross-institutional)</td>
<td>Number of submissions</td>
<td>BEACON researchers submitted 36 proposals for external funding concerning evolution in action, and &gt;$13M in external funding was granted</td>
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<td></td>
<td>Award dollars</td>
<td>BEACONites have been awarded over $13M from outside BEACON in this funding period (&gt;9M for cross-disciplinary proposals), well exceeding goal of $5M/year</td>
<td></td>
</tr>
<tr>
<td>Effective support of Center operations by Management team</td>
<td>Survey for participants about management team</td>
<td>2018 study has focused on BEACON's successes in promoting multidisciplinary research and increasing diversity, as well as studying alumni career paths</td>
<td></td>
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<tr>
<td></td>
<td>Feedback from External Advisory Committee</td>
<td>Feedback has been positive and encouraging (Appendix C)</td>
<td></td>
</tr>
<tr>
<td>Center is perceived by NSF as exemplary</td>
<td>Renewal of NSF funding</td>
<td>BEACON’s 5-year renewal proposal was approved and funded in 2015.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of public mentions made by NSF about BEACON</td>
<td>Multiple mentions and retweets on NSF’s Twitter feeds</td>
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</table>

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. As BEACON is now in the final two years of STC funding, the team is focusing on learning what aspects of BEACON's strategies have been most successful in promoting multidisciplinary research, increasing diversity in science, and helping alumni further their careers. This year they have been interviewing faculty about their multidisciplinary research teams, working with leadership on documenting BEACON’s diversity processes, and reporting the career paths of BEACON’s graduates (M.S., Ph.D. and postdoc).

Center-Wide Outputs

- Publications submitted: 122 reported
- Conference presentations and other dissemination activities (including lectures, seminars): 122 reported
- Awards and Honors: 26 awards and honors reported
- Students that graduated (reported): 12 PhDs, 1 Bachelors
- General outputs of knowledge transfer activities: 1 patent filed
- Participants: 422 participants, plus another 274 affiliates (under 160 hours/year in Center activities), for a total of 696 BEACONites
- Media publicity: Since the previous annual report, we have put out 7 press releases so far. Over 15 features on BEACON activities appeared in the mainstream and online media in the last reporting period.

Indirect/Other Impacts

International activities: BEACON is engaging in international activities on 4 continents, including field research and education in Kenya; multiple engineering research collaborations with researchers and organizations in China, Switzerland, Denmark, and Mexico; and experimental and digital evolution research collaborations in France.
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 55 research projects were supported by BEACON, including 30 projects that just began in summer/fall 2018. 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.

<table>
<thead>
<tr>
<th>GOAL</th>
<th>METRICS</th>
<th>PROGRESS</th>
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<tbody>
<tr>
<td>New research collaborations</td>
<td>Number of interdisciplinary/multi-institutional research projects and publications</td>
<td>55 projects currently underway, 1348 publications reported to date (122 submitted in the current reporting period)</td>
</tr>
<tr>
<td>and proposals</td>
<td></td>
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<tr>
<td>New paradigms for research</td>
<td>Number of new sessions at scientific meetings or scientific meetings hosted at BEACON</td>
<td>None to report in this period</td>
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<td>in organic and digital</td>
<td></td>
<td></td>
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<tr>
<td>domains</td>
<td>Number of new journals and societies</td>
<td>None to report yet</td>
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<tr>
<td></td>
<td>New or increased funding for biocomputational research</td>
<td>BEACON researchers submitted 36 proposals for external funding concerning evolution in action, and &gt;$13M in external funding was granted</td>
</tr>
<tr>
<td>Increase in publications</td>
<td>Number of BEACON faculty</td>
<td>BEACON publications are</td>
</tr>
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</table>
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 ninth annual BEACON Congress in August 2018. The Congress is now a full 3 days and features numerous networking events. The 2018 Congress also included a fourth day dedicated to Dr. Erik Goodman's
75th birthday, and featured 20 talks, many of which were presentations by notable scholars of evolutionary computation including John Koza, Stephanie Forrest, Darrell Whitley, and Maggie Epstein.

- **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.

- **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, 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 computational 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. Here, 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) adaptation in action; (2) effects of genetic interactions on evolution, including epigenetics and gene regulatory networks; (3) evolution of complexity; and (4) development of new tools for studying evolution in action. A total of 17 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.

#### Adaptation in action

Celeste Brown (UI), Clinton Elg (UI graduate student), Chris Rhoades, Geoffrey Severin (MSU graduate student), Eva Top (UI), and Chris Waters (MSU) are characterizing unique genomic islands in modern pandemic *Vibrio cholerae* evolution. The bacterium *Vibrio
*V. cholerae* is the causative agent of the diarrheal disease cholera and is annually estimated to afflict ~2.9 million individuals resulting in ~95,000 deaths. Since 1821 there have been seven recorded cholera pandemics caused by two *V. cholerae* biotypes, classical and El Tor. While the first six pandemics were caused by classical *V. cholerae* strains the current (7th) pandemic, which began in 1961, is being perpetuated by circulating strains of El Tor *V. cholerae*. Despite both biotypes sharing a common ancestor, the El Tor biotype became the etiological agent driving modern day cholera by displacing classical *V. cholerae* in both endemic and clinical populations on a global scale. El Tor’s mysterious supplantation of the classical biotype has been a curiosity in the cholera field and it has been postulated this global event was potentiated by El Tor’s acquisition of two unique genomic islands, VSP-1 and 2, just prior to the initiation of the 7th pandemic. VSP-1 and 2 represent the greatest genetic difference between the two biotypes, accounting for 35 hypothetical genes. Only three of these genes have been definitively characterized and this team has proposed to synergize computational genomic analysis with wet-lab techniques to rapidly identify and assign functions to genes and gene clusters encoded on these islands. Completion of this project will expand our understanding of how the El Tor biotype leveraged these islands to its advantage in this global “evolution in action” displacement event and how distribution of these genes may contribute to bacterial fitness more broadly.

Ingo Braasch (MSU), Arjun Krishnan (MSU), and Andrew Thompson (MSU postdoc) are developing methods to detect functional evolutionary change in expression profiles of rapidly evolving killifishes. Studies on gene expression can shed light on how organisms function, respond to their environment, and change during development. Most gene expression studies to date have focused on changes within a single species or population. This is because there is no developed software or bioinformatic pipelines that allow scientists to compare changes in expression between species taking correlated evolution via phylogeny into account. Without proper comparative methods, it is difficult to interpret how transcription shifts over evolutionary time between different lineages. This team is using a system of annual killifishes that have convergently evolved annualism, a highly labile trait that allows them to survive in temporary ponds and is associated with rapid aging and dormancy (diapause) stages. They have designed a simple experiment using annual and non-annual killifishes to explore shifts in gene expression and transcriptional modules that led to the repeated gain or loss of dormancy. They hypothesize that killifishes with similar annual life histories use similar gene expression profiles and transcriptional modules during dormancy that are different from non-annuals. They plan to apply empirical data derived from this and previous experiments to develop new software in a bioinformatic pipeline that will allow biologists to study the evolution of gene expression in action.

Jeffrey Barrick (UT), Jason Bundy (MSU graduate student), Joseph Graves (NCAT), Minako Izutsu (MSU postdoc), Devin Lake (MSU graduate student), Richard Lenski (MSU), and Misty Thomas (NCAT) are conducting experiments with bacteria and Avida to test the effects of population bottlenecks on the dynamics of adaptive evolution. This new project examines the effects of population bottlenecks on the rate of adaptive evolution, and the team has already made substantial progress. The long-term evolution experiment with *E. coli*—the LTEE, for short—has provided many insights into the dynamics of adaptive evolution including the effects of clonal interference, diminishing–returns epistasis, and mutation rate. However, there remain important unanswered questions about the factors that control the rate of adaptation (gains in fitness), both in that particular context and more generally in evolution. One such question concerns the effects of population bottlenecks on the dynamics of adaptive evolution. A simple
theoretical model makes a concrete prediction, but it rests on assumptions that may not be fulfilled, and its predictions have not yet been tested. To that end, this group has proposed to tackle this issue by conducting rigorous experiments with bacteria evolving under several different bottleneck regimes. To test the effects of varying bottlenecks, they are using marker-divergence experiments with *E. coli*. In this design, each replicate population starts with an equal mix of two genotypes that are identical except for a selectively neutral marker. The ratio of the two markers remains constant, except for statistical fluctuations, until a beneficial mutation arises and spreads through one or the other lineage. Beneficial mutations cause sustained perturbations to the ratio of the two lineages in a given population, but across replicates in the same treatment the direction of the perturbation is random. Between treatments, however, the distribution of the trajectories allows one to see and quantify differences in the speed of adaptation.

**Effects of Genetic Interactions on Evolution**

Cynthia Chang and Thelma Madzima (both UW Bothell) are examining **plasticity and epigenetic modification as a form of bet-hedging in a highly variable environment.** Environmentally induced epigenetic modifications could provide the basis for phenotypic plasticity and adaptive ability to stressful and variable environments, where the intensity and length of stress is unpredictable. Epigenetic modification provides a transgenerational response to environmental stress (“memory”), which is particularly important in the face of future climate change scenarios. Climate models predict both greater periods of drought and a more variable environment, which will drive the evolutionary ecology of how plant species respond to these environments. Evolutionary theory on the adaptive value of phenotypic plasticity provides insight into generational responses to environmental stress. When it comes to highly variable environments, there is much discussion about the value of bet hedging as a strategy. Bet hedging predicts that phenotypically diverse offspring are more favorable under variable, unpredictable conditions. Epigenetic “memory” of a high stress experience (eg. drought) could be potentially beneficial to the offspring in a highly variable stress environment. Together, plasticity and epigenetic modification may provide the keys to a population’s ability to adapt to climate change. The team predicts that as the environment becomes more variable, there is an increase in the adaptive value of both plasticity and epigenetic modifications beneficial to high stress environments. This team is using *Arabidopsis thaliana*, a fast-growing, primarily selfing, annual plant to understand the role of epigenetics and plasticity in adaptation to a highly variable environment. These faculty members are also harnessing an existing research program that conducts course-based research with undergraduates at the University of Washington Bothell.

Dukka KC (NCAT), Robert Newman (NCAT), and Claus Wilke (UT) are conducting **computational studies to elucidate evolutionary conservation of phosphorylation sites.** Phosphorylation is a key post-translational modification that controls the regulation of nearly all cellular processes in eukaryotes. Therefore, it is important to understand how phosphorylation networks are organized and regulated in both physiological and pathological states. Importantly, because cellular phosphorylation networks play a central role in regulating gene expression patterns and cellular metabolism, re-organization (or re-wiring) of these networks is likely to lead to systems-level changes in cellular physiology that can impact evolutionary parameters in a manner analogous (or complementary) to genetic variation. Interestingly, though phosphorylation-dependent signaling is a highly conserved mode of information processing...
across eukaryotic species, previous studies suggest that individual phosphorylation sites on orthologous proteins vary substantially across species. Past studies suggest that, on the one hand, phosphorylation might be subject to rapid evolution while, on the other, there may be functional constraints with respect to which substrates a particular kinase is likely to regulate. The team’s goal is to perform a systematic comparison of the organization of phosphorylation networks between species. For this particular pilot project, their objective is to develop species-specific general phosphosite prediction tools to expand the list of candidate phosphosites in *C. reinhardtii* and to perform comparative analysis of conservation of phosphorylation sites across species.

Jianrong Wang (MSU) and David Arnosti (MSU) are examining the **evolutionary rewiring of regulatory networks by transposable elements**. Large-scale regulatory networks involve sophisticated interactions between regulatory elements, transcription factors and genes to precisely control tissue-specific transcriptional programs. It is of fundamental importance to understand the mechanism of how regulatory networks formed and rewired through evolution. Transposable elements (TE), as the most dynamic genomic units, are widely spread across the human genome and have been suggested to contribute regulatory elements on gene expression in some cases. It is therefore intriguing to systematically characterize the mechanism of network rewiring mediated by TEs. It has been challenging for traditional approaches to tackle this question because 1) repetitive sequences of TEs are difficult to analyze, 2) TEs located distal to genes may involve long-range regulation, and 3) heterogeneous regulatory grammar might be utilized by distinct TE families. To overcome these critical barriers, based on the strength of this team's inter-disciplinary expertise, they are developing innovative machine learning algorithms to comprehensively dissect TE-derived regulatory networks genome-wide in diverse human tissues, followed by detailed experimental interrogation of regulatory grammar associated with TE-derived regulatory elements. They will further apply advanced network deconvolution and analysis approaches to systematically delineate evolutionary dynamics of TE-based network rewiring. This integrated research strategy will not only generate novel machine learning algorithms and genome-wide resources of predictions, but will also gain systems-level insights on regulatory network evolution. In addition, the network rewiring patterns characterized in this work will indicate generalizable dynamics rules for other network-evolving systems.

Acacia Ackles (MSU graduate student), Ingo Braasch (MSU), Julia Ganz (MSU), and Arend Hintze (MSU) are studying **genome duplications and their effect on brain complexity and its rapid diversification**. Ever since Ohno’s seminal book ‘Evolution by Gene Duplication’ (1970), whole genome duplication (WGD) has been considered as a main mechanism for evolutionary change. Most gene duplicates are lost secondarily, but this group recently found that genes involved in cognition and behavior show especially high duplicate retention after a WGD in teleost fish (the Teleost Genome Duplication or TGD), in particular glutamate receptor genes. They hypothesize that sub- and neofunctionalization of these glutamate receptor duplicates had profound impact on teleost brain functions and that WGDs in general have facilitated brain diversity and complexity in vertebrates. This multidisciplinary team is 1) using comparative genomic analyses to study glutamate receptor evolution following the TGD and other vertebrate WGDs; 2) employing comparative gene expression analyses in brains of divergent teleosts (zebrafish and medaka) in comparison to the unduplicated gar outgroup to test for lineage-specific glutamate receptor duplicate sub- and neofunctionalization; and 3) using Markov Brains to model the effect of WGDs on the evolution of brain complexity and diversity in comparison to the biological fish system. This will show that the effects of WGDs are not limited to teleosts, but that they are general evolutionary phenomena. This project is significant for evaluating the
contribution of WGDs to biodiversity and organismal complexity and has broader impacts by engaging underrepresented minorities in research and by developing various outreach activities that include neuroscience, evolution, and computation.

Jannell Bazurto (UI postdoc), Eric Bruger (UI postdoc), Norma Cecilia Martinez-Gomez (MSU), and Christopher Marx (UI) are applying Tn-Seq technology to questions of pleiotropy and evolvability on a genomic scale. How evolution has proceeded and may do so in the future is a question of primary interest for both fundamental questions to evolutionary biology, as well as evolutionary applications to many fields such as medicine and agriculture. One way in which evolution may be constrained is through pleiotropy, wherein a single mutational change may impact multiple traits. This is especially true when the fitness effects upon different traits oppose one another – or antagonistic pleiotropy. In this way, the evolution of modularity, or the separation of system components – in this case traits and functions, is expected to diminish the occurrence of pleiotropy by allowing traits to evolve more independently of one another, and also promote the extent of evolvability, or ability for a system to evolve. However, convincing examinations of these connections are lacking. And the few reported large scale investigations into pleiotropy to date have been restricted to the eukaryotes, and the possibility remains that the level of overall pleiotropy may be much higher in bacteria and archaea. The extent of evolvability of a system is of much interest intellectually and also of great importance to a number of practical concerns ranging from promoting protein evolution in biotechnology to limiting adaptation in the presence of antibiotics or pesticides. This team is determining patterns of pleiotropy across the genome of Methylobacterium extorquens by exposing transposon-tagged pools to a diverse variety of growth conditions, and determining the patterns of evolvability among loci in transposon insertion pools of M. extorquens.

Ashley Teufel (UT postdoc) and Ben Kerr (UW) are testing competing lock-and-key hypothesis for constrained protein-protein evolution. Many proteins require tight binding with a specific protein partner to function properly, reminiscent of a lock and its key. Evolutionary diversification has produced an array of different lock and key proteins and these protein partners often belong to families with shared ancestry. However, the fact that even a single mutation in one protein partner can impair functionality presents a paradox: how can these lock-and-key proteins diversify? This paradox is clearly apparent in the diverse colicin-immunity system of Escherichia coli, and over 20 unique but related Col-Imm pairs have been described. Simultaneous change in both partners yielding a new functional match is possible but quite improbable. It is more likely that one component will change before the other. However, if the lock is modified first, then the old key no longer fits, rendering the new lock inoperative and vice versa. Two primary models have been proposed to account for the diversification of such lock-key systems, a master key model and an extra key model. Using computational simulations of protein evolution, the researchers are comparing these two models of diversification to identify how Col-Imm pairs diversify. Further, they will test the ability of their simulations to produce functional protein pairs through experimental validation.

Osama Alian (MSU graduate student), Matthew Schrenk (MSU), and Jesse Zaneveld (UW) are linking habitat filtering, horizontal gene transfer, and intraspecific competition at life’s upper temperature extreme. Hydrothermal vent chimneys compress thermal and chemical gradients over short distances (10’s of cm) and impose extreme selective pressures upon the microbial populations hosted within their walls. Culture-independent analyses of microbial communities at these high temperatures have shown low taxonomic diversity and an extremely
high percentage of transposases and other mobile genetic elements (MGE) in their metagenomes. This study explores the hypothesis that several unusual observations of microbial ecology in vent chimneys, including extreme habitat filtering, low microbial community diversity, and extremely high abundances of transposases and other MGE are not separate coincidences, but instead represent interconnected aspects of the same evolutionary process. The team is combining approaches in microbial ecology, bioinformatics, and evolutionary modeling to address the driving forces behind these observations. Specifically, they are evaluating whether genes that are horizontally transferred are involved in diversification and niche expansion, are involved in hyperthermophily, or are neutral in their effects. This work plan combines evolutionary simulations with carefully targeted metagenomic observations to test the predictions of this hypothesis against several competing alternatives.

Norma Cecilia Martinez-Gomez (MSU), Christopher Marx (UI), Jagdish Patel (UI postdoc), and Sergey Stolyar (UI) are considering pleiotropy vs. evolvability within an enzyme by using deep mutational scanning, molecular modeling, and experimental evolution to address constraints in a promiscuous enzyme. They aim to identify the relationship between pleiotropy and evolvability when considering substitutions in a single enzyme. By using deep mutational scanning with ExaF, an ethanol dehydrogenase discovered by Martinez-Gomez, the team will be able to widely characterize changes in protein structure and their impact on function. Changes in substrate affinity and promiscuity, as well as specificity for different cofactors (different light lanthanides), can be correlated with growth rate. Further, they will test if stabilizing mutations that individually do not have an effect on activity can serve as backgrounds that are generically permissive for later activity-changing mutations that otherwise would generally be destabilizing. Molecular modeling has been proven to efficiently predict folding stability, therefore they predict that it can also efficiently predict evolvability.

Matthew Faber (MSU graduate student), Craig Miller (UI), and Tim Whitehead (MSU) are traversing multi-gene fitness landscapes in alternative phiX174 hosts. Predicting the tempo and trajectory of evolutionary change in the complex environments encountered by viruses and bacteria remains a challenge. Two obstacles preventing better predictions are the vast number of possible mutational combinations that can occur—even in short adaptive walks and small genomes—and the oversimplification of the environment in experimental evolution studies compared to wild conditions. Advances in DNA sequencing and synthesis have opened new ways to study microbial evolution and overcome some of these obstacles. Saturation mutagenesis can be used to sample much larger regions of a fitness landscape. Deep sequencing allows tracking individual genotypes through time and in response to dynamic selective pressures (e.g., antibiotic exposure), thereby revealing interactions between alleles (epistasis) and population dynamics (e.g., clonal interference). Research on epistasis has tended to focus either on mutagenesis of single genes or limited sets of adaptive mutations across genomes, but saturation mutagenesis of sets of interacting genes has not been done. Because selection acts on protein complexes, we expect epistasis between interacting genes to be common, important, and different than within genes. The bacteriophage PHIX174 is an ideal system to initiate this effort because of its genetic manipulability, small genome size, and conduciveness to experimental evolution. Using the capsid and spike proteins of phiX174, this team will contrast the patterns of epistasis observed in pairs of mutations within a gene versus pairs on separate genes and to ask how general the resulting patterns are across hosts.
Evolution of Complexity

Chris Adami (MSU), Rich Lenski (MSU), and Claus Wilke (UT) are modeling the evolution and de-evolution of biological complexity. This team proposed that the manner in which populations de-evolve from the fitness peak they occupy when their population size is reduced depends on the functional complexity of their genotype. According to this theory, measuring the rate of decay of fitness as a function of the population size is a proxy for the accumulated functionality (complexity) when climbing that peak. Put in other words: as organisms descend the peak they climbed in their evolutionary history they map out a part of the fitness landscape they inhabit (even though the sequence of mutations they “give up” is likely different from the sequence that led them to the point from which they descend). The LTEE lines provide a special opportunity to test this theory as we are already in possession of the “forward trajectories.” Carrying out multiple “de-evolution” experiments for each forward trajectory provides a principled way of mapping fitness peaks.

Development of New Tools for Studying Evolution in Action

Eric Bruger (UI postdoc), Christopher Marx (UI), and Sergey Stolyar (UI) are working on deep-sequencing and metabolomics analysis as a framework for uncovering fitness landscapes and modeling evolvability in engineered metabolic networks. Epistasis – non-linear interactions between genotypic changes upon phenotypes – represents a critical challenge to optimization of biological systems, whether by evolution or engineered via synthetic biology. When mutational effects upon growth or product generation depend on the genetic background, assessing performance across the entire parameter space of any system of realistic size quickly becomes impossible. This is especially problematic when there is sign epistasis – mutations that change from beneficial to deleterious depending upon the other loci – as this creates ridges and peaks on the fitness landscape that can restrict stepwise optimization via either synthetic biological changes or beneficial mutations. Development of kinetic computational models of metabolism can provide guidance, but unfortunately these models are dogged by numerous free parameters. There is an immediate need for two linked developments: empirical techniques that can rapidly generate and assess rational, combinatorial variants, and modeling techniques to incorporate these data and predict where in parameter space further rounds of generation and assessment of variation would be most effective.

Jeffrey Barrick (UT) and Maitreya Dunham (UW) are developing methods for multiplex measurement of mutation rates and spectra. The rate at which new mutations arise and the types of sequence changes they introduce into a genome (i.e., the mutation spectrum) are key parameters that determine evolutionary dynamics and adaptive potential. Cells with elevated mutation rates (hypermutators) often arise in microbial evolution experiments, chronic infections, and cancer. Cells with reduced mutation rates (antimutators) are useful in engineering because they make designed functions encoded in a cell's DNA less likely to 'break' due to evolution. Current techniques for measuring mutation rates and spectra-such as fluctuation tests and genome sequencing of mutation accumulation lines-have limited accuracy, applicability, and throughput. This team will further develop and apply two methods for measuring mutation rates and spectra that can be used to profile many microbial strains at once: multiplexed chemostat sequencing (MCS) and maximum-depth sequencing (MDS). MCS monitors the accumulation of new mutants in a chemostat for many barcoded strains simultaneously. MDS uses error-corrected consensus reads from deep-sequencing of a specific locus to directly measure mutation rates and
spectra. They are using both methods to examine a population from the Lenski long-term experiment with *E. coli* that evolved hypermutation and then compensatory mutations that later reduced mutation rates and to characterize antimitator strains of *E. coli* found in a directed evolution experiment. These pilot studies will establish whether these new methods will be useful for better characterizing mutation rates and spectra in other systems.

Diane Blackwood, Arend Hintze, undergraduate Robin Miller, and Robert Pennock (all MSU) are developing an **EvoSphere Common Garden Experiment**. EvoSphere is a unified digital evolution experimental platform they have developed to apply evolution in a 3D physics-based environment. It allows users to conduct new sorts of experiments to examine the generality of evolutionary processes. The team wants to provide a platform that will allow a wide variety of experiments, such as how morphological changes over evolutionary time scales or morphological plasticity and variability drive the evolution of intelligent behavior. EvoSphere provides a foundation for answering questions that are central to the BEACON mission of showing how biological and computation evolution unite within a single theoretical sphere. The team will evolve different computational controllers (ANN, GP, Markov Brains, Avida like CPUs) in combination with different physiological bodies (Sim’s Bodies, fixed morphologies, sticks and jointed walkers, and MossBlocks) and test how they evolve differently, or what their communalities are. Secondly, they will perform direct competitions among systems, where organisms with different morphologies and different behavior controllers are pitted against each other.

**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 7 projects listed below are studying (1) effects of brain function on social behavior; (2) the evolution of communication, in both acoustic and chemical modalities; and (3) theoretical and practical applications of intelligence.

**Effects of brain function on social behavior**

Kay Holekamp (MSU) and collaborators Frants Jensen (postdoc, Aarhus University), Andy Gersick (postdoc, Princeton), and Ari Strandburg-Peshkin (postdoc, Max Planck Institute for Ornithology) are studying the **role of individual intelligence in the evolution of collective sensing and defense**. Cooperation across dispersed, heterogeneous social networks is a keystone aspect of human society, yet its origins are unclear. Recent research has shown that simple individual rules can drive coordinated movement in dense, homogenous groups such as fish schools. Far less understood are the mechanisms of coordination under conditions of social and cognitive complexity, as in stable societies with differentiated relationships mediated by long-
term memory. Like humans, spotted hyenas hold a dominant ecological niche largely via collective action. Hyenas disperse widely to forage in small subgroups, but clans converge rapidly to defend prey and territory against lions and rival groups. Lone hyenas recruit allies using long-distance “whoop” calls, allowing clans to collectively detect threats. This system depends on enough individuals responding to these calls, but not all hyenas do. By assessing how hyenas “decide” whether to opt into collective action, this group aims to illuminate the role of two aspects of intelligence (recognition of clan-mates and memory of past events) in shaping this behavior. Combining field experiments with novel tags that continuously record movements and vocalizations, they are investigating hyenas’ recruitment system on two timescales: immediate responses to signals, and long-term ranging patterns following exposure to threats. They are also using movement and evolutionary models to link individual decision-making to collective outcomes, and to investigate the evolutionary history of individual cognition supporting collective action in a complex social species. This BEACON support led to development of a Workshop on Communication and Movement in Animal Groups (September 2017) at the International Bio-Logging Conference in Europe, September 2017, co-organized by Ariana Strandburg-Peshkin, Andrew Gersick, and Frants Jensen. This workshop brought together researchers working in collective animal behavior, animal communication, and bioacoustics for multidisciplinary discussion of how to incorporate active signaling into our understanding of group coordination across diverse animal societies. See https://www.bio-logging.net/SYMPOSIUM/Programme/. This BEACON support also led to development of a Workshop on Collective Behavior, Social Media, and Systemic Risk (August 2018) held at Princeton University, co-organized by Andrew Gersick.

Chris Adami, Eben Gering, Thomas Getty, Arend Hintze, and Kay Holekamp (all MSU) are investigating the impacts of brain-manipulating parasites on host fitness and social behavior. Parasites have evolved to manipulate hosts throughout the tree of life, from zombie ants to whirling fish. These manipulations have profound medical and ecological significance, but their evolutionary impacts are underexplored. The team has proposed tests of how Toxoplasma gondii, a parasite that infects nearly all vertebrate species and ~30% of humans, influences fitness and social behavior in co-evolving hosts. Like many other parasites, T. gondii can be transmitted vertically (parent-to-offspring), trophically (prey-to-predator), and also environmentally as infectious spores shed by definitive feline hosts. In most non-definitive (non-feline) hosts that have been studied, T. gondii upregulates risky behavioral boldness and decreases coordination, presumably to drive transmittance to feline predators. This manipulation targets conserved features of the nervous system; thus, T. gondii also alters behavior in host species, including humans, that are seldom predated by felines. Extensive prior research has asked how parasites like T. gondii impact evolution of host life histories, mating preferences, migrations, and morphologies. In this project, the researchers predict they can also influence the collaborative behaviors of social hosts. The rationale is that: 1) in social animals, behavioral decision rules are under selection to maximize the ratio of benefits (e.g. reciprocity and inclusive fitness) to costs (e.g. received aggression and predation), and 2) parasites that reduce behavioral inhibition and/or coordination will likely interfere with cost-benefit assessments or implementation of behavioral decisions, potentially causing collaborative behavior that is individually maladaptive. Thus, manipulative parasites could indirectly promote evolution and expression of social behaviors in hosts. To examine the provocative central hypothesis, the team devised integrative studies that will reach from virtual worlds in the MSU computer cluster to the fields and butcher stalls of sub-Saharan Africa. First, they examining how the evolution of
collaborative behavior is influenced by co-evolving, manipulative parasites. To answer this question, they will use a computational model to evolve cooperating agents that can additionally be infected by parasites, allowing us to observe their co-evolutionary interactions. Second, they ask how host behavior and fitness change as a result of human influences on parasites. To explore this question, they are measuring *T. gondii* antibody titers (n=180) in previously collected hyena blood samples (using ELISA), and regressing infection statuses and antibody titers onto field data to look at interactions with habitat disturbance, host characteristics, and group foraging behavior.

**Evolution of communication**

Andrew Gersick (Princeton postdoc), Kay Holekamp (MSU), Frants Jensen (Aarhus University postdoc), and Ariana Strandburg-Peshkin (University of Zurich postdoc) are studying the biological and algorithmic evolution of acoustic recognition. Individual recognition forms the basis for development and maintenance of differentiated social relationships and evolution of cooperation in many systems. Spotted hyenas live in clans with multiple unrelated matrilines that cooperatively defend communal territory from neighboring clans and from other large carnivores. They depend on long-range acoustic vocalizations to recruit distant conspecifics for collective action, and these vocalizations have been suggested to allow discrimination of individuals to help assess clan membership and risk of engaging in cooperation. The team is combining evolutionary algorithms with gradient boosting to classify hyena vocalizations from a large acoustic dataset of 5 individual hyenas fitted with acoustic collars recording continuously for 45 days. They will then use empirical measurements of sound propagation in the Maasai Mara National Reserve, Kenya, to model how acoustic features attenuate across distances where hyenas naturally communicate. Finally, they will combine these two approaches to investigate individual recognition of hyena calls that have been degraded to simulate propagation through a hyena social network and to identify the features that hyenas are likely to use for discriminating conspecifics.

Danielle Whittaker (MSU), Kevin Theis (Wayne State), and Joel Slade (MSU postdoc) are evaluating the contribution of symbiotic microbes to reproductive isolation of vertebrate populations. Chemical signals can play a key role in speciation when they contribute to premating reproductive barriers. In terrestrial vertebrates, many chemical signals involved in social and reproductive behavior are produced by symbiotic microbes, suggesting a potential role for microbes in the process of animal speciation. To test the hypothesis that symbiotic microbes can influence speciation in their hosts, empirical studies are needed to understand the relationships among microbes, host phenotypes, and host biology and behavior, ideally in populations that are currently in the process of diverging. The results of such work will lead to new perspectives on environmental effects on host phenotypes via symbiont colonization, the links between symbionts and host behavior, and the process of speciation. The team’s long-term goal is to understand the contribution of symbiotic (i.e. resident) microbes to reproductive isolation and speciation of animal hosts. The objective of this project is to test hypotheses about how host biology and behavior relate to symbionts’ influence on one premating reproductive isolating mechanism: chemical signals used in mate choice. The central hypothesis of the research is that host social networks, in addition to host genotype, strongly influence the symbiotic microbiota that contribute to chemical signals used in mate choice, and this process facilitates host reproductive isolation and speciation. The group has approached this work through both
experimental and observational studies in a rapidly evolving vertebrate species, the dark-eyed junco (Junco hyemalis). This species has rapidly differentiated into several subspecies since the last glaciation (~12,000 years ago), and shows limited gene flow among these groups despite geographic overlap. The team is focusing on two seasonally sympatric subspecies in Virginia, northern (J. h. hyemalis) and Carolina (J. h. carolinensis) juncos. Due to their geographic distribution, morphological variation, and apparent rate of change, the junco subspecies have been described as an example of “speciation in action” and provide an excellent opportunity to test hypotheses about the role of symbiotic microbes in the process.

The same group of researchers (Whittaker, Theis, and Slade) is also expanding this research to examine whether rapid changes in scent-producing symbiotic microbes shift host reproductive signals. Rapidly changing environments offer opportunities to observe the adaptation in real time. Although the process of divergence can be lengthy in vertebrates, phenotypes contributed by co-evolved symbiotic bacteria can change very rapidly. The team will take advantage of a natural experiment and examine the microbial and chemical signal changes in a population of dark-eyed juncos (Junco hyemalis thurberi) that recently (~1980) colonized the urban UC San Diego campus. Relative to the ancestral mountain population, colonist juncos evolved differences in morphology, plumage, behavior, hormone levels, and breeding phenology, as well as chemical signals. Host genotype – e.g. immune system genes such as the major histocompatibility complex (MHC) – can regulate host individuals’ microbiotas, and are also reflected in host chemical signals. Microbes have been suggested as the "missing link" between MHC genotype and chemical signals, but no study has yet demonstrated a relationship among all 3 factors in the same system. Furthermore, hosts may exchange microbes through social interactions, and thus individual signaling phenotypes may also reflect behavior. The team hypothesizes that host social networks and host MHC genotype interact to influence the symbiotic microbiota that contribute to chemical signals used in mate choice, and that this process facilitates host reproductive isolation and speciation.

**Theoretical and Practical Applications of Intelligence**

Two projects in this thrust group could be considered Evolutionary Applications, but they are included here because they also yield insights into the evolution of behavior and intelligence.

Chris Adami (MSU), Thassyo Pinto (MSU graduate student), and Xiaobo Tan (MSU) are working on the evolvability of Markov Brain controllers for soft robots. Most research conducted in bio-inspired robotics has usually investigated multiple aspects from nature, in animals and plants, with the goal to understand fundamental processes regarding the evolutionary success of different organisms, and then engineered these ideas to produce more efficient robotic systems. In a similar manner, the soft robotics area has brought up insights that the body material properties could be the key elements for achieving robust and adaptive behavior in biological and simulated creatures. For instance, a soft machine is capable of withstanding damage, wear and stress, while providing safe interaction. Despite these advantages, the modeling and control design for soft robots can be very challenging due to highly nonlinear deformations and large model uncertainties. In this work, the team has proposed to investigate the development of an evolutionary computation platform with embedded soft body dynamics tools for evolving Markov Brain controllers specialized in solving tasks for soft-bodied robots. These artificial brains can then be transferred to real-world soft robots to evaluate their task performance. Not only will this facilitate prototyping, but it also will contribute to
achieving more adaptive and resilient soft machines. As a result, the implementation findings could lead to investigation about intelligence, adaptive behavior, and cognitive processes in many soft biological organisms.

Xun Li (UT graduate student) and Risto Miikkulainen (UT) are creating a killer app for evolutionary computation through opponent modeling in poker. As a classic example of imperfect information games, poker, e.g. Heads-Up No-Limit Texas Holdem (HUNL), has been studied extensively in recent years. A number of computer poker agents have been built with increasingly higher quality. While agents based on approximated Nash equilibrium have been successful, they lack the ability to model and exploit their opponents effectively. In addition, the performance of equilibrium strategies cannot be guaranteed in games with more than two players and multiple Nash equilibria. This project focuses on devising an evolutionary method to discover opponent models based on recurrent neural networks. A series of computer poker agents called Adaptive System for Hold’Em (ASHE) were evolved for HUNL. ASHE 1.0 models the opponent implicitly using LSTM modules. ASHE 2.0 models the opponent explicitly using Pattern Recognition Trees (PRTs) and LSTM estimators. ASHE 2.1 to 2.3 upgrade the key components of the system. ASHE 2.1 introduces default and board-texture-based PRTs. ASHE 2.2 optimizes decision-making through Recursive Utility Estimation, and ASHE 2.3 introduces Hand Range Estimator to improve showdown value estimation. Experimental results show that (1) the ASHE series models and exploits opponents with high to moderate level of exploitability more effectively than Nash-equilibrium-based agents, and (2) ASHE 2.1 and later versions are able to defeat top-ranking equilibrium-based poker agents. Thus, this project provides an effective new approach to building high performance computer agents for poker and other imperfect information games.

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) host-parasite evolutionary dynamics; (2) competition and niche construction; (3) microbiome evolution; and (4) evolution of antibiotic and antimicrobial resistance. Nine funded projects currently fall into this thrust group.

Host-parasite evolutionary dynamics

Andrew Ellington (UT) and Holly Wichman (UI) are conducting rapid analysis of parasite dynamics and evolution in arthropod populations. Many viruses that afflict and threaten humanity are carried by insects, such as the recent Zika virus outbreak that is carried by mosquitoes. Being able to monitor the spread of the virus through insect and human populations, and being able to chart viral evolution, are of key importance for public health decisions. However, it is difficult to monitor viruses in the wild, because we lack instrumentation to do so. It is also difficult to develop instrumentation, because experiments with diseases require extensive and expensive containment. The Ellington lab has developed a portable device that can ascertain molecular signatures of infection in the field. The Wichman lab has developed a model system for infecting the laboratory organism Drosophila with arboviruses. This team is using the point-of-care device to monitor the spread of arboviruses in Drosophila, with an eye towards understanding whether this exercise could be extended to mosquito populations and more deadly
arboviruses in the wild. In addition, the Drosophila system can be used to monitor the spread of the bacteria Wolbachia, which is being considered as a countermeasure to arboviruses. However, there are legitimate concerns about containing countermeasures, and a study that can measure interactions between host (Drosophila), pathogen (arbovirus), and countermeasure (Wolbachia) will greatly inform the scientific and public health communities regarding how to best intervene in insect-borne epidemics. The team has made significant progress towards their goal of developing a genetic method that can type hundreds of insects quickly under field conditions and test the method in a Drosophila system to monitor infection, transmission, and the spread of viruses in a controlled setting. They have developed a smartphone-imaged LAMP-OSD assay specific for the wsp gene of wAlbB/wPip strains of Wolbachia prevalent in mosquitoes such as Aedes albopictus, as well as a companion OSD assay for the cytochrome oxidase I (coi) gene of the mosquito Aedes aegypti. In a blinded test of 90 field-caught mosquitoes, the coi LAMP-OSD assay demonstrated 98% specificity and 97% sensitivity in identifying Ae. aegypti mosquitoes even after 3 weeks of storage without desiccant at 37°C. Similarly, the wsp LAMP-OSD assay readily identified the wAlbB Wolbachia strain in field-collected Aedes albopictus mosquitoes without generating any false positive signals.

Joel Slade (MSU postdoc), Elizabeth MacDougall-Shackleton (University of Western Ontario), and Danielle Whittaker (MSU) are investigating the interactions between loss of migratory behavior and parasite-mediated population divergence. Shifts in life-history traits such as seasonal migration can generate parasite-mediated population divergence and speciation. Animals that halt their migratory behavior and remain sedentary year-round will encounter only local parasites, potentially intensifying local arms races. In contrast, migratory animals encounter multiple environments with different parasite communities, potentially favoring diverse immune defenses. Populations that differ in migratory behavior, and the diversity of parasites encountered, should differ in allele frequencies and diversity at immune genes such as the major histocompatibility complex (MHC). This group is assessing evidence for parasite-mediated divergence at MHC in dark-eyed juncos (Junco hyemalis), using two geographically distinct systems. Migratory and sedentary populations diverged approximately 12,000 years ago in Virginia, but just 37 years ago in California: in each system, migratory and sedentary populations are sympatric during the nonbreeding season. They predict that migratory individuals in each system will be more diverse at MHC, due to balancing selection associated with travel through multiple environments. This difference should be most evident in the historically-diverged (Virginia) system. The team will characterize haemosporidian parasites encountered by each of the four populations, and class I MHC diversity within individuals and populations. To unravel effects of selection from those of genetic drift, they will compare differentiation at MHC to neutral-locus (microsatellite) differentiation. With human activities increasingly disrupting migratory routes and behavior, examining parasite-mediated divergence in recently versus historically isolated populations allows forecasting future effects on divergence, and ultimately speciation in action.

**Competition and niche construction**

Joshua Nahum (MSU postdoc) and Katrina van Raay (UW graduate student) are investigating what they describe as a “one-two punch”, in which microbes combine killing systems in a single cell. Chemical warfare in the microbial world is ubiquitous. One kind of chemical weapon microbes employ is a proteinaceous toxin called a bacteriocin. The best-
studied bacteriocins are the colicins, produced by and active against Escherichia coli. Many colicin systems encode suicidal lysis genes, such that the producing cell releases the toxin through cell lysis. Released colicin kills sensitive competing cells allowing immune clones of the producer to capitalize on the liberated resources. However a major group of colicin systems lacks this lysis gene, and it has been unclear how such toxins were released from the producing cell. This team has explored a newly discovered union between such a colicin system and a prophage (bacterial virus that has been incorporated into the bacterium’s genome), where release of the colicin occurs via phage-encoded cell lysis. This union should be detrimental to susceptible cells, which would be hit by a one-two punch: once by the colicin, once by the phage. Preliminary mathematical modeling suggests that the success of this dual killing system depends on the prophage’s ability to produce infectious virions. If the prophage is cryptic (encoding lysis, but not producing infectious phage), then this dual system is susceptible to invasion by “cheaters” that only possess the colicin system (and its immunity) but do not lyse. The team is exploring this social dilemma and its potential resolution in detail through a combination of mathematical modeling, microbial evolution experiments, and agent-based simulations. Using the agent-based model, they have shown that this costly union between a dysfunctional colicin and dysfunctional prophage can be maintained if there is spatial structure due to rock-paper-scissors dynamics. The focus of this project has shifted to further explore these rock-paper-scissors dynamics through additional computational modeling. Currently they are developing a model to explore how this may fit into theory about negative niche construction.

Nkrumah Grant (MSU graduate student), Ben Kerr (UW), Richard Lenski (MSU), Christopher Marx (UI), Sergey Stolyar (UI postdoc), and Katrina van Raay (UW graduate student) are examining whether selection for increased competitive ability results in bigger cells. Twelve replicate populations of Escherichia coli have been evolving in Lenski’s Long Term Evolution Experiment (LTEE) in flasks for over 67,000 generations in a shared nutrient environment. The evolved bacteria grow 70% faster than their ancestor, but experience a decrease in yield, consistent with a tradeoff between growth rate and yield. Interestingly, cell size also increased in all lineages through at least 10,000 generations. In the Kerr lab, work investigating the growth-yield trade off using media-in-oil emulsions has revealed that selecting for increased yield results in a decrease in cell size. The team is now investigating the relationship between cell size, growth rate, and yield using a combination of experimental evolution, genetic analysis, and phenotypic assays. This work will involve reanimating frozen LTEE samples as well as initiating new emulsion evolution experiments. They aim to determine the generality of cell size as a covariate of growth rate and yield, as well as the potential molecular mechanisms mediating changes in cell size. Grant has so far found that cell size has increased among all 12 LTEE lineages through 50,000 generations. However, there does not seem to be a uniform relationship whereby cell size consistently increased in all populations between generations 10,000 and 50,000. In particular, at least one lineage decreased in size over that period. Furthermore, Grant also observed that some lineages produce cocccoidal cells atypical of the rod shape that is typical of E. coli as a species. Additionally, Grant observed “ghost cells” present in the micrographs of the Ara-3 lineage, which is the only one that has evolved the new capacity to utilize citrate, and where previous work suggested the cells may struggle with achieving so-called balanced growth. Future research includes increasing the temporal resolution of volumetric and shape measurements between generations 10,000 and 50,000 in select populations in an effort to identify when the aforementioned phenotypes evolved and their correlations with mutations that arose in those lineages.
Brian Connelly (UW postdoc), Ben Kerr (UW), Joshua Nahum (MSU), and Katrina van Raay (UW graduate student) are testing how tradeoffs during niche adaptation stabilize niche construction. Through just about all that they do, organisms change their environments. From metabolizing resources to building dams, these niche constructing behaviors can profoundly influence natural selection in both positive and negative ways. This project will develop and test a new theory that as populations modify their niches, tradeoffs can emerge that enable positive niche constructing behaviors to be maintained by a paper-rock-scissors dynamic. The team is also extending their model to include epistasis, which may lead populations to become “addicted” to niche construction as they continue to adapt to their environment.

Microbiome evolution

Kay Holekamp (MSU), Kevin Theis (Wayne State), and Connie Rojas (MSU graduate student) are examining the evolution of the gut microbiome in a wild mammal population. Host-associated microbial communities are fundamental to the nutrition, immunity, development, and behavior of their animal hosts. Despite the ample individual variation in microbiota among hosts, the assembly and persistence of microbes on animals’ bodies are not random. Instead, microbiota are often host species-specific and niche-specific to particular body sites on the host. There has been much research on the influence of the microbiome on host evolution, but less about the potential impact of the host on the evolution of microbiomes. Microbial populations like many populations, are subjected to dispersal, diversification, environmental selection, and ecological drift. Microbes interact with one another and undergo rapid evolution, due to their fast growth rates and high amounts of horizontal gene transfer. But how much do these dynamic mixed microbial communities and their individual populations change over time within a host and across host generations? What are the functional consequences for the host? And, are there any host or ecological correlates that can explain variation in and potentially drive the evolution of animal microbiomes? This team is capitalizing on a unique 30-year, longitudinal data set of fecal samples collected from a wild population of spotted hyenas (Crocuta crocuta) in Kenya to document how the behavior and socio-ecology of these animals shapes their gut microbiota and microbiome over tens of thousands of microbial generations. They are using amplicon and metagenomics sequencing to assess the stability, structure, function, and diversity of the gut microbiota and microbiome of four hyena matrilines spanning three decades.

James Foster (UI), Joseph Graves (NCAT), Scott Harrison (NCAT), Eric Mittelstaedt (UI), and Janet Williams (UI postdoc) are studying microbes and microplastics to discover whether there is evidence for selection in a novel deep ocean niche. Plastics are a serious threat to ocean ecosystems. Plastics are bio- and photo-degraded into tiny fragments being found in deep-sea sediments on the ocean floor in amounts comparable to levels found in sediments of shallow and intertidal zones. Recent studies have identified plastics to be almost ubiquitous across samples assayed in several deep-sea environments including the North Atlantic, the Southern Ocean, the Gulf of Guinea, and the Mediterranean Sea. Another study has examined how this “plastic rain” affects the ocean floor ecosystem, finding that six of nine animals examined from diverse parts of earth’s oceans had microfiber plastics in their systems. It is reasonable therefore to suppose that there is recent (in evolutionary terms) emergence of niches for plastic-degrading bacteria in deep ocean sediment that would lead to selection for those bacteria. Mittelstaedt recently collected ocean sediment cores from the Mid-Atlantic ridge. The team’s goals are to
quantify changes in microbial communities’ composition and strength of selection across sediment locations and layers, and to examine deep ocean plastic fragments directly for bacterial inhabitants. In short, they are studying evolution in action, by comparing pre-plastic and no plastic sediment layers and locations to how other parts of the deep ocean sediment microbiome have been impacted by the presence of plastic. This work occurs in conjunction with their study of a unique and largely unexplored plastic cycle from the Mid-Atlantic surface to the sea floor.

**Evolution of antibiotic and antimicrobial resistance**

Eva Top (UI) and Ben Kerr (UW) are examining the evolution of plasmid persistence and host permissiveness and their effects on the emergence of multi-drug resistance. Antibiotic resistance is commonly spread through bacterial populations via conjugative plasmids, extra-chromosomal pieces of DNA that can transfer between bacteria and often contain antibiotic resistance genes. Plasmids are generally considered costly towards their host in the absence of selection for the plasmid (e.g., an antibiotic-free environment). However, coevolution between a host and its plasmid can reduce plasmid carriage costs through compensatory mutations. While this can lead to greater maintenance of that plasmid in the population (and thus an increased proportion of antibiotic-resistant cells), it is unclear how these mutations affect the persistence of other novel plasmids in the environment, i.e., plasmid permissiveness. The team is testing the effects of host/plasmid coevolution on plasmid persistence and permissiveness by evolving multiple host/plasmid pairs and comparing the ability of the evolved vs. ancestral hosts to maintain their own and novel plasmids in the absence of antibiotic selection. They will coculture the resulting compensated pairs and determine whether there is an increase in multi-drug resistance (resulting from the co-occurrence of both plasmid types in the same host), compared to when a co-culture of the ancestral pairs is propagated. They will further test whether this can lead to the creation of multi-drug resistant plasmids via recombination of both plasmid types into a single larger plasmid. These experiments are complemented with mathematical modeling. This study will lead to a better understanding of how multi-drug resistant plasmids and bacterial populations arise, which has important relevance in our fight to mitigate multi-drug resistance in agricultural and clinical settings.

Alita Burmeister (Yale postdoc), Jorden Schossau (MSU postdoc), Jim Smith (MSU), and Paul Turner (Yale) are exploring gene-level selection, phage, and the evolution of antibiotic resistance. Gene-level selection appears to be common in nature, where it underlies the spread of factors important to human health, such as antibiotic resistance genes and pathogenicity islands. However, the evolutionary and ecological mechanisms underlying gene-specific replication in natural populations have been understudied. Molecular biology studies have determined that replication of individual genes can occur through horizontal gene transfer from one genome to another. One of the major modes of horizontal gene transfer involves the packaging of host DNA into phage capsids, which deliver the DNA to another cell where it recombines into the chromosome. This process, termed transduction, has long been used to transfer genes in laboratory molecular biology. This BEACON research will identify basic principles of how Salmonella phage transduction evolves in natural populations, laboratory populations, and in theoretical computational populations. These basic principles will help predict future pathogen evolution and will inform policy and best practices for long-term effectiveness of antimicrobial drugs and therapeutic phages.
Kyle Card (MSU graduate student), Nkrumah Grant (MSU graduate student), Joseph Graves (NCAT), Richard Lenski (MSU), and Misty Thomas (NCAT) are examining correlated responses in metabolism and antibiotic resistance in the Long Term Evolution Experiment. Populations often face environmental changes that reduce or even eliminate selection for the maintenance of previously essential traits. Adaptation to a changed environment can thus affect an organism’s fitness in its prior environment and other environments where the corresponding selection is relaxed. In their previous work, Grant and Card used E. coli strains from the long-term evolution experiment (LTEE) to study these correlated fitness responses. During the LTEE, there has been constant aeration in a culture medium without antibiotics. As expected, antibiotic resistance has tended to decay, whereas anaerobic metabolism unexpectedly tended to improve. These studies lead to interesting questions about (i) the physiological mechanisms underlying the positive correlation seen in metabolism; and (ii) if one re-evolves antibiotic resistance, whether the genes responsible for resistance changed as the level of resistance has declined. To address the former question, this team is obtaining gene-expression profiles and coupling these data with prior knowledge of candidate genes; and they will attempt to decouple anaerobic and aerobic metabolisms using a penicillin-enrichment technique. To address the latter question, they will perform genome sequencing on dozens of antibiotic-resistant mutants isolated from the ancestral and LTEE-derived strains.

Thrust Group 4: Evolutionary Applications.

Technological applications of evolution have become more prominent in BEACON, as has knowledge transfer, and this Thrust Group is 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 applications for (1) biotechnology; (2) agriculture; and (3) healthcare and forensics; as well as (4) development of evolutionary computation methods. Below we describe 12 projects currently funded in this thrust group.

Biotechnology Applications

Jeffrey Barrick (UT), Christoph Adami (MSU), and Luis Zaman (University of Michigan) are engineering fitness landscapes to delay unwanted evolution. Synthetic biology is rapidly advancing our ability to create complex genetic circuits and perform feats of metabolic engineering. This progress is enabling medical, manufacturing, and energy breakthroughs. However, when organisms are engineered to perform some desired task, it is typically at the expense of resources that would otherwise be invested in producing more offspring. For this reason, evolution often favors organisms that have accumulated mutations disrupting the engineered function. This team is working to harness clonal interference, a phenomenon that occurs in large asexual populations whereby competition between multiple beneficial mutations slows the fixation of any one allele, as a means of prolonging the lifetime of a burdensome function in a population. The basic setup is to add the possibility for one or more decoy mutations into the fitness landscape of a cell. The decoy mutations are designed to “distract” adaptive evolution from inactivating the engineered function. The two key questions for this proof-of-principle seed project are: (1) What is the optimal design for a suite of decoy mutations to maximally extend the lifetime of the desired function in a population? (2) Can the half-life of
an engineered trait be extended even further by dynamically altering the environment in a way that replenishes the supply of decoy mutations? The team is examining both questions using a BEACON-inspired combination of modeling approaches and microbial evolution experiments.

Jeffrey Barrick (UT), Robert Newman (NCAT), and Eva Top (UI) are working on detecting unplanned evolution in a plasmid repository. Plasmid repositories are important shared resources for the exchange of DNA sequences with well-characterized functions. Many plasmids encode functions that are burdensome or toxic to the E. coli cells that are used to copy them. Therefore, there can be strong selection for mutations that alter or eliminate the designed function of a plasmid. Mutations can also accumulate in plasmids as they are passed between labs and retransformed through single-cell bottlenecks. In the past, reliable DNA sequence information for most plasmids was fragmentary. With the decreasing costs of next-generation sequencing, it has become possible to sequence nearly every new plasmid submission to a repository using the Illumina platform. These sequencing data provide a new opportunity to identify evidence of previously undetected and possibly unwanted evolution. This team will do so by (1) comparing consensus plasmid sequences to user-submitted plasmid sequences, (2) examining variation in common sequence elements across the entire plasmid repository, and (3) identifying variation within the population of DNA molecules present in each plasmid sample. Then, they will experimentally test mutations that they identify related to a common expected evolutionary outcome: selection for lowering plasmid copy number to reduce the burden on a host cell. Detecting unintended evolution in widely used plasmid repositories would show how evolution in action can impact progress and reproducibility in science and engineering.

Tomislav Ticak (UI postdoc) and Jessica Lee (UI postdoc) are studying step-wise evolution of growth on lignin-derived substrates by the biotechnological platform organism Methylobacterium extorquens PA1. This project is aimed at understanding metabolic integration of foreign pathways into model organisms. In short, all biochemical pathways were built up and integrated over generational time, and often in metabolic engineering, the question of how to build an effective pathway is not directly asked. Using M. extorquens PA1 as the model organism, the team took the protocatechuic acid degradation pathway of a close relative, M. nodulans, to understand toxicity, flux, and genetic control of protocatechuic acid degradation in naïve PA1. Generating and evolving a protocatechuic-acid-degrading strain of PA1 allows for a starting point in PA1 to degrade many various protocatechuic acid derivatives and understand a novel pathway for protocatechuic acid degradation. The first goal for this project is to generate several various evolved lineages of varying genetic potential either through an intermediate approach—i.e., evolution of strains to various metabolites step-by-step, or an all-at-once methodology—i.e., evolving the whole pathway. Parallel to this, the researchers aim to build a flux-balance analysis (FBA) model for understanding metabolic control of these new carbon precursors and intermediates in PA1 which is to be refined through metabolic analysis via Mass Spec and HPLC. They will sequence intermediate populations in the step-wise process vs. the all-at-once approach and compare it to known aromatic degrading methylotrophs to analyze genetic differences between the approaches in the lab and throughout nature.

Wolfgang Banzhaf (MSU), Cedric Gondro (MSU), and Ian Whalen (MSU graduate student) are working on evolutionary methods for feature selection in genomic prediction. The use of genetic variation (DNA markers) has become widespread for prediction of genetic merit in animal and plant breeding and it is gaining momentum as a prognostic tool for susceptibility to disease in human medicine. Genomic prediction is the idea of using a very large number of
markers to predict phenotypes and, in essence, consists of estimating the individual effects that thousands, or even millions, of markers have on a particular trait. The sum of these marker effects can then be used to predict phenotypes or breeding values for new individuals that do not have trait information but do have marker information (genotypes). Over the past ten years, genomic prediction has been widely adopted in genomic selection for agricultural applications and in human studies. Although conceptually straightforward, genomic prediction is a very challenging problem. Genotyping and trait recording are costly and time-demanding exercises; the result is that most genomic datasets will have hundreds of thousands or even millions of marker effects that need to be simultaneously estimated from usually only a few thousand phenotyped individuals. This means that the datasets are underdetermined ($p \gg n$ problem) and suffer from the curse of dimensionality (COD). In effect, genomic prediction can be treated as a high dimensionality, sparse data problem and, consequently, suffers from the same issues as other problems in this domain. Most notably is that the prediction models derived by statistical inference are sub-optimal since the accuracy of the parameter estimates (marker effects) rapidly decays as the number of features that needs to be estimated increases. The accuracy of prediction is also conditional on the complex relationship between genotypes and phenotypes, which varies widely from trait to trait; e.g., highly heritable traits regulated by a few genes of large effect are easier to predict than lowly heritable traits regulated by many genes with small effects. The main goal in this project is to develop EC methods to evolve an optimal subset of markers that have high predictive accuracy for a broad range of traits and species with different heritabilities and population structures. Smaller panels have immediate commercial value as it reduces genotyping costs and increases industry adoption rates.

**Agricultural Applications**

Erik Goodman, Erik Runkle, Lihong Xu, graduate student Jose Llera, and postdoc Yuanping Su (all MSU) are finalizing their *evolutionary greenhouse control model* for testing in China. Optimizing crop value (including seasonally and quality-adjusted prices of crop produced) while minimizing greenhouse energy costs requires development of a sophisticated controller, and evolutionary processes are used in this project to evolve such controllers. That evolutionary process must be repeated for each particular greenhouse location and type of crop. Since evolutionary multi-objective optimization can optimize several conflicting objectives and obtain many optimal tradeoff solutions at the same time, it is suitable to use such methods to solve this multi-setpoint optimization problem. The first challenge is that the controller should be robust against reasonably extreme weather conditions, which implies that the controller must be evolved under sets of conditions (seasons of weather) adequate to challenge the robustness of its performance. This must still be done in a general context, so that a robust controller can be evolved for any particular location and level of greenhouse control technology (growers in different regions typically use different levels of technology, particularly as to cooling mechanisms and supplemental lighting). Stochasticity in a multi-objective environment poses a special set of problems, as a solution that may be Pareto-optimal in one year’s weather may not be in another year’s conditions. The second challenge is that conditions for optimum growth (or more precisely, to maximize the ultimate economic value of the crop produced over the entire season) change during the crop’s growth and development, in several phases. That implies that the control strategy should be allowed to change, but not so as to optimize instantaneous growth, but
rather to maximize the value of the yield over the season. These optimal conditions change not only seasonally, but also diurnally, so that different conditions are appropriate for different times of day, and also for different climatic conditions (photosynthetically active radiation, for example). This dramatically increases the number of variables to be optimized on the chromosome. Llera and Su have made significant progress addressing these two challenges, and the team will work together to generate a more advanced controller implementing many of their ideas. The plan is then to test and potentially implement such a controller in a series of greenhouses being designed and built in China under the leadership of Prof. Xu and his team there.

Kalyanmoy Deb, A. Poyan Nejadhashemi, graduate student Proteek Roy, and postdoc Mohammad Abouali (all MSU) are developing **evolutionary optimization of water and nutrient use efficiency for sustainable agricultural intensification**. In today's world, we are facing the challenge of meeting the growing demand of food with limited environmental resources. Water and nutrient availability are the major production limiting abiotic factors in the regions where the yield gaps are high. In this regard, effective water and nutrient management plays a crucial role in food security by closing the yield gaps. Optimizing water and nutrient management not only improves crop yield, but also reduces production cost, conserves resources, and protects our environment. Due to the presence of multiple objectives, expensive simulation routines, and nonlinearity in objectives and constraints, evolutionary optimization methods with their recent advances remain as potential tools for addressing these important socio-economic problems. In the regions where both nutrient and water availability constraints to crop yield (e.g., Sub-Saharan Africa), combined water and nutrient management is essential to increasing food production. In summary, intensification of agricultural production cannot be achieved in a sustainable manner unless water and nutrient management are considered together, which is the goal of this study. The team is developing a fully integrated crop model (DSSAT) within an optimization platform that can be used for any major crop and location around the world. The application programming interface (API) was written in Java, which allows the project to easily be scaled in a server environment. Also, the package follows an object-oriented programming (OOP) design, which allows for further development and the addition of more features in the future. The system has been linked to an optimization platform called NSGA-III. Five objective functions have been considered in this optimization platform that include: 1) maximizing crop yield, 2) minimizing irrigation water used, 3) minimizing the amount of nutrients applied, 4) minimizing the nutrient loss/leaching, and 5) maximizing producer income.

Kalyanmoy Deb, graduate student Ian Kropp, A. Pouyan Nejadhashemi, postdoc Melissa Rojas-Downing, graduate student Proteek Roy, and Janice Siegford (all MSU) are developing an **integrated nutrition-water-nutrient decision support system to optimize sustainable food production and nutrition security based on evolutionary computation**. This project introduces a comprehensive, integrated modeling framework for Water for Food Production Systems by: 1) advancing our understanding of relationships between key elements of the system; and, 2) considering nutritional needs, rather than simply food production levels, as a new measure of food security. The integrated nutrition-water-nutrient decision support system (DSS) will consist of two major components: 1) a socioeconomic assessment to evaluate the impacts of the interaction between agricultural production and social influences on both land use and nutrition security, and 2) a biophysical assessment that evaluates and optimizes the physical output of crops (e.g. food and feed crops) and livestock, subject to resource constraints. In this
study, the team will use nutritional security instead of food security as a better indicator of present population dietary needs. Toward this end, their goal is to develop a multi-criteria decision support framework to assess and optimize food production and nutrition security through the lens of water and nutrient use efficiency. The framework will be based on integrated crop and livestock models, current and projected climate variabilities and uncertainties, socioeconomic trends, and technological intervention. They will combine crop and animal production for site-specific applications to: 1) satisfy human food needs by addressing population nutritional requirements, 2) enhance environmental quality by minimizing water use and nutrient loss, 3) improve nonrenewable resource use efficiency by minimizing nutrient applications, 4) sustain the economic viability of farms by maximizing producer income, and 5) enhance quality of life by increasing the amount and availability of healthy, locally-produced food while continuing to contribute the region’s share to the national food supply.

Healthcare and Forensic Applications

Joseph Graves and Shyam Avaranudhan (NCAT) are examining the evolvability of resistance to 3D printed nanostructures that may stab, poison, or do both to planktonic or biofilm bacteria. Nanoparticle shape was found to have profound impacts on silver nanoparticle (AgNP) toxicity. Specifically, triangular AgNPs were far more effective in reducing bacterial growth compared to spherical one. The team is using hybrid nanocomposite 3D printing technology to print sharp pyramidal ABS structures (at micron to nanoscale). These will be compared to flat surfaces for survival of E. coli, Pseudomonas aeruginosa, and Staphylococcus aureus biofilms over 24 hours. They are also examining the interaction of shape with poisonous compounds by embedding these with AgNPs and iron oxide NPs (FeNPs), and comparing them to flat surfaces with AgNPs and FeNPs for survival of E. coli, Pseudomonas aeruginosa, and Staphylococcus aureus biofilms over 24 hours. To test whether geometry and poison affect the evolvability of resistance, bacteria surviving 6-h treatment on the nanosurfaces will be collected and grown over night in standard culture conditions. Samples of these bacteria will be reapplied to the surface the next day. Measurements of bacterial survival will be determined over the course of the experiment. Bacteria seem to have standard methods of addressing toxic materials—e.g., prevention of entry, efflux, or alteration of target substrates. Protection from physical damage is often mediated by the secretion of extracellular polysaccharides. The team is using whole genome sequencing to determine genomics changes associated with resistant phenotypes from all treatments. RNAseq will be used to characterize gene expression changes associated with the selection treatments.

Gregory Bonito and Kevin Liu (MSU) are developing a novel phylogenomic framework for forensic DNA localization. Forensic DNA analysis is indispensable to criminal investigation and the criminal justice system. The goal of this interdisciplinary project is to create and validate a novel tool for localizing DNA samples, including trace evidence from non-human organisms. This computational tool will provide important investigatory clues, especially in international cases (e.g., “hit-and-run” terrorism using air travel), and criminal evidence. The key insight is that evolutionary relatedness between a forensic DNA sample and population-based DNA samples from a particular locale is a telltale signature of local origin. The team’s phylogenomic pipeline incorporates FastNet, their recently developed computational method for fast and accurate phylogenomic inference, for accurate reconstruction of evolutionary relationships between forensic and population-based DNA samples. Statistical approaches will be used to test
for significant sample enrichment from a single location of origin. This yields greater forensic power since the probability that multiple independent samples originate from the same location by chance becomes vanishingly small as more samples are considered. The team will perform an empirical cross-validation study to demonstrate the power of the tool in comparison to the current state-of-the-art. The study provides a proof-of-concept using genomic DNA sampled from globally distributed fungal populations. More broadly, they intend to demonstrate the power that phylogenomics and evolutionary thinking can bring to forensic DNA analysis.

**Development of Evolutionary Computation Methods**

Wolfgang Banzhaf, Vishnu Boddeti, Kalyanmoy Deb, Erik Goodman, William Punch (all MSU), and graduate students Zhichao Lu, Ian Whalen and Yashesh Dhebar (all MSU) are using evolutionary computation for designing deep neural network architectures. Neural networks are a biologically inspired programming paradigm that enables computers to learn from observational data. Developments over the past few years have shown that it is now feasible to train deep neural networks, consisting of several layers and possibly different types of neurons. This has enabled deep neural networks (DNNs) to be overwhelmingly successful across a broad range of domains and applications, such as computer vision, speech recognition, natural language processing, machine translation, bio-medical data analysis, and many more. A large part of this success has been thanks to the design of many effective DNN architectures (types of neurons, combinations of neurons, connections between neurons, etc.), including AlexNet, VGG, Inception and ResNet, to name a few. Designing novel DNN architectures typically involves adjusting many different hyper-parameters, such as number of layers, number of neurons on each layer, connections, neural functions, etc. Furthermore, experimental evidence has shown that different DNN architectures excel at different kinds of learning tasks. Designing the best performing DNNs architectures, even for a specific problem of image classification, typically required many years of focused investigation by hundreds of researchers. Therefore, the current process of designing novel DNN architectures, involving trial-and-error experimentation and hand-design, is painfully slow and does not scale very well across a myriad of potential applications. Overcoming this drawback necessitates addressing the general problem of: given a task, design the optimal DNN structure that maximizes performance while satisfying application constraints such as number of nodes or computational effort. This team aims to address the problem of automated design of DNN architectures through multiobjective evolutionary methods.

Wolfgang Banzhaf, Charles Ofria, graduate student Emily Dolson, undergraduate Steven Jorgensen, graduate student Alexander Lalejini, and postdoc Michael Wiser (all MSU) are harnessing eco-evolutionary dynamics for open-ended evolution of intelligence. When trying to solve complex problems, we often have intuition about the building blocks needed to find a solution. However, it is challenging to transfer this intuition to an evolutionary algorithm without restricting or misleading evolution. This team's previous research on Eco-EA, an evolutionary algorithm that uses ecological dynamics to maintain diverse populations, provides a potential solution. By associating limited resources with tasks that may be useful as “hints” to solving a larger problem, a diverse ecology of partial solutions can be created, wherein only a subset of the community will follow each hint. If a hint proves to be incorrect, few lineages will follow it to an evolutionary dead end. The team is expanding this approach and testing its effectiveness in a complex domain: evolving an intelligent board-game-playing agent. This project is uniting ideas
from evolution, ecology, and artificial life to advance the state of the art of evolutionary computation and evolved artificial intelligence.

Sandeep Kulkarni (MSU) Kaushik Roy (NCAT), and graduate student Prosenjit Chatterjee (NCAT) are exploring new approaches to ensemble and neural network topological evolution for touch-based authentication. The traditional method for authenticating an individual requires that individuals use some knowledge or token to confirm their identity. A biometric-based authentication system can also be implemented. This system has an advantage over knowledge-based and token-based systems in that biometric modalities are difficult to replicate and are unique to individuals. However, once authentication has taken place, a session remains active and a device remains unlocked until an individual or the server closes the session. As long as sessions remain active, typical systems are at risk to being taken over by someone other than the individual if that individual leaves the device. To counteract this, active authentication can be implemented to continuously monitor the identity of the individual using a device. Behavioral biometrics can be monitored unobtrusively in the background, without the need to explicitly query the user for input. In this project, the team is investigating touch dynamics to actively authenticate on a case-by-case basis. The goals of this work are three-fold. First is to collect data and establish a set of baseline classifiers for performance comparison. These will include a traditional feature-distance-based classifier, a Convolutional Neural Network (CNN) [15], and a Recurrent Neural Network (RNN). Phase 2 will convert the feature-based classifiers from phase 1 into neural networks, and use them as a seed population to evolve an optimum ensemble using diversity as part of the fitness function. The researchers will then apply stacked-generalization in an effort to further improve ensemble accuracy. Phase 3 will explore the use of a learned fitness function to accelerate the fitness evaluation in the evolution of domain-specific deep-nets.

2b. Progress towards metrics listed above.

Integrative Research Goals

1. New research collaborations and proposals

- Of the 55 projects currently underway, 30 are new projects and include new collaborations.
- 122 publications submitted this reporting period, of which about 41% 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 36 proposals, and >$13M in external funding has been granted.
3. Increase in publications related to evolution in action

- Number of publications: 122 publications submitted by BEACONites to date in the current reporting period
- High visibility science journalism about BEACON research: Since our previous annual report, there have been 7 university press releases about BEACON research. Over 15 features on BEACON research appeared in the mainstream and online media in this period.

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

- The Avida-ED application has been accessed 20,441 times over the past year.
- About 2,000 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 at BEACON in the current reporting period, including a new module on Objectivity.
- The very multi-disciplinary weekly Friday meetings have been going on continuously since October 29, 2010. 22 seminars have been offered so far 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: 122 reported to BEACON February-October (goal is 150 per reporting period, February-January)
- Conference presentations: 132 reported (goal is 150)
- Grant proposals submitted: 36 submitted (goal is 40)
- Our original goal was 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 was achieved for conference presentations and grant proposals, and nearly achieved for publications. Our current 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. The primary barrier to achieving this goal appears to be not a lack of productivity but a lack of reporting by BEACONites, as members are admitting to “reporting fatigue.”

2. BEACON research output will be perceived as making an important contribution to the literature
• Seventh External Advisory Committee meeting was held August 2018.
• 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 2019. We will hold our project selection process for Year 10 (see explanation in VII. Management) in February 2019 in order to choose projects that will begin in August 2019. 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.

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). 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.

<table>
<thead>
<tr>
<th>GOAL</th>
<th>METRICS</th>
<th>PROGRESS</th>
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<tbody>
<tr>
<td>Multidisciplinary Ph.D. graduates and post-docs placed in faculty positions at rates approaching averages across engineering, computer science, and biology</td>
<td>Fraction of BEACON graduate students and post-docs receiving offers of faculty positions</td>
<td>Among BEACON’s alumni to date: 16/118 (14%) PhDs and 17/35 (49%) postdocs are now in faculty positions. 64 (54%) of BEACON PhD graduates went on to postdoctoral positions.</td>
</tr>
<tr>
<td>Increased public literacy in evolution and the nature of science</td>
<td>Development of educational materials</td>
<td>Testing, presentation, and publication of educational materials. Evaluation instruments are being used to assess effectiveness.</td>
</tr>
<tr>
<td></td>
<td>Adoption of materials by teachers; frequency of public use of online materials and</td>
<td>Cross-institutional dissemination of materials is underway.</td>
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visits to museum exhibits

| Increased interest in STEM careers in both academia and industry | The creation of programs that provide for the sustainability of students interested in STEM | Programs like the Luminaries Scholars and URA program at KBS assist in these areas. |
| Communication of the diversity of careers associated with STEM disciplines | Participation in diverse careers workshops, and tracking our own students. | |

1c. Problems encountered in making progress towards goals

**Internal education activities:** We continue to discuss and evaluate the effectiveness of our educational programs. Our graduate training courses create unique inter-institutional challenges such as different academic calendars (for example UW is on a quarter system whereas MSU is on a semester system). During the Spring 2018 semester we were able to offer Research Methods, however, we were unable to offer Computational Science for Evolutionary Biologists CSE 801 during the Fall 2018, the establishment of the new CMSE department resulted in changes to current faculty commitments. There were four students either enrolled or auditing Evolutionary Biology for Non-life Scientists during the Fall 2018 semester. There does seem to be a fair degree of fluctuation year to year, due to the varying numbers of new graduate students associated with BEACON.

**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

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Interdisciplinary Graduate Education</th>
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<tbody>
<tr>
<td>Led by</td>
<td>Arend Hintze, Louise Mead, Mike Wiser, Chris Adami, and Wolfgang Banzhaf (MSU)</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Beginning graduate students</td>
</tr>
<tr>
<td>Approximate # of attendees</td>
<td>~10-15 per year</td>
</tr>
</tbody>
</table>

BEACON has instituted, and continues to offer, 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 Drs. Louise Mead and Mike Wiser; and Multidisciplinary Approaches to the Study of Evolution (CSE 891, Spring) taught by Wolfgang Banzhaf.
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 class was not offered during the Fall 2018 semester due to departmental changes but we should be able to offer the course next fall.

Evolutionary Biology for Non-Life Scientists: ZOL 890-60x is currently being taught at MSU, with an enrollment of three students. 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 Drs. Louise Mead and Michael Wiser. The opportunity to engage a postdoctoral researcher as a co-instructor provides additional training.

Multidisciplinary Approaches to the Study of Evolution: In Spring 2018, nine students were enrolled in the course. 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 when possible, 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. Drs. Wolfgang Banzhaf and Chris Adami co-instruct the course.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>A short-course in microbial metagenome analysis</th>
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<tr>
<td>Led by</td>
<td>Ashley Shade and Tracy Teal (MSU)</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Graduate students, postdocs, and faculty</td>
</tr>
<tr>
<td>Approximate # of attendees</td>
<td>20-30</td>
</tr>
</tbody>
</table>

BEACON continues to support EDAMAME (Explorations in Data Analyses for Metagenomic Advances in Microbial Ecology). In 2018 the course was offered as a seven-day, intensive short-course at Kellogg Biological Station co-taught by Drs. Ashley Shade and Adina Howe. Learning goals for the course include (1) increasing computing literacy, (2) developing proficiency in cloud computing, (3) analyzing microbial amplicon sequences; (4) analyzing microbial shotgun metagenome sequences; (5) applying ecological statistics to analyze and interpret microbial sequencing data; (6) access resources provided by public sequence databases. In addition to Drs. Shade and Howe, the course included 12 guest lecturers and teaching assistants. 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.
BEACON funding supported four (4) students to participate in the Undergraduate Research Apprentice (URA) program at KBS. The URA program provides students an integrated research and educational experience that increases their understanding of evolution and the nature of scientific research and introduces them to career opportunities in STEM. The URA program complements the NSF funded REU program at KBS by focusing on early career undergraduates (rising freshman and sophomores) and community college transfer students with little to no research background and introduces them to skills needed to be successful in further research experiences. URAs gain research experience by taking 1-3 courses at KBS (tuition funded separately), working as a research assistant with a graduate student or postdoctoral mentor, and participating in professional development activities and seminars at KBS. In addition, seven (7) MSU students were partially or fully funded by BEACON to work with five MSU faculty (Conner, Lau, Haddad, Wetzel and Evans) at KBS on a wide range of projects associated with BEACON priorities.

The URA and REU program provides students with an opportunity to gain experience in communicating their experiences by presenting a poster at the KBS Undergraduate Symposium and are also strongly encouraged to participate in the BEACON All Scientist meeting (August) and UURAAF (April) at MSU and to present their research at regional and national meetings; funding is available for this. Evaluation of the program is done by post-program surveys of the participants (students and mentors) coordinated with the review of the NSF REU program using surveys and social media connections to track student career trajectories. For 2018 program the NSF BIO-REU URSSA (Undergraduate Student Self-Assessment) was used to evaluate all of the undergraduate research programs at KBS. This assessment tool was recently revamped by faculty at the University of Wisconsin and is should allow inclusion of more program specific queries. Students who have responded to date are rating their research experience at KBS between 4 and 5, on a 5-point Likert Scale; which is higher (0.5-1.0) than the national average for all NSF BIO-REU programs.

2b. Professional development activities

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>BEACON and Beyond: Broadening Participation and the Scope of Public</th>
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</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Tessa Solomon-Lane (UT), Hans A. Hofmann (UT), Travis Hagey (MSU), Alexa Warwick (MSU)</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>BEACON Graduate students, postdocs, and faculty</td>
</tr>
<tr>
<td>Approximate # of attendees</td>
<td>20-40</td>
</tr>
</tbody>
</table>

Engaging with the public is a fundamental professional responsibility for academic scientists, and it is expected by many funding agencies. Engagement is also a civic duty for many. Although Americans have confidence in science and trust in scientists, science denial and the spread of
false claims, especially in politics, can be dangerous for society. However, participation in public engagement is often limited to “the dedicated few,” as many are unaware that public engagement benefits professional development and scholarship. An innovative, evidence-based program that motivates, recruits, and trains graduate students and postdocs in best practices for public engagement and pairs them with opportunities to engage was developed, specifically expanding the program content in two important ways. First, the team developed a module on how to frame a scientific message for different audiences, one of the most important communication skills. Second, they developed a module on how to engage effectively with public policy and policy makers.

Our data show that BEACONites currently engage the public in a wide variety of ways, but there is a striking underrepresentation of policy engagement, despite the fact that many scientists are interested in this type of engagement. Therefore, long-term goals include integrating science communication and public engagement skills and experience into the standard scientific training curriculum. Towards achieving this goal, the team led a series of workshops on topics specifically requested by BEACONites grappling with making their communication goals a reality: framing and public policy. The first two workshops took place at the 2017 BEACON Congress. The full day workshop at UT Austin took place in February 2018. At the workshop, participants had an opportunity to develop their story of self, practice and receive feedback on their communication with other scientists, learn from public policy experts, and find new, local opportunities to engage. Information about the workshop was shared in a BEACON blog post on March 13th, entitled: “Workshop highlights! How public engagement (and science communication) is a social endeavor.” Resources curated for these sandboxes and workshops have also been shared on the 500 Women Scientists website to be broadly and freely accessed by scientists (https://500womenscientists.org/comms-toolkits).

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>A Virtue-based Approach to RCR Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Robert Pennock, Michael O’Rourke, Chet McCleskey (MSU)</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Undergraduates, Graduates, Faculty</td>
</tr>
<tr>
<td>Approximate # of attendees</td>
<td>~100</td>
</tr>
</tbody>
</table>

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, “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 develop and offer virtue-based RCR modules at our annual Congress, helping grad students and post-docs fulfill their RCR requirements and pioneering training methods that could result in much more widespread use.
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. As our available funding begins to decrease we are working with external groups to facilitate continued implementation of these projects.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>BEACON TEACHERs Researching EVOLUTION (TEACHER REVOLUTION) – National</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Louise Mead and Kara Haas (MSU)</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>K-12 Educators</td>
</tr>
<tr>
<td>Approximate # of attendees</td>
<td>10</td>
</tr>
</tbody>
</table>

There were ten participants in the 2018 summer RET cohort. Two of the participants (one middle school and one high school teacher) worked out of Kellogg Biological Station on plant ecology research. The remaining eight teachers worked in a university lab that was the closest to their place of residence. We were able to expand the reach of this program beyond the reach of the BEACON consortium, with additional funding from SSE/Wiley Publisher, which allowed us a test run at creating a national network of evolution-themed RETs. Recruiting faculty mentors was our first step. We used a Google form and spread the word via SSE and BEACON listservs. We were overwhelmed with the response: 12 BEACON scientists and 17 SSE scientists responded. In the end we had more faculty interested than we had funding or teachers to place. We utilized video conferencing and social media to connect teachers during the summer. Our webinars/video conferences were well attended by participating teachers and we were able to record them for later viewing by teachers that could not attend the meetings. These methods worked well for sharing information and checking in on teachers’ progress.

Faculty mentors and the teachers in their labs expressed positive outcomes from the RET program. Specific examples include having great working relationships and pairings. Teachers were eager, excited and easy to work with and the mentors were encouraging and patient. Teachers became an integral part of the lab and continually building long-term collaboration and ways to integrate what is taking place in the lab into the classroom is something the faculty mentors are looking forward to. The majority of teachers responded neutral when asked if they gained knowledge of applicable journals/magazines useful to their teaching career but responded to an open-ended question noting the articles were extremely informative and plan to refer to them in the future. All teachers claimed that the program increased their enthusiasm and self-confidence in teaching science and that they have acquired an inquiry-based methodology specifically aligned to the curriculum that will relate their teaching to real life situations. The meetings with cohort participants served as time for reflection on how to be a more effective teacher and discussion with other teachers about their research experience and ways to bring it back into the classroom. The meetings proved to be beneficial to the teachers. Aside from having a videoconference for all meetings, the teachers mentioned that an online forum (aside from our
Facebook page) to respond to and reflect on assigned articles would have been helpful. One teacher enjoyed the fact that she was working so closely with graduate and undergraduate students as it reminded her of where her students are headed and the skills that will be necessary for them to have if pursuing a degree in the sciences. Other teachers enjoyed working with technology while interpreting their data in order to improve their technological and statistical skills.

Teachers do have the option to travel to the Evolution 2019 conference. We will provide funding to cover most of the expenses and hope that they will be traveling with their faculty mentors. Teachers will be presenting posters at this conference and will have the opportunity to meet each other in person.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>YEvo: teaching eukaryotic genetics and evolution using yeast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Maitreya Dunham (UW), Bryce Taylor (UW), Alexa Warwick (MSU)</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>High school students</td>
</tr>
<tr>
<td>Approximate # of attendees</td>
<td>100s expected</td>
</tr>
</tbody>
</table>

This team set out to leverage resources available in the yeast community to develop a simple, robust lab experiment that can address this issue and demonstrate evolution in action. In the YEvo (yeast evolution) lab exercise, students evolve yeast strains over the course of a few weeks in the presence of safe, cheap, over-the-counter antifungal agents using protocols that have been streamlined to minimize time and financial investment. Over time, students will observe increases in fitness by measuring culture density and simple competition experiments. Assessment of student learning will also be included.

Dr. Warwick has developed a series of questionnaires to administer as a pretest before the students begin the lab exercises and these have been sent to participating high school classes. Dr. Skophammer, the lead teacher on the project, was selected for a workshop at the National Association of Biology Teachers conference and will present the lab there to a wider audience. The website, www.yevo.org, will be populated with materials in time for the conference in November. Dr. Taylor will also attend the conference, as planned in the budget.

Additionally, strains and sequence data Dr. Skophammer generated last year are being compiled for use by other classrooms that can’t or prefer not to devote a longer period of time to the lab. These so far consist of a lab evolution module, where the students perform the serial dilution experiment; a sequencing analysis module, where the students don’t perform the evolution experiments themselves but are able to re-analyze the sequence data we already have in hand, and a competition module, which can be appended to either of the other topics. Three more teacher-partners have been recruited. AB Biology teacher at a large and diverse public high school in Seattle spent a week in the Dunham lab over the summer to learn yeast and help develop new selection environments. Other teachers have also indicated an interest in implementing the lab in their classrooms and it is anticipated that all materials will be available on the website by the end of the granting period.
Salmon Run aims to take evolutionary educational gaming to the next level, by not only illustrating the working of general evolutionary mechanisms, but also by displaying how they operate within the life cycle of an organism and in relation to its environment, incorporating evolutionary ecology. Salmon provide the perfect system to demonstrate the interplay between evolutionary dynamics, ecological processes, and anthropogenic influences. Their complex life cycles and economic and social import provide a unique opportunity to help students grasp the complexity of the natural world while gaining an understanding of the fundamental processes that shape diversity on this planet and an appreciation for the role human activities have in affecting this diversity. It is targeted for late middle school students.

The project formally started in August 2018, and to date work has been done to connect specific middle-school science standards and the life cycle of the salmon, discuss classroom elements with Tony Gendreau (an 8th grade science teacher consultant), and produce an initial set of conceptual drawings of both environments and fish bodies. Continued development is planned for the coming year.

Salmon Run: An Evolutionary Ecology Educational Game

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Evaluating Curriculum Goals in Undergraduate Evolution Education</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Tessa Andrews (MSU), Scott Harrison (NCAT), Louise Mead (MSU), Barrie Robison (UI), James Smith (MSU), Alexa Warwick (MSU)</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Undergraduate biology instructors</td>
</tr>
<tr>
<td>Approximate # of attendees</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Evolution is central to the biological sciences and one of the four core concepts for undergraduate biological literacy identified by Vision and Change (AAAS 2011), however, an agreed-upon set of learning objectives for undergraduate courses in evolution has yet to be
developed. This team plans to survey life science faculty in the United States about teaching evolution to undergraduate biology majors in order to identify evolution learning objectives. Currently collaborators are reviewing a draft of the planned survey questions and the existing learning objectives, with the goal of surveying the community before the end of December. They may need to re-deploy the survey in January 2019, depending on how many and how diverse our respondents are (institution geographic area, type, etc.).

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 regularly publish and present their work on BEACON education projects (Publications: Royer and Schultheis, 2014; Lark et al., 2014; Weigiel et al., 2014; Tran et al., 2014; Suwa and Williamson, 2014; Schultheis and Kjelvik, 2015; Burmeister and Smith, 2016; Smith et al. 2016, Kohn et al 2018. Presentations: deLima 2017, Kohn et al 2018, Wiser et al. 2018). 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 Education and Outreach activities, distributed across different audiences, are listed below.

<table>
<thead>
<tr>
<th>Audience</th>
<th>People in attendance</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-12 students and teachers</td>
<td>10-50</td>
<td>27</td>
</tr>
<tr>
<td>General public</td>
<td>50-1000s</td>
<td>13</td>
</tr>
<tr>
<td>Undergraduates</td>
<td>50-150</td>
<td>16</td>
</tr>
<tr>
<td>Faculty and graduate students</td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td>Conference attendees</td>
<td>100s</td>
<td>157</td>
</tr>
</tbody>
</table>

The **MSU Museum exhibit** (BEACON Gallery) is now complete. In addition, the final element of the Evo Hub deployed there is an interactive component that is also being tested in local classrooms.

The BEACON fall graduate courses continue to receive funding to integrate personal genomics into the courses, allowing students to explore evolutionary, genomic, and computational aspects of their person genomes. While kits are supplied to all BEACON graduate students taking the Fall BEACON courses, they have the option to use them, and are not expected to share their data. Instead, a curated data set is made available to students for analysis.

**Tri-Society Outreach.** Historically BEACON collaborated with National Evolutionary Synthesis Center (NESCent) to organize education and outreach at a national level. When NESCent funding came to an end, BEACON was provided with an opportunity: team up with the Society for the Study of Evolution, the American Society of Naturalists, and the Society of Systematic Biology, allowing many of these national programs to continue.

Through these collaborations, BEACON continues to co-sponsor the Evolution Symposium at the National Association of Biology Teachers annual professional development conference, the Undergraduate Diversity at Evolution (UDE) program at the annual meeting of the three
societies listed above, ecology and evolution events at the annual meeting of the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS), and The Darwin Day Roadshow. Details of these programs follow.

At the National Association of Biology Teachers (NABT) annual conference November 6-12, 2017 in St. Louis, Missouri. BEACON organized a two-part Evolution Symposium. First, Dr. Robert Cox (Univ. of Richmond) presented his research on evolution in anole lizards. In the second part the Data Nuggets team, and Aaron Reedy, a graduate student in the Cox lab, presented a workshop featuring a new Data Nugget based on Dr. Cox’s current research. We had approximately 57 attendees for the science talk and 25 attendees for the workshop.

The Darwin Day Roadshow (DDR) in 2018 brought evolutionary biologists to eight different schools, and a total of 44 classes. In addition to support from BEACON, free materials for the teachers were donated by HHMI, Oxford University Press, University of Chicago Press, Princeton University Press, Wiley and Sons/Wiley Blackwell, Bone Clones Inc., The Vaccine Makers Project, Fountainhead Press, and Save our Monarchs Foundation.

BEACON is currently working a paper reporting long term outcomes of The Undergraduate Diversity at Evolution (UDE) program co-sponsored with SSE. The program was not run in 2018 because Evolution 2018 was organized by the European Society of Evolutionary Biology (ESEB) but will be offered in 2019.

SACNAS is a national organization focused on increasing the participation of underrepresented groups in science, technology, engineering, and math (STEM) fields. The Ecology/Evolution events at SACNAS 2018 included a field trip, a “conversations with scientists” session, and a scientific symposium. The field trip included a visit to the unique habitat of San Antonio’s Mitchell Lake Audubon Center that included a hike through the wetlands as well as learning about host-pathogen interactions of the native animals and plants of the area. The Conversations with Scientists session and the Scientific Symposium were also well-attended events. The Ecology and Evolution Symposium also featured host-microbe interactions Speakers included BEACON graduate student Connie Rojas who presented her work on, the microbiome in wild spotted hyenas, Dr. Luis Zaman from the University of Michigan who presented his working experimenting with digital and microbial evolution, Dr. Lisa Burrow who presented on variable host susceptibility, and Dr. Kat Milligan-Myhre who presented her work on using an evolutionary model to determine the role of host genetic backgrounds.

BEACON and Beyond:

A number of our faculty and graduate students are also involved in evolution education research efforts, many of these projects are now externally funded following an initial investment by BEACON. Louise Mead continues as advise 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 is making connections between the curriculum and BEACON science. Drs. Ben Kerr and Scott Freeman, and graduate student Katie Dickinson (UW) continue with development of an experimental evolution lab for large undergraduate biology courses, and are now focused on identifying potential barriers for underrepresented minority students in particular. Drs. Mead, Pennock, Smith, postdoctoral fellow Mike Wiser, and graduate student Cory Kohn continue to work on an HHMI project at
Michigan State University aimed at transforming some of the gateway courses in STEM (Kohn et al. 2018).

The Avida-ED team is also providing instructor training workshops at MSU and our consortium institutions, funded by an NSF IUSE grant Active LENS: Learning Evolution and the Nature of Science using Evolution in Action.

BEACON Education Director, Dr. Louise Mead and postdoctoral fellows Dr. Elizabeth Schultheis and Melissa Kjelvik received NSF funding for Collaborative Research: Scientific Data in Schools: Measuring the efficacy of an innovative approach to integrating quantitative reasoning in secondary science. The project is collaboration between BEACON and the Biological Sciences Curriculum Study (BSCS), testing the efficacy of Data Nuggets. Data collection is complete and analysis underway.

BEACON is also enabling a third NSF funded project Collaborative Research: Connected Biology: Three-dimensional learning from molecules to populations. The project is a collaboration between MSU and The Concord Consortium, focused on developing three-dimensional curriculum around the Evo-Ed Cases. The project staff includes Drs. Mead, White, Smith, and Warwick.

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

<table>
<thead>
<tr>
<th></th>
<th>Masters</th>
<th>PhD</th>
<th>Postdoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graduate School</td>
<td>9 (26%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postdoc</td>
<td></td>
<td>64 (54%)</td>
<td>8 (23%)</td>
</tr>
<tr>
<td>Faculty Position</td>
<td>1 (3%)</td>
<td>16 (14%)</td>
<td>17 (49%)</td>
</tr>
<tr>
<td>Industry</td>
<td>13 (38%)</td>
<td>23 (19%)</td>
<td>9 (26%)</td>
</tr>
<tr>
<td>Government</td>
<td>1 (3%)</td>
<td>3 (3%)</td>
<td>1 (3%)</td>
</tr>
<tr>
<td>K-12 Education</td>
<td>3 (9%)</td>
<td>3 (3%)</td>
<td></td>
</tr>
<tr>
<td>Unknown</td>
<td>7 (21%)</td>
<td>9 (8%)</td>
<td></td>
</tr>
<tr>
<td>Total # graduates</td>
<td>34</td>
<td>118</td>
<td>35</td>
</tr>
</tbody>
</table>

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

We continue to engage our graduate students in writing Evo101 Blog Posts for the BEACON website. These are incorporated into the BEACON fall course. Posts introduce the general public to basic evolutionary concepts and principles.

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.
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 represented at the MSU Science and Engineering Festival again in 2019 as we were in 2018. We continue to send scientists to classrooms and promote Skype a Scientist. Undergraduate research experiences offered at Kellogg Biological Station provide an opportunity for students from underrepresented groups to gain training in research.

2f. Educational plans for next reporting period

Goals for the coming reporting period include facilitating continued collaborations with scientific societies to allow for the continuation of some of our education projects beyond the NSF funding being provided by BEACON. We are analyzing data on the efficacy of Data Nuggets in the high school classroom and look forward to publishing these results. A few new projects are also just getting started this year; these include the Yevo project and efforts to generate a list of learning outcomes for undergraduate evolution education. We anticipate this project to be complete by the next annual report.
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 during its early operation, 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.

<table>
<thead>
<tr>
<th>Knowledge Transfer Goals</th>
<th>GOAL</th>
<th>METRICS</th>
<th>PROGRESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>New collaborative research with industry partners</td>
<td></td>
<td>The number of external industry/government laboratory collaborations with BEACON through its member universities</td>
<td>In addition to working with existing industrial collaborators, this past year, BEACON has added several additional industrial collaborators.</td>
</tr>
<tr>
<td>Number of joint grant proposals submitted with industrial partners</td>
<td></td>
<td>Two proposals funded by Axia Institute, an industrial consortium founded by Dow and MSU (successor to MRIVCC); proposal to DARPA as subcontractor to Siemens was funded. Risto Miikkulainen has been on leave, working at Sentient Technologies, the largest AI startup. One proposal is funded by General Motors on large-scale constrained multi-objective evolutionary optimization.</td>
<td></td>
</tr>
<tr>
<td>Number of publications submitted that arise from industry-provided challenge problems and data</td>
<td>At least 5 in the current reporting period</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receiving industry-provided challenge problems and data with feedback</td>
<td>Number of instances that challenge problems, data, and feedback are received</td>
<td>At least 10 companies are providing challenge problems and feedback.</td>
<td></td>
</tr>
<tr>
<td>Spinoffs formed</td>
<td>Number of spinoffs formed</td>
<td>Jeffrey Barrick (UT) established an LLC spinoff during the reporting period, called Evolvomics. This spinoff was a result of Barrick and collaborator participating in the NSF I-Corps program, where their project was to develop an online software analysis pipeline for scientists at strain engineering companies. Their company submitted an STTR grant in December 2017, but it was not funded. Nonetheless, they have managed to establish a small client base.</td>
<td></td>
</tr>
</tbody>
</table>

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

Siemens: BEACON investigators Ron Averill (M.E.), Alejandro Diaz (M.E.), Kalyanmoy Deb (ECE) and Erik Goodman (ECE) were collaborators on a proposal to DARPA’s 16-39-TRADES-PA-008 solicitation, entitled “UHD-SoS: Enabling Design of Ultra High Definition Structure of Structure,” which was funded in 2017 with Siemens as the prime contractor. The MSU portion of the work is to create algorithms to allow simultaneous design of the microstructure (for example, lattices or structures of a variety of composite materials) and the macrostructure (to be fabricated from the microstructured materials), which requires sophisticated multi-level optimization. The total budget is $4.8 million over 4 years, and MSU’s portion is $600,000.

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. At the end of 2016, Betty Cheng (as a member of BEACON at MSU) collaborated with colleagues from Criminal Justice to propose another project to Ford, as part of the MSU-Ford Alliance, working with a Ford cybersecurity manager. This project targeted the area of cybersecurity for automotive systems. This multidisciplinary project proposes to integrate the social aspects of crime with technological approaches to develop techniques to prevent and detect cybersecurity threats. Cheng will leverage the use of evolutionary computing techniques to explore cybersecurity threats, with particular attention focused on those threat surfaces and threats that are most at risk, based on the analysis of social media forums and dark web data. In early 2017, this project was selected for funding. Cheng and her collaborators from Criminal Justice are actively working with Ford in assessing both the technical threats and the information posted on social media regarding automotive cybersecurity threats.

In 2018, the project is continuing as more information is collected from the literature and relevant websites are mined for discussions regarding cybercrime relating to automotive systems.

**ZF-TRW**: After two rounds of reviews and a selection process within the College of Engineering at Michigan State University, Betty Cheng’s proposal on developing a model-based framework to support the design and analysis of autonomous features to handle cybersecurity threats for automotive systems was selected for funding. The kickoff meeting and funding award for this project was held in October 2017. Participants at the kickoff included Vice President of Engineering & North America Applications, Director of Global Safety and Security, Senior Communications Manager, and Senior Technical Specialist.

During 2018, the project has made good progress towards its initial research goals and even exceeded our knowledge transfer goals. Preliminary results for the project have yielded a template for describing security design patterns that are specific to the automotive sector. Extensive literature review has led to the specification of a number of design patterns that have been presented to the industrial sponsor. The information was sufficiently compelling and detailed that the industrial cybersecurity expert was able to develop another security design pattern to be included in the collection. We are in the process of exploring how their development process can be augmented to make use of the proposed security design patterns.

**BBN**: Betty Cheng and Philip McKinley are collaborating with BBN Corporation in writing a DARPA proposal that addresses the assurance of autonomous system with machine learning elements – LECs (learning-enabled components). Cheng is the PI and MSU is the prime for this multi-million dollar DARPA proposal, where the pre-proposal abstract was selected and recommended for a full proposal.

Significant effort was expended in writing a $7.4M proposal to the DARPA program involving 2 subcontracts, including BBN. Ultimately, the proposal was not selected for funding, but the feedback from the program manager at DARPA was extremely encouraging. Specific suggestions were made to obtain preliminary results and the program manager expressed interest in either funding a follow-on proposal and/or helping our group find a suitable DoD program. He was particularly intrigued by the evolutionary aspect of the proposal, as it was a key innovation that was not seen in other proposals. The key negative was lack of evidence in being able to perform the run-time monitoring and adaptation portion of the proposed work, which is an area that is indeed a key challenge, particularly when considering evolutionary techniques.
**MSU-Ford Alliance Framework:** Betty Cheng (as a member of BEACON at MSU) submitted a proposal in response to the request for proposals. Her project was awarded a 2-year grant, starting January 2016. Her proposal addresses the use of evolutionary computing techniques to address uncertainty and feature interaction detection for powertrain features in multicore environments. Cheng is continuing work with this project and exploring automatic code generation capabilities for performing mapping to multicore platforms.

In 2018, this project also explored the use of supplemental capabilities for the additional cores, such as run-time monitoring, diagnostics, and feature interaction analysis. The run-time monitoring is looking for adverse conditions that might impact the functional safety of the vehicle, including cybersecurity breaches and functional failures due to uncertainty.

**Optimal Casings and Covers for Electronic Equipment:** This project started in 2014 and has continued since, 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 from heat management point of view and covers for electronic equipment to satisfy various criteria – amount of air movement versus steady-state temperature inside the enclosure. 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).

**Protein evolution:** Led by Andy Ellington (UT Austin). During the last year the Ellington lab has used directed evolution methods to generate a thermostable, error-correcting reverse transcriptase (http://www.ncbi.nlm.nih.gov/pubmed/27339990). This enzyme provides an interesting window on the evolution of replication, in that natural reverse transcriptases are not error-correcting, likely in part because they co-evolved with short RNA genomes. In addition to its scientific import, RTX has great commercial relevance, as it can directly convert RNA to double-stranded DNA, and thus is greatly enabling for broadly used techniques such as RT-PCR and RNASeq. Unsurprisingly, a number of large companies are in discussions with the University of Texas at Austin regarding potential commercial opportunities with this enzyme. Similarly, the Ellington lab has used cell-based evolution (similar to that carried out in the Lenski lab) to generate bacteria that can insert selenocysteine at high yield across from virtually any amber stop codon. This allows the scalable production of proteins that can form diselenide bonds, and a start-up company to exploit this opportunity has been formed in Boston.

**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 and 2016, Cheng and McKinley have continued to explore collaborative investigations with members of Metron. Discussions continue with collaborators at Metron, exploring different funding opportunities, including SBIR, DARPA, and ONR.

**Tri-level Supply Chain Management Decisions:** Led by Profs. Kalyanmoy Deb and Erik Goodman. This project is funded by the Axia Institute (formerly the 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. The achievements of the one Dow-funded project in 2015-16 led to two funded projects for 2016-17.

The new project is aimed at developing an automated system to assist Dow employees in performing Harmonious Tariff Classification, a process that assigns each product shipped internationally a classification code that determines its handling and duties assessed. That project has proven to be very successful, and Dow and the MRIVCC are in discussion with MSU about possible extension of the project to handle materials not shipped by Dow, with an eye toward possible commercialization. Dow has applied for a patent (September, 2018) with the MSU investigators as co-patentees, entitled "Hybrid Machine Learning Model for Tariff Code Classification."

**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 Cheng have worked together with the Ford contacts and have created software models that can be analyzed for various properties. Cheng continues to work with collaborators in exploring how formal analysis can be analyzed for feature interactions.

**Ford Motor Company:** Led by Kalyanmoy Deb (MSU). This project developed a metamodeling based multi-objective optimization algorithm that works in a collaborative manner with Ford. New solutions are created at MSU using metamodeling based evolutionary optimization method and were evaluated at Ford using their computationally expensive but high-fidelity proprietary evaluation codes. A trust region based method is also used to create meaningful and confident optimization runs. The developed algorithm is applied to Ford’s water jacket problem and a diesel engine combustion problem.

**Continental Automotive and now Hyundai MOBIS:** 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. Her main contact at Continental Automotive has moved to Hyundai MOBIS and is now the Project Manager for their Autonomous Systems Group. Her collaboration continues in developing challenge problems and exploring how modeling, evolutionary computation techniques, and formal analysis can be used to address uncertainty that plagues onboard autonomous subsystems.

**BAE Systems:** Led by Betty Cheng (MSU). Cheng continued to collaborate with BAE Systems to support the project: "Harnessing Evolutionary Computation to Support Software Composition with Code-Level Adaptors." The research explored 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. Cheng and her
students also applied their techniques to a new challenge problem involving e-commerce. This project has concluded formally with 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 on 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 including the interactions with safety properties. During this past year, Cheng and her students are also exploring how to augment symbolic analysis techniques with evolutionary computation to identify multiple counterexamples when performing formal analysis. The first targeted area of study is analyzing hierarchical requirements models to detect incomplete requirements. With their new approach, they are able to identify multiple counterexamples, rather than a single counterexample (that is typically returned with symbolic analysis alone). The multiple counterexamples better inform the developer as to the impact of uncertainty on the requirements and provides more insight as to how to revise the requirements to mitigate the problem.

**General Motors:** Led by Kalyanmoy Deb (MSU). In this project (completed in March 2018), power law rules are developed from multiple bi-objective optimization results to decipher design principles that are common to them. Deb suggested an “innovization” procedure some years ago, but applied the concept in a car frontal crash design problem of GM, besides applying to a number of small-scale engineering design problems. In this project, “innovization” problem is reformulated to classify non-dominated solutions from dominated solutions.

**General Motors:** Led by Kalyanmoy Deb (MSU). In this project (ongoing), we are using a classifier based rule discovery method for a manufacturing process involving time series data. GM is interested in knowing simple rules involving different features of the time series data that will classify GO data from No-GO data, so that the classifier can be used during the manufacturing process and also to have a better understanding of the complex manufacturing process.

**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.

**Polymorphic Games:** Led by T. Soule and B. Robison (UI). An administrative supplement in the summer of 2015 ($5k) and a 2016 BEACON award (Teaching evolution through game based simulation) supported the establishment of Polymorphic Games, an interdisciplinary video game design studio housed at the University of Idaho. In the summer of 2016, Polymorphic Games created "Darwin's Demons" a video game in which the player battles against a population of evolving enemies. On Darwin Day of 2017 (Feb 12th), Darwin's Demons was released on STEAM, an online gaming platform with hundreds of millions of subscribers world wide. Polymorphic Games worked closely with the UI Office of Technology Transfer to facilitate the sale of the game. To our knowledge, Darwin's Demons is the first implementation of a video
game that features a population of enemies that evolve according to the principles of Darwinian evolution. The website http://www.polymorphicgames.com features a free demo.

Polymorphic Games is now close to releasing its second game, Project Hastur. Project Hastur is an evolutionary tower defense game in which the player's strategic choices cause adaptation in the enemy population. Project Hastur is a fully 3D game environment, and the creatures in the game are encoded by digital genomes. These genomes determine morphology, behavior, and performance traits. Mutations of the genome can be dynamically represented in the game engine, and are fully integrated into the animations. Procedural generation of video game enemies using an evolutionary model is a unique feature of Project Hastur. Project Hastur is in the advanced beta stage, and Polymorphic Games hopes to release the game on STEAM by January 2019.

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

Kalyanmoy 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 Skovde in Sweden, Aalto University School of Business in Finland, Indian Institute of Technology Kharagpur, India and also internally within BEACON. These papers are kept for circulation at http://www.coin-laboratory.com.

Kalyanmoy Deb is collaborating with High Performance Computing Infrastructure (HPCI) and Joint Usage/Research Center for Interdisciplinary Large-scale Information Infrastructure (JHPCN) at Hokkaido University, Japan, to optimize computationally expensive practical problems using their 172 TFlops computing facility funded by Hokkaido University.

Scott Harrison (Dept of Biology faculty, NCAT) and Renuka Panchagavi (PhD student in Computational Science and Engineering, NCAT) received an NSF iCorps sub award on exploring innovative solutions in aquatic microbiology. This award has resulted in designing a business canvas, discovering a customer-base (more than 8 customers interviewed), two months of business development training, and discussions with the university's Division of Research and Economic Development on a patent application. The team interacted with Justin Streuli at HQ Greensboro, a business incubator, and Technology Commercialization Counselor, Christopher Veal, of the Small Business & Technology Development Center (State of North Carolina).

Scott Harrison and Omoanghe Isikhuemhen (NCAT) have filed with NCAT's Division of Research and Economic Development for a business startup involving cloud computing support of analytics and workflows in the life sciences.

2c. Progress towards indicators/metrics listed above

1. Establishing collaborative research relationships with industrial sponsors; producing grant proposals and publications. 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. Cheng has expanded the list of collaborators from Ford who are providing challenge problems, particularly in the area of autonomous features for automotive systems. 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. Digital Certainty, Inc. was acquired by Sentient Technologies, Inc. in May 2016. Sentient has continued to develop its evolutionary-computation-based conversion rate optimization product further, and re-launched it in September 2016 as Sentient Ascend. It optimizes selection and presentation of features of a web interface, typically for on-line marketers. Risto Miikkulainen was on leave from UT Austin 2015-2017, working at Sentient Technologies, Inc. on applications of evolutionary computation in general, and neuroevolution in particular; he has since returned full time to UT Austin. Sentient also started a summer internship program in 2016, employing three BEACON students. In 2017, Miikkulainen became Vice President of Research at Sentient and in 2018 became CTO at Sentient, but he continues to serve BEACON as its lead at University of Texas.

In the current reporting period, Jeffrey Barrick (UT) established an LLC spinoff called Evolvomics. This spinoff was a result of Barrick and collaborator participating in the NSF I-Corps program, where their project was to develop an online software analysis pipeline for scientists at strain engineering companies. Their company submitted an STTR grant in December 2017, but it was not funded. Nonetheless, they have managed to establish a small client base.

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), iDigBio, iPlant Collaborative, National Earth Observatory Network (NEON) and Data Carpentry/Software Carpentry organization.

Narrative:

Background:

BEACON received a $200K supplemental grant to address cyberinfrastructure across multiple NSF centers. Led initially by BEACON’s Prof. 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 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 subsequent 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 she founded received a grant from the Moore Foundation Data-Driven Discovery initiative, administered through BEACON. In a 2-day workshop at MSU in October, 2016, but accessible virtually from anywhere, MSU’s ICER staff prepared additional people to become instructors of Data Carpentry or Software Carpentry workshops.

2017 Development and 2018 Status:

So successful has been the operation of the Data Carpentry not-for-profit organization under the leadership of BEACON’s Dr. Tracy Teal that the organization sponsoring the Software Carpentry workshops has decided to merge with the Data Carpentry organization under Dr. Teal’s leadership. This new combined organization represents a large contribution to the national infrastructure for preparing biologists to use computational resources in support of their research and teaching, and is a direct result of BEACON’s sponsorship, NSF’s supplement to BEACON, and BEACON’s leadership of the effort. That organization continues to operate very successfully as of the time of this report, and represents a self-sustaining part of BEACON’s legacy.

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 began contributing greatly to forming a pipeline for undergrads into our graduate programs, especially for URM students. However, in fall, 2016, she accepted a position at another university, so the role she had planned to play in the BEACON Luminaries program that was funded by a supplement to BEACON will be taken on by others. However, she will continue to collaborate with BEACON faculty in her own research program.

The successful BEACON External Faculty Affiliate program stopped recruiting new affiliates after Dr. Grabowski’s appointment, but all remain active in BEACON. Dr. Briscoe and Dr. Turner continue to recruit students and postdocs who are highly engaged with BEACON.

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

Organizations/people involved: BSCS (Biological Sciences Curriculum Study)
Narrative: Education Director Louise Mead received funding through the DRK12 program at NSF to continue collaborative research with the Biological Sciences Curriculum Studies (BSCS) group in Colorado. We are working 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 continues to collaborate 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.

In addition to the NIH SEPA project, Louise Mead is co-PI in a funded DRK12 project focused on connecting genetics and evolution within the NGSS 3-Dimensional learning framework for high school biology. The project is a collaborative project with CREATE, Concord Consortium, and MSU (Peter White in Lyman Briggs College (MSU) is the PI).

Activity: Evolution education and outreach activities

Organizations/people involved: Society for the Study of Evolution, Society for Systematic Biologists, American Society of Naturalists

Narrative: BEACON is working with each of the three societies listed to engage in additional education and outreach activities (Undergraduate Diversity at Evolution; Darwin Day Road Show; Evolution and Ecology events at SACNAS). The events are funded by the societies and administered by BEACON.

Activity: Promoting Evolution-in-Action in the Artificial Life community

Organizations/people involved: International Society for Artificial Life, MIT Press

Narrative: BEACON is working with the International Society for Artificial Life (ISAL) on a range of efforts, including: (1) to promote the development and use of evolution-in-action software for both research and education, (2) to encourage "wet" experimental evolution research within the artificial life community, and (3) to directly involve more traditional evolutionary
biologists in the artificial life field. Furthermore, the MIT Press Artificial Life journal has agreed to consider bacterial experimental evolution research in the domain of Artificial Life, and encourage a related special issue. BEACON members regularly comprise a sizable contingent at Artificial Life conferences (including numerous talks, posters, workshops, and administrative support) and publish in the Artificial Life journal. Co-PI Ofria is the current president of ISAL and an associate editor for the Artificial Life Journal. BEACON alumna Anya Vostinar (graduated with PhD in Computer Science from MSU, now faculty at Grinnell College and ongoing BEACON collaborator) is now the book review editor for the journal.

**Visiting researchers during this reporting period:** Professor Lihong Xu (Tongji University), Chunteng Bao (Tongji University), Professor Meng Yao (East China Normal University), 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), Julian Blank (University of Magdeburg, Germany), Chunteng Bao (Tongji University, China), Chaoda Peng (Guangdong University of Technology, China), Yuanping Su (Jiangxi University of Science and Technology, China), Marco Tomassini (University of Lausanne, Switzerland), Julian Miller (University of York, UK) Stephen Kelly (Dalhousie University, Canada).

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

*Visiting speakers:* BEACON hosts a number of visiting speakers each year, who travel to Michigan State to meet with researchers and students, and give presentations at the weekly Friday seminars which are videoconferenced across all five partner institutions. Many of these speakers are co-hosted by other MSU departments and gave multiple talks, which allows us to share travel costs. This year several of the speakers were co-hosted by the MSU Ecology, Evolutionary Biology, and Behavior program. This year’s visitors included:

- Meg Crofoot, University of California at Davis
- Stephen Kelly, Dalhousie University
- Eileen Hebets, University of Nebraska, Lincoln
- Jonathan Pruitt, McMaster University

2c. Progress towards goals

Because the BEACON external partnerships are so intertwined with our broader research and education goals, we aren’t tracking these activities as separate goals. 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 continue its effective partnership activities with no plans for change.
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. These accomplishments, as shown in the timeline figure, transcends the cursory goals of increasing the number of diverse participants and demonstrates a strategic and thoughtful culture that demonstrates diversity within its infrastructure – e.g., research opportunities, grant submissions, broader impacts efforts, educational outreach activities, formal mentoring training/support, fellowships, and direct student support funds.

BEACON’S Evolutionary Timeline

- **2009**
  - BEACON proposal was crafted with the diversity goal to “Exceed national norms for diversity at all level in the Center”
  - Diversity Director, Judi Brown Clarke was hired

- **2010**
  - BEACON awarded NSF’s Science and Technology grant for $25 million
  - NCA&T was selected as a full partner

- **2011**
  - Conducted a comprehensive evaluation of the summer REU research and recruitment program
  - Faculty Affiliate Program to recruit diverse faculty from non-BEACON school started

- **2012**
  - BEACON Day @ NCA&T
  - Established baseline data for comparative National Norms

- **2013**
  - Hosted 1st BEACON Day @ NCA&T
  - Established Diversity Committee with partner school leads, added a rotating seat from the Graduate Student-Post-Doc Group

- **2014**
  - Surpassed National Norms for URMs, Females & Disabilities
  - Initiated the Disability Action Plan, updated website for accessibility

- **2015**
  - 66% Faculty Affiliate Awardees were diverse
  - 66% of Distinguished Post-Doc Fellows were female and/or URM
  - Surpassed National Norms for URM, Females & Disabilities
  - Provided lab supervisor training in mentoring to address diversity

- **2016**
  - Diversity with internal funded research project: 47% has diverse PI/co-PI status
  - 87% of project had diverse participants
  - Provided lab supervisor training in mentoring to address diversity

- **2017**
  - Published article, “Factors influencing the career pursuit of underrepresented minorities with an interest in biology”, Evolution: Education and Outreach
  - 90.5% (77/85) of internal funded research & educational projects had diversity goals and outcomes
  - Established the Native American/Alaskan Native Initiative

- **2018**
  - Established the Native American/Alaskan Native Initiative
  - Received NSF Supplemental Funding w/ Spelmam, Luminary Scholars Research Program

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 diversity through its inclusive efforts of continuous conversations, inclusive recruiting, supportive environments, and the leveraging of strong partnerships and programming to ensure consistency and sustainability.
To establish National Norm for baseline comparison data, BEACON collected data on the numbers & percentages of undergraduate and graduate students, post-docs, and faculty participants from diverse demographic groups. Specifically, the National Science Foundation (NSF) requires targeting women, underrepresented minorities, and individuals with disabilities.

In an effort to make accurate comparisons, BEACON captured and weighted national norm data for BEACON-specific disciplines using the NSF 2012 data tables (http://www.nsf.gov/statistics/wmpd/start.cfm) which includes:

- Biological/Natural Science: includes anatomy, biochemistry, biology, epidemiology, botany, cell biology, ecology, entomology, genetics, mathematics/applied math, microbiology/immunology/virology, neuroscience, pathology, physiology, zoology
- Computer Science
- Engineering: includes biomedical, electrical and mechanical

When crafting the original proposal, the following three critical steps were taken based on a “People First” model:

1. BEACON founders embracing diversity -- Center Director Erik Goodman had an extensive history of mentoring, recruiting and partnering with diverse students, post-docs and faculty; and Executive Committee Member and Chair of the Diversity Committee Percy Pierre was the founder and PI of MSU’s Alfred P. Sloan Foundation’s Program of Exemplary Mentoring Grant.

2. BEACON ensured the Diversity Director position was separate and had no other combined job responsibilities, thereby allowing a strategic and dedicated focus on diversity, equity and inclusion across the consortium at all levels and participants/affiliates.

3. When selecting an HBCU/HSI partner school, great efforts were taken to select a school that had a rigorous curriculum and established research agenda around both evolutionary computation and biology. North Carolina Agriculture and Technology College (NCA&T) met these criteria and had established faculty relationships.

The “People First” model efficiently evolved into a sustainable “systems” model, where diversity and inclusion became core values and “owned” by the entire consortium.
BEACON has a Diversity Steering Committee with Representatives from all the partner schools, including graduate students/post-docs. The Committee consisted of “decision-maker” representatives from each partner school. Constant monitoring of diversity progress with continuous and active feedback and improvement was critical to sustained success.

By having many points of feedback with “gatekeepers” across the partner school at every level; e.g., undergraduates, graduates, post-docs, faculty, staff . . . in the classrooms, labs and fieldwork, BEACON was able to identify unmet needs and gaps problems quickly, problem solve, and share successes.

The Diversity Director worked “top down” with the Diversity Committee and faculty, and “bottom up” with graduate students and post-docs, using active involvement and advocacy to meet and exceed diversity and inclusion expectations.

**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](http://www.nsf.gov/statistics/wmpd/start.cfm)).

**Underrepresented minorities (URMs):** Currently BEACON participants are: 53% White, 24% Black, 10% Asian, 5% Hispanic/Latino, 1% Native American, and 7% two or more races/ethnicities. 37% of BEACON participants are self-reporting as URMs, which is 20.1% above the National Norm (30.8%).

Majority of this diversity has been achieved through undergraduate student participation, where 17% (17 of 98) of graduate students and 68% (52 of 76) of the undergraduates (principally REU students) are URM’s; and across the entire consortium, 11% (10 of 90) of the post-docs are URMs.

This diverse consortium reflects inclusive efforts have effectively increased and sustained the number of URM participants.

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**2018 Diversity Committee -**

<table>
<thead>
<tr>
<th>Name</th>
<th>Contact Information</th>
<th>Short Bio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percy Pierre</td>
<td>Email: <a href="mailto:pierre@msu.edu">pierre@msu.edu</a> Phone: 517.432.5146</td>
<td>Percy is Vice President/Dean and Professor of Electrical and Computer Engineering of MSU. He created and directs the Sloan Engineering Program which recruits, helps fund, and mentors domestic engineering doctoral students, with an emphasis on underserved groups.</td>
</tr>
<tr>
<td>Judi Brown Clarke</td>
<td>Email: <a href="mailto:jbc@msu.edu">jbc@msu.edu</a> Phone: 517.353.5985</td>
<td>Just is the Diversity Director for the BEACON consortium. Her responsibilities include the facilitation of overarching visions, development of strategic goals, evaluation of policies and practices, and the daily oversight of BEACON’s initiatives across the five-school consortium for consistency of effective practices and impacts.</td>
</tr>
<tr>
<td>Joseph Graves</td>
<td>Email: <a href="mailto:gwenn@ncat.edu">gwenn@ncat.edu</a> Phone: 336.285.2838</td>
<td>Joe is the Interim Dean of the Joint School of Nanoscience and Nanotechnology. He has published over eighty papers and book chapters concerning biological concepts of race in humans. He is a member of the “New Genetics and the African Slave Trade” working group of the W.E.B. Du Bois Institute of Harvard University.</td>
</tr>
<tr>
<td>James Foster</td>
<td>Email: <a href="mailto:foster@uidaho.edu">foster@uidaho.edu</a> Phone: 208.885.7052</td>
<td>James is a professor of Biological Sciences with a background in evolutionary biology, computer sciences, and philosophy. His work with BEACON and the Institute for Bioinformatics and Evolutionary Studies has brought together interdisciplinary study of evolution globally.</td>
</tr>
<tr>
<td>Risto Miikkulainen</td>
<td>Email: <a href="mailto:risto@cs.utexas.edu">risto@cs.utexas.edu</a> Phone: 512.471.9571</td>
<td>Risto focuses on biologically-inspired computation such as neural networks and genetic algorithms. The goal is to simulate biological information processing and to develop intelligent artificial systems that learn and adapt by learning and interacting with the environment.</td>
</tr>
<tr>
<td>Ben Kerr</td>
<td>Email: <a href="mailto:kerrb@u.washington.edu">kerrb@u.washington.edu</a> Phone: 206.221.3996</td>
<td>Ben use a combination of mathematical analysis, computer simulation, and laboratory experiments with microbes to explore theoretical and empirical angles on topics in ecology, evolutionary biology, and the philosophy of biology. Currently 70% (7/10) of research trainees in Ben’s lab are female.</td>
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Female: BEACON’s strategic efforts to increase overall female participation across all levels has resulted in the fact that 43% of BEACON participants are female, which is 31.1% higher than the National Norms of 32.8%.

The proportion of female faculty is 39% (93 of 236), which also surpasses the national norm of 31.0% by 25.8%. Women make up 38% of BEACON’s post-docs (34 of 90), which surpasses the national norm of 35.5% by 7%. The percentage of female undergrads is 43%, which also surpasses the national norms of 36.6% by 17.5%.

Working strategically, BEACON recruited graduate students from across its partner schools, coordinated with faculty advisors at Minority Serving Institutions (MSI), and networked with other NSF STC colleagues to create a robust and diverse candidate pools of post-doc from which to hire.

Individuals with Disabilities: Currently 6.4% of BEACON participants self-reported as having a disability, which exceeds the National Norms (3.3%) by 93.9%.

By demonstrating a commitment to being inclusive and establishing a welcoming consortium, the proportion of undergraduates reporting a disability has increased to 7.1%, which is a 51% increase over the National Norm (4.7%); the proportion of graduate students has increased to 8.2%, which is an 43.8% increase over the National Norm (5.7%). The proportion of post-docs reporting a disability (where National Norm data is unavailable) was maintained at the 2016 level of 2%; and the proportion of faculty (2.7%) is equal to the National Norm (2.7%).

BEACON’s Disability Action Plan, called ThisAbility, worked hard to establish best-practice activities for increasing adaptive learning and research/lab strategies, and as a result, the learning environments (e.g., classrooms, fieldwork and labs) are enriched and inclusive of all participants. We created a webpage, with opportunities to blog on the issues around disabilities that allow participants across the consortium can submit content or ask for assistance, and created a repository of best practices and adaptive software in an effort to provide scalable models and tools.

BEACON’s ongoing challenge is to reassure individuals with disabilities that reporting their status will not result in any vulnerability and/or biases against them. BEACON works hard to communicate and provide safe, accommodating, and adaptive environments. While we are pleased that more individuals have self-reported, we acknowledge that our numbers are still underreported and our efforts continue.
BEACON’s Native American/Alaskan Native Initiative (NAANI). The focus of NANNI is to:

- Create collaborations in support of STEM education for NA/AN students,
- Establish a research agenda aimed at closing knowledge gaps on barriers and best practices related to NA/AN participation in STEM
- Increase participation by NA/AN in setting the national research agenda on issues that impact Native lands
- Provide a forum to communicate educational opportunities for NA/AN American students
- Understand and respect indigenous Traditional Knowledge

STCs are thought of as being at the forefront of discovery and innovation in STEM nationally; however, there is a notable lack of diversity, specifically for Indigenous students, staff, and faculty. Indigenous communities possess historical and Traditional Knowledge (TK) that has yet to be understood and as valued at the same level as western science. BEACON’s Native American/Alaskan Native Initiative (NAANI) aims to recruit, retain and thereby empower Indigenous people as well as increase innovation in STEM through an ethically and culturally responsible way.

BEACON accomplished and surpassed all stated goals:

1. In partnership with MSU’s Native American Institute, a summer intern was recruited to work on curriculum for K-12 students at the Hydaburg School District.
   a. The “text” book uses TK coupled with STEM and includes activities for each grade level, currently five chapters are near completion.
      i. During the 2017-18 school year the TK will be given to the Haida translation class to translate the book into the Haida Language.
      ii. Curriculum is still being developed and the book is scheduled to be given to the Hydaburg School District for the 2018-19 school year.

2. Three summer interns were hired to work on an ongoing evolutionary environmental project.
   a. Nevaeh Peele and Andrea Cook, pre-college Haida students, worked on the shipworm and clam habitat and assessment.
   b. Lila Afifi, an MSU undergraduate, analyzed a metagenome of biofilm communities from an Mn-depositing hot spring.

3. Two interns attended the AISES National Conference in Oklahoma City, OK presenting posters of their summer research projects.

4. Presentations:
a. Workshop presenter at Michigan Indian Education Council’s Native American Critical Issues Conference; Ziibiwing Center of Anishinabe Culture; March 23, 2018 – Mt Pleasant, Michigan

b. The Living Breath of Water: Indigenous Foods and Ecological Knowledge Symposium; May 5-6, 2018 – University of Washington, Seattle Washington

c. Workshop presenter for the American Indian Science & Engineering Society National Conference, October 4-7, 2018

5. Two papers are in process for publication from the work conducted on this project.

1c. Problems encountered

As BEACON enters it final years of being NSF-funded as an STC, we are diligently capturing our effective efforts and activities by creating legacy documents.

A continued challenge is maintaining our “stretch goals” of sustained diversity outcomes and ensuring our environments supports and advances inclusive participation throughout BEACON and across our collaborative partners.

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 institutional change, therefore we will continue to diligently support the unique needs of underrepresented minorities, females, and individuals with disabilities.
**BEACON Travel Awards:** BEACON provides travel awards for students to attend professional conferences and present their research. Many of our URM students are taking advantage of this funding opportunity and are getting valuable exposure to professional networks, discipline peers, and content experts.

**Postdoctoral Programs:** The Distinguished Postdoctoral Fellows Program funded postdoctoral scholars to pursue interdisciplinary research with BEACON faculty members in the fields of biology, computer science, and/or engineering. Applicants proposed a research project within the scope of BEACON’s mission and had to have two BEACON faculty sponsors who would serve as research mentors. The successful applicants helped foster collaborations among faculty and disciplines, and served as a professional model for pre-doctoral trainees. Collectively these two programs supported six post-doc Fellows, 67% (4 of 6) were females and 33% (2 of 6) were URMs. The program could not be continued beyond 2018 because of sunsetting finances.

**Integrating Research, Diversity, and Education into the Long-Term Evolution Experiment:** The Long-Term Evolution Experiment, or LTEE, has been running for over 28 years and 65,000 bacterial generations. It is an exemplar of evolution-in-action studies and, as such, it is also one of BEACON’s cornerstones. The LTEE has been successful in large measure because of the creativity and dedication of many talented students and collaborators. This two-year project contributes not only to the research mission of BEACON, but also to BEACON’s goals for diversity and education. To those ends, it supports three graduate students who are from underrepresented groups, have disabilities, or both, and who are conducting research on the LTEE lines. The project also supports two high-school biology teachers to develop microbial evolution-in-action experiments for their students.

**Undergraduate Programs:** BEACON’s Research Experience for Undergraduates (REU) Program is a 10-week intensive residential program, which targets 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. BEACON has served approximately 500 undergraduate students (freshman to 5th-year seniors) and spent over $2 million by leveraging funding from several sources. For every $1 dollar spent, BEACON has consistently blended/braided/matched approximately $3 from external leveraged funds from other sources.

BEACON’s Luminary Scholars is a research program that provides opportunities for a diverse, multidisciplinary group of MSU students to conduct year-round research with faculty, graduate students and post-doc mentors. Research settings included wet & dry labs, computer simulations, field experiences, and/or a combination. Majority of summer research program use their funds as a recruiting tool for external students, which has been very challenging for MSU students wanting to stay on campus and conduct summer research. While our limited funding restricts the amount of students we can accept, since 2013, we have provided support to sixty-two (62) MSU undergraduates for year-round research experiences.

In 2018, BEACON secured $40,000 from MSU’s Office of the Provost–Undergraduate Education/Undergraduate Research (UG-ED/Research), which was leveraged with $24,260 of other funds for a total budget of $64,260 to support six (6) MSU undergraduate students. Based
on past leveraging of UG-ED/Research allocations, there are six additional students conducting year-round research supported completely by their respective research labs.

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.

In May 2018, Dr. Brown Clarke provided a formal mentoring training session for twenty-five (25) 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 discuss their activities and progress during the preceding week and their plans for the following week. This interactive system works well for ensuring clear communication between students and their mentors, as well as for signaling potential problems as they might arise.

Dr. Brown Clarke facilitates 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 96.1% of interns reported a significant increase in research skills and confidence, and 97% 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. This makes the formal mentoring activity a much more targeted activity with proven positive effects.

BEACON was successful in securing another $40,000 from the MSU Office of the Provost – Undergraduate Education Office to support year-round research opportunities for twelve diverse MSU undergraduate students to conduct research with BEACON faculty.

BEACON’s REU Field Experience at Kellogg Biological Station provides funding for MSU students to participate in the Undergraduate Research Apprentice (URA) program at KBS for two summers (2017 & 2018). The URA program provides students an integrated research and educational experience that increases their understanding of evolution and the nature of scientific research and introduces them to career opportunities in STEM. The URA program complements the NSF funded REU program at KBS by focusing on early career undergraduates (rising sophomores) and introduces them to skills needed to be successful in further research experiences. BEACON funding leverages support from other sources for the KBS URA program and provides a scaffolding to the NSF-funded REU site grant that supports more advanced
students. URAs gain research experience by taking 1-3 courses at KBS (tuition funded separately), working as a research assistant with a graduate student or postdoctoral mentor, and participating in professional development activities and seminars at KBS. In 2017, we supported 4 MSU students (3 females) working on a wide range of projects associated at KBS focused on BEACON theme of evolution in action, specifically focusing on how populations and species interactions respond to climate change.

**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 200 girls grade 6th-8th providing hands-on math and science experiences. BEACON also funded citizen science day activities and *Darwin Day Road Show* at various urban & rural classrooms and museums across the nation.

**Outside of BEACON:** Dr. Brown Clarke is 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).

**NSF Supplemental Funding:** 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 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.

Spelman College has been awarded a subcontract, where Dr. Aditi Pai, Associate Professor and Co-Director of the Teaching Research & Resource Center, directly supervised the Spelman students working in her research lab. She utilized these supplemental grant funds to financially support the Spelman research students throughout the academic year. The subcontract provides funding for a research cohort of four students, working up to 10/hours a week. We have budgeted $3950 per student for Dr. Pai to use for set-up costs and support of the laboratory facilities and supplies for the students’ projects.

Five Spelman undergraduates have collectively attended MSU’s summer research program on the East Lansing Michigan campus. In August, BEACON provided support for Dr. Pai to travel to Michigan State University to coordinate with the MSU summer faculty supervisor, Dr. Fred Dwyer for the subsequent academic year’s continuation of the research at Spelman and to present at BEACON’s 2018 annual congress. All five of the Spelman students have presented their summer research posters at different professional conferences throughout this fall; three have submitted a paper for publication (pending) with Dr. Pai on their research project.

**2b. Impact of these activities on enhancing diversity at the center**
2c. Progress towards goals

To summarize our diversity statistics:

- **URMs**: BEACON participants are: 53% White, 24% Black, 10% Asian, 5% Hispanic/Latino, 1% Native American, and 7% two or more races/ethnicities. 37% of BEACON participants are self-reporting as URMs, which is 20.1% above the National Norm (30.8%).

- **Women**: BEACON’s strategic efforts to increase overall female participation across all levels has resulted in the fact that 43% of BEACON participants are female, which is 31.1% higher than the National Norms of 32.8%. The fraction of female faculty is 39%, which also surpasses the national norm of 31.0% by 25.8%.

- **Individuals with Disabilities**: Currently 6.4% of BEACON participants self-reported as having a disability, which exceeds the National Norms (3.3%) by 93.9%. By demonstrating a commitment to being an inclusive and welcoming consortium, undergraduates have increased to 7.1%, which is an 51% increase over the National Norm (4.7%); graduates has increased to 8.2%, which is an 43.8% increase over the National Norm (5.7%), post-docs (where National Norm data is unavailable) maintained at the level of 2%, and faculty (2.7%) are equal to the National Norm (2.17%).
Key strategies to BEACON’s continued success:

• Over the past eight years there was continuity of staff, leadership, vision and values

• Stability of executive management, who were paid competitively and supported in their development of professional skills; e.g., encouraged to teach, solicit grants, conduct research, publish articles, and present/attend professional conferences

• Diversity Committee consisted of “decision-maker” representatives from each partner school
  – Constant monitoring of diversity progress with continuous and active feedback and improvement

• Many points of feedback with “gatekeepers” across the partner school at every level; e.g., undergraduates, graduates, post-docs, faculty, staff … in the classrooms, labs and fields
  – Able to identify unmet needs and gaps problems quickly, problem solve, and share successes

• Diversity Director worked “top down” with the Diversity Committee and faculty, and “bottom up” with graduate students and post-docs, using active involvement and advocacy

Established structures to ensure outcomes:

• Establish “buy-in” and ownership among the participants

• Get people “leaning in” versus “leaning back” on diversity, equity and inclusion

• Change the atmosphere by clarifying and operationalizing the core values

• Establish a compelling argument using a cost-benefit business perspective that frames the “high performance” advantages of a diverse organization; e.g., diverse perspectives facilitate innovation and creative solutions

2d. Plans for the next reporting period

• BEACON will collaborate with its partners/collaborators to create legacy documents, efforts and resources that can be sustained at the partner schools post-NSF funding

• BEACON will continue to leverage funding and secure grants to support diversity efforts and research opportunities for URMs, females and individuals with disabilities

• BEACON will work with our external evaluators, Drs. Patricia Farrell-Cole and Marilyn Amey and their graduate student team to conduct a comprehensive evaluation of diversity outcomes and climate/program impacts.
VII. MANAGEMENT

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

The Center's overall organizational strategy and rationale is unchanged since the last reporting period.

*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 has evolved over the last several years as the Executive Committee identifies necessary refinements, but we have not made any substantial changes since the previous reporting period.

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.
<table>
<thead>
<tr>
<th>GOAL</th>
<th>METRICS</th>
<th>PROGRESS</th>
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<tbody>
<tr>
<td>Increase in cross-disciplinary research</td>
<td>Number of paper/conference submissions by BEACON authors</td>
<td>41% of publications and 48% of presentations reported as interdisciplinary</td>
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<tr>
<td>and education</td>
<td>Number of students enrolled in cross-disciplinary courses</td>
<td>12 in semester-long courses, plus hundreds in workshops on computational science for biologists</td>
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<td></td>
<td>Number of funding proposals submitted</td>
<td>24 of 36 grant proposals submitted (67%) reported as interdisciplinary; 11 of 36 (31%) inter-institutional</td>
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<tr>
<td>Increase in cross-institutional research</td>
<td>Number of paper/conference submissions</td>
<td>33% of all publications and 38% of presentations reported to be cross-institutional</td>
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<tr>
<td>and education</td>
<td>Number of new courses and workshops</td>
<td>As discussed in Education section, many Data Carpentry workshops were offered to a national audience in the reporting period, plus one EDAMAME (Explorations in Data Analyses for Metagenomic Advances in Microbial Ecology) workshop.</td>
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<td></td>
<td>Number of students in cross-institutional courses</td>
<td>In 2018, there were 12 MSU students enrolled in semester-long BEACON courses. Some BEACON partners offered local equivalents to these MSU courses. Hundreds participated in workshops on computational science for biologists</td>
</tr>
<tr>
<td>Increase in new funding sources (cross-disciplinary and cross-institutional)</td>
<td>Number of submissions</td>
<td>BEACON researchers submitted 36 proposals for external funding concerning evolution in action, and &gt;$13M in external funding was granted</td>
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<td></td>
<td>Award dollars</td>
<td>BEACONites have been awarded over $13M from outside BEACON in this funding period (&gt;9M for cross-disciplinary proposals),</td>
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Effective support of Center operations by Management team | Survey for participants about management team | 2018 study has focused on BEACON's successes in promoting multidisciplinary research and increasing diversity, as well as studying alumni career paths

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 in 2015.

Number of public mentions made by NSF about BEACON | Multiple mentions and retweets on NSF’s Twitter feeds

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*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 inter-institutional.

**Research:** The graph below illustrates the reported percentage of paper and grant proposal submissions in each year that are interdisciplinary and inter-institutional. 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. Recent years show that this rate has largely plateaued, and about 40-50% of current BEACON outputs are self-reported as interdisciplinary and about 30-40% as inter-institutional. 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 a total of 12 students in 2018. The leadership efforts of Dr. Tracy Teal have allowed the Data Carpentry workshops to be organized as a not-for-profit organization and offered nationally at many sites. After initial support from NSF via a supplement to BEACON, the Moore Foundation funded this effort with a grant administered through BEACON, with Dr. Teal as the PI. In 2017, the Software Carpentry organization decided to merge with Data Carpentry, and Dr. Teal is the executive director of the resulting combined not-for-profit. Data Carpentry and the new combined organization arose due to BEACON and its collaboration with sister NSF biology centers, and serve the national community of biologists interested in learning how better to apply computational methods in their research.

The fourth annual Explorations in Data Analyses for Metagenomic Advances in Microbial Ecology (EDAMAME), organized and taught by Ashley Shade, Tracy Teal, and Adina Howe, was offered this summer. This intensive 7-day summer workshop provides computational training to microbial ecologists. EDAMAME is supported by grants from the NIH and the National Institute of Food and Agriculture, as well as by BEACON funds.

Funding sources: BEACON researchers reported submitting 36 grant proposals for well over $27M during this reporting period, 24 (67%) of which are interdisciplinary, and 11 (31%) of which are inter-institutional. Of these, 16 [44%] have been funded so far, among them, 8 [50%] were interdisciplinary and 5 [31%] were inter-institutional. Total funded was over $13M in external funds, from NSF, NIH, DARPA, Department of Energy, and USDA, among others. 8 submitted proposals were declined, and no decision has yet been reported for another 12 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. As BEACON is now in the final two years of STC funding, the team is focusing on learning what aspects of BEACON's strategies have been most successful in promoting multidisciplinary research, increasing diversity in science, and helping alumni further their careers. This year they have been interviewing faculty about their multidisciplinary research teams, working with leadership on documenting BEACON’s diversity processes, and surveying BEACON’s alumni (M.S., Ph.D. and postdoc) to understand the impact BEACON has had on their interdisciplinary thinking and their career paths.

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 address these challenges 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 the center’s ongoing activities and who is involved in them. Our email lists are also heavily used to distribute information. We use our videoconferencing technology during our weekly BEACON seminar, our BEACON classes, and other long-distance collaborative activities.

Need for increased face-to-face interaction. Despite progress in long-distance communication technology, our participants continue to express the feeling that the best way to communicate and create a sense of community is with face-to-face interaction. We provide travel funding for members to visit participating institutions for collaborative work. Our primary face-to-face event is the 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. At the 2013 Congress, we 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 has been repeated every year since 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, continues to work on 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 week since April 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 blog posts are searchable (by matching typed-in words) on the main BEACON page and the Research page on the public website. In addition, we also post news stories about BEACON research and education activities in that space. Other pages in the website describe BEACON’s 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. That Intranet site contains useful information about BEACON members, and much of that content is being migrated, in a somewhat protected form, to the public pages as the new content of the People page.

**Social media.** We also connect with our members and the general public via Facebook (http://www.facebook.com/BEACONCenterEvolution, 783 “likes” as of 9/25/18, and Twitter (@BEACON_Center, 1432 followers as of 9/25/18, an increase of 10% since the last reporting period). 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 greatly increases BEACON’s visibility in scientific social media circles. These social media feeds are updated at least 2-3 times a week by the Managing Director, Education Director, and Evolution Education & Outreach Postdoc Alexa Warwick.

**Videocommunications systems.** For our weekly Friday all-location meetings we are using Polycom and Tandberg dedicated videoconferencing equipment, augmented by 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

There were no changes to the BEACON External Advisory Board in 2018.

<table>
<thead>
<tr>
<th>External Advisory Board</th>
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<tbody>
<tr>
<td>Name</td>
<td>Affiliation</td>
</tr>
<tr>
<td>Meghan Duffy</td>
<td>University of Michigan</td>
</tr>
<tr>
<td>Scott Edwards</td>
<td>Harvard University</td>
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<tr>
<td>John Koza</td>
<td>Stanford University</td>
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</table>
The seventh meeting of BEACON’s External Advisory Board was held August 10, 2018, at Michigan State University, during the BEACON Congress. The summary report from that meeting is provided in Appendix C.

4. Changes to the Center's strategic plan

We have made no major changes to any of the outcomes or metrics in our Strategic Implementation Plan.
VIII. CENTER-WIDE OUTPUTS AND ISSUES

1a. Center publications

Peer-Reviewed Publications


46. Gunn D, Roy K, Bryant K. In Press. Simulated Cloud Authentication Based on Touch Dynamics with SVM.


95. Strauss E, Holekamp K. Submitted. Social alliances improve rank and fitness in a matrilineal society. *PNAS.*


**Book Chapters**


8. Lalejini A, Ofria C. What else is in an evolved name? Exploring evolvable specificity with SignalGP. *Genetic Programming in Theory and Practice XVI.*


**1b. Conference presentations**

*Talks*


5. Card KJ. Maintenance of antibiotic resistance traits during a long-term experiment with *E. coli.* 2018 Midwest Ecology and Evolution Conference. Kellogg Biological Station, Michigan State University. 4/7/18


15. Kendig C. Does the holobiont idea challenge the concept of "individual"?. Unmasking Common Principles Governing the Microbiome. Madison Microbiome Meeting. University of Wisconsin-Madison. 4/26/18
16. Kendig C. What are we doing when we describe something as being a part in a biological parts repository. The 7th Biennial Conference of the international Society for Philosophy of Science in Practice. Ghent, Belgium. 7/2/18
17. Kendig C. Ontology engineering in synthetic biology. Varieties of Experiment and Measurement in Technoscience: The Case of Synthetic Biology. Darmstadt, Germany. 9/7/18
19. LaBar T. Drift robustness and the evolution of genome architecture. Society for Molecular Biology and Evolution 2018. Yokohama, Japan. 7/12/18
22. Lenski R. Evolutionary Insights from the Long-Term Evolution Experiment - Two Recent, Unpublished Vignettes. Evolution 2018. Montpellier, France
24. Li X. Opponent Modeling and Exploitation in Poker Using Evolved Recurrent Neural Networks. The Genetic and Evolutionary Computation Conference (GECCO). Kyoto, Japan. 7/19/18
25. Liang J, Meyerson E, Miikkulainen R. Evolutionary Architecture Search For Deep Multitask Networks. GECCO. Kyoto, Japan. 7/19/18
26. Maiden M. Discovery of a Novel Resistance Mechanism in Pseudomonas aeruginosa Using Evolution in Action
30. Miikkulainen R. Evolutionary computation: The next deep learning. O'Reilly Artificial Intelligence Conference
31. Miikkulainen R. Evolving Multitask Neural Network Structure. Symposium on Metalearning at NIPS
32. Miikkulainen R. Harnessing Machine Creativity in Digital Marketing through Evolutionary Computation. Empowers Marketers Workshop
33. Miikkulainen R. Massively Parallel Evolutionary Computation. Hardware for Next Generation AI workshop of the The Electronics Resurgence Initiative conference
34. Mobley R. Interactions Driving Sensory Ecology and Evolution
38. Montgomery T, Holekamp KE. Traits that govern participation in cooperative mobbing by potted hyenas. ISBE. Minneapolis, MN. 8/16/18
40. Ollodart A. A high-throughput method for mutation rate determination. Engineering Biology Research Consortium Fall Retreat
43. Skophammer R. Evolving yeast to resist an antifungal compound in a long-term project integrated into a high school biology class. Genetics Society of America Yeast Genetics Meeting
45. Slade J, Watson M, Kelly T, MacDougall-Shackleton E. MHC-Mediated Mate Choice and Preen Oil as a Chemical Signal of MHC Similarity in Song Sparrows (Melospiza melodia). Society of Integrative and Comparative Biology Meeting. San Francisco, CA. 1/7/18
48. Strandburg-Peshkin A. Collective Movement in Animal Societies. Conference on Collective Behavior. Centre for Theoretical Physics, Trieste, Italy
49. Strauss E, Holekamp KE. Early life dominance interactions predict longevity in spotted hyenas. ISBE. Minneapolis, MN. 8/16/18


52. Wang J. Decode genetic basis of disease mechanisms by integrative modeling of regulatory networks. NRT kick-off Symposium. Michigan State University. 8/22/18


54. Whittaker DJ. With a little help from my friends: social effects on the chemosignaling microbiome in songbirds. Social Olfactory Communication Symposium. Bielefeld, German. 10/9/18


57. Yuan Y, Banzhaf W. ARJA: Automated Repair of Java Programs via Multi-Objective Genetic Programming. COW Workshop at UCL. University College London. 2/26/18

58. Yuan Y, Banzhaf W. ARJA: Automated Repair of Java Programs via Multi-Objective Genetic Programming. Dagstuhl Workshop on Genetic Improvement. Schloss Dagstuhl, Germany. 1/31/18

Posters


5. Cavalieri CN, Holekamp KE, Lundrigan B. Shifting to a new place: influence of developmental timing on life-history schedules in Order Carnivora. Joint Congress of Evolutionary Biology. Montpellier, France. 8/2/18


11. Hristova AE, Sakai ST, Lundrigan B. Brain shape evolution in the mustelid adaptive radiation. Joint Congress of Evolutionary Biology. Montpellier, France. 8/22/18
23. Phillips JG. Genome evolution following adaptive shifts to an ecological extreme. IBEST Expo. University of Idaho. 7/11/09
27. Rupp T, Eisthen H. Sensory mechanisms for localizing spermatophores in the axolotl (Ambystoma mexicanum). International Congress of Neuroethology. Brisbane, Australia. 7/20/18

1c. Other Dissemination Activities

3. Goodman ED. Some Recent Progress in Evolutionary Computation at BEACON Center. Keynote at Founding of Key Laboratory of Computational Intelligence. Southern University of Science and Technology, Shenzhen, China. 11/15/17
7. Miikkulainen R. Computational Intelligence in Games. IEEE CIS Distinguished Lecture. Beijing, China
8. Miikkulainen R. Evolution of Neural Networks. IEEE Symposium Series on Computational Intelligence
9. Miikkulainen R. Evolution of Neural Networks. Hyderabad, India
10. Miikkulainen R. Evolution of Neural Networks. IBM Hyderabad, India
11. Miikkulainen R. Evolution of Neural Networks. Gokaraju Rangaraju Institute of Engineering and Technology, Hyderabad, India
12. Miikkulainen R. Tutorial: Evolution of Neural Networks. GECCO.
13. Braasch I. Of Fish and Men: What fish can tell us about the genetic basis of our evolution, development, and diseases. MSU Board of Trustees Meeting 08/31/2018. Michigan State University
14. Braasch I. Of Fish and Men: What fish can tell us about the genetic basis of our evolution, development, and diseases. MSU Infrastructure Planning Facilities, Faculty Research Presentation 09/20/18. Michigan State University
16. Dunham M. Genome evolution in yeast hybrids in and out of the lab. University of Idaho
17. Goodman ED. Robust Multi-objective Evolutionary Optimization to Allow Greenhouse Production/Energy Use Tradeoffs. Greenhouse Research Team, Tongji University. Shanghai, China. 11/6/17
18. Goodman ED. Recent Progress in Evolutionary Computation at BEACON Center. International Joint Research Laboratory on Evolutionary Intelligence and Engineering Applications. Shantou, China. 11/9/17
20. Lenski R. Dynamics of Phenotypic and Genomic Evolution in a Long-Term Experiment with E. coli. Cambridge, UK
21. Lenski R. Dynamics of Phenotypic and Genomic Evolution in a Long-Term Experiment with E. coli. Northwestern University Medical School
22. Lenski R. Dynamics of Phenotypic and Genomic Evolution in a Long-Term Experiment with E. coli. University of Michigan Medical School
23. Miikkulainen R. Evolution of Neural Networks. Department of Brain and Cognitive Sciences, MIT
24. Miikkulainen R. Evolution of Neural Networks. Biodesign Institute, Arizona State University
25. Perofsky A, Lewis R. Drivers of gut microbial composition and transmission within and among wild lemur populations. Fogarty International Center (NIH) seminar. Bethesda, MD
26. Smythe WF. Its a Good Day To Be Indigenous. NSF. Alexandria, VA
27. Strandburg-Peshkin A. Collective Movement in Animal Societies. EEBB seminar. MSU.
29. Strandburg-Peshkin A. Collective Movement in Animal Societies. Swarthmore College, Swarthmore, PA,
30. Top EM. Compensatory mutations pre-adapt bacteria to diverse antibiotic resistance plasmids. Departmental Seminar, University of Alaska Fairbanks. Fairbanks, Alaska. 3/2/18
33. Whittaker DJ. Using Common Scents: Chemosignaling with symbiotic microbes in songbirds. The University of Auckland. Auckland, New Zealand
# 2. Awards and Honors

<table>
<thead>
<tr>
<th>Recipient</th>
<th>Award Name and Sponsor</th>
<th>Date</th>
<th>Award Type</th>
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<tr>
<td>Bernot, Kelsie MarEdith</td>
<td>Junior Faculty Teaching Award, North Carolina A&amp;T State University</td>
<td>2018</td>
<td>Education-Related</td>
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<tr>
<td>Blount, Zachary</td>
<td>Ralph Evans Award, MSU Department of Microbiology and Molecular Genetics</td>
<td>2018</td>
<td>Scientific</td>
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<tr>
<td>Deb, Kalyanmoy</td>
<td>2018 Evolutionary Computation Pioneer Award, IEEE Computational Intelligence Society</td>
<td>2018</td>
<td>Scientific</td>
</tr>
<tr>
<td>Deb, Kalyanmoy</td>
<td>2018 Outstanding Conference Paper Award, IEEE Congress on Evolutionary Computation</td>
<td>2018</td>
<td>Scientific</td>
</tr>
<tr>
<td>Grant, Nkrumah</td>
<td>Rudolf Hugh Award, MSU Department of Microbiology and Molecular Genetics</td>
<td>2018</td>
<td>Scientific</td>
</tr>
<tr>
<td>Graves, Joseph, et al.</td>
<td>NCA&amp;T 2018 Research Award: Interdisciplinary Team Award</td>
<td>2018</td>
<td>Scientific</td>
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<tr>
<td>LaBar, Thomas</td>
<td>SMBE 2018 Young Investigator Travel Award</td>
<td>2018</td>
<td>Scientific</td>
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<tr>
<td>Lalejini, Alexander</td>
<td>Honorable Mention, Engineering Graduate Research Symposium Recognition for Outstanding Research</td>
<td>2018</td>
<td>Scientific</td>
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<tr>
<td>Laubach, Zachary</td>
<td>Dr. Marvin Hensley Fellowship, MSU Department of Integrative Biology</td>
<td>2018</td>
<td>Scientific</td>
</tr>
<tr>
<td>Lehmann, Kenna</td>
<td>MSU CNS Dissertation Continuation Fellowship</td>
<td>2018</td>
<td>Fellowship</td>
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<tr>
<td>Lehmann, Kenna</td>
<td>EEBB Summer Fellowship</td>
<td>2018</td>
<td>Fellowship</td>
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<tr>
<td>Lenski, Richard</td>
<td>Outstanding Supervisor Award, MSU</td>
<td>2017</td>
<td>Education-Related</td>
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<td>Lenski, Richard</td>
<td>Elected Member of the American Philosophical Society</td>
<td>2018</td>
<td>Scientific</td>
</tr>
<tr>
<td>Macias-Munoz, Aide</td>
<td>Hewitt Foundation for Medical Research Fellowship</td>
<td>2018</td>
<td>Fellowship</td>
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<tr>
<td>Maiden, Michael</td>
<td>Rudolf Hugh Award, MSU Department of Microbiology and Molecular Genetics</td>
<td>2018</td>
<td>Scientific</td>
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<tr>
<td>McGowan, Craig</td>
<td>Mid-Career Award, UI</td>
<td>2018</td>
<td>Education-Related</td>
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<tr>
<td>Miikkulainen, Risto, et al.</td>
<td>IAAI Deployed Application Award</td>
<td>2018</td>
<td>Scientific</td>
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<tr>
<td>Moberly, Robert</td>
<td>Shaver Award, MSU IBIO Department</td>
<td>2018</td>
<td>Scientific</td>
</tr>
<tr>
<td>Moberly, Robert</td>
<td>Summer Dissertation Continuation Fellowship, MSU</td>
<td>2018</td>
<td>Scientific</td>
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<tr>
<td>Moreno, Matthew Andres</td>
<td>NSF Graduate Research Fellowship Program Award</td>
<td>2018</td>
<td>Fellowship</td>
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<tr>
<td>Perofsky, Amanda</td>
<td>Summer Semester Continuing Fellowship, UT-Austin Graduate School</td>
<td>2018</td>
<td>Fellowship</td>
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<tr>
<td>Rojas, Connie</td>
<td>MSU Graduate School Research Enhancement Award</td>
<td>2018</td>
<td>Fellowship</td>
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<tr>
<td>Rojas, Connie</td>
<td>Alliances for Graduate Education and the Professoriate (AGEP) Scholar Award</td>
<td>2018</td>
<td>Fellowship</td>
</tr>
<tr>
<td>Rojas, Connie</td>
<td>MSU EEBB Summer Fellowship</td>
<td>2018</td>
<td>Fellowship</td>
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<tr>
<td>Slade, Joel</td>
<td>Animal Behavior Society, Allee Award - 2nd Runner Up</td>
<td>2018</td>
<td>Scientific</td>
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3. Undergraduate, M.S. and Ph.D. students who graduated during the reporting period

<table>
<thead>
<tr>
<th>Student Name</th>
<th>Degree</th>
<th>Years to Degree</th>
<th>Placement</th>
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<tbody>
<tr>
<td>Tanush Jagdish</td>
<td>Bachelors</td>
<td></td>
<td>Phd Student, Harvard</td>
</tr>
<tr>
<td>Amir H. Alavi</td>
<td>PhD</td>
<td>3</td>
<td>Asst Prof, University of Missouri</td>
</tr>
<tr>
<td>Carina Baskett</td>
<td>PhD</td>
<td>7</td>
<td>Postdoc, IST Austria</td>
</tr>
<tr>
<td>Rosangela Canino-Koning</td>
<td>PhD</td>
<td>7</td>
<td>Postdoc, Michigan State University</td>
</tr>
<tr>
<td>Colleen Friel</td>
<td>PhD</td>
<td>5</td>
<td>Postdoc, Michigan State University</td>
</tr>
<tr>
<td>Julia Greenberg</td>
<td>PhD</td>
<td></td>
<td>Government</td>
</tr>
<tr>
<td>Thomas LaBar</td>
<td>PhD</td>
<td>5</td>
<td>Postdoc, Harvard</td>
</tr>
<tr>
<td>Dacia Leon</td>
<td>PhD</td>
<td>5</td>
<td>Zymergen</td>
</tr>
<tr>
<td>Xun Li</td>
<td>PhD</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Aide Macias-Munoz</td>
<td>PhD</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Amanda Perofsky</td>
<td>PhD</td>
<td></td>
<td>National Institutes of Health</td>
</tr>
<tr>
<td>Aditya Rawal</td>
<td>PhD</td>
<td></td>
<td>Uber Technologies Inc.</td>
</tr>
<tr>
<td>Julie Turner</td>
<td>PhD</td>
<td></td>
<td>Postdoc, Memorial University, Newfoundland</td>
</tr>
</tbody>
</table>

4a. General outputs of knowledge transfer activities

*Patent Filed:* Dow Chemical Company has filed for a patent (September, 2018) with Kalyanmoy Deb and Erik Goodman (MSU) as co-patentees, entitled "Hybrid Machine Learning Model for Tariff Code Classification." The patent was generated from Deb & Goodman's Axia Institute project work on Tariff Classification jointly with Dow Chemical Company, Midland (funded during 2016-17).

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

<table>
<thead>
<tr>
<th>Organization Name</th>
<th>Organization Type</th>
<th>Address</th>
<th>Contact Name</th>
<th>Type of Partner</th>
<th>160 hours/ more?</th>
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</thead>
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<tr>
<td>1 Ford Motor Company</td>
<td>Company</td>
<td></td>
<td></td>
<td>KT</td>
<td>N</td>
</tr>
<tr>
<td>2 Metron</td>
<td>Company</td>
<td>1818 Library Street, Suite 600 Reston, VA 20190</td>
<td></td>
<td>KT</td>
<td>N</td>
</tr>
<tr>
<td>3 Continental Automotive GmbH</td>
<td>Company</td>
<td>Vahrenwalder Straße 9 30165 Hanover Germany</td>
<td></td>
<td>KT</td>
<td>N</td>
</tr>
<tr>
<td>4 General Motors</td>
<td>Company</td>
<td>PO Box 33170 Detroit, MI 48232-5170</td>
<td></td>
<td>KT</td>
<td>N</td>
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<tr>
<td>5 Dow Chemical Company</td>
<td>Company</td>
<td>S Saginaw Rd, Midland, MI 48640</td>
<td></td>
<td>KT</td>
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<tr>
<td>6 Hyundai MOBIS</td>
<td>Company</td>
<td></td>
<td></td>
<td>KT</td>
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<tr>
<td>7 Sentient Technologies, Inc.</td>
<td>Company</td>
<td>One California St., Suite 2300 San Francisco, CA 94111</td>
<td></td>
<td>KT</td>
<td>Y</td>
</tr>
<tr>
<td>8 Yale University</td>
<td>Other (Academic)</td>
<td>New Haven, CT 06520</td>
<td>Paul Turner</td>
<td>Research, Education, Diversity</td>
<td>Y</td>
</tr>
<tr>
<td>9 University of California, Irvine</td>
<td>Other (Academic)</td>
<td>Irvine, CA 92697</td>
<td>Adriana Briscoe</td>
<td>Research, Education, Diversity</td>
<td>Y</td>
</tr>
<tr>
<td>10 Spelman College</td>
<td>Other (Academic)</td>
<td>350 Spelman Ln Atlanta, GA 30314</td>
<td>Aditi Pai</td>
<td>Research, Education, Diversity</td>
<td>Y</td>
</tr>
<tr>
<td>11 SESYNC</td>
<td>Other</td>
<td>1 Park Place Suite 300 Annapolis, MD 21401</td>
<td>Mary Shelley</td>
<td>Research, Education</td>
<td>Y</td>
</tr>
<tr>
<td>12 iDigBio</td>
<td>Other</td>
<td>105 NW 16th Street Gainesville, FL 32611</td>
<td>Charles Ofria</td>
<td>Research, Education</td>
<td>N</td>
</tr>
<tr>
<td>13 International Society for Artificial Life</td>
<td>Other</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>14 National Association of Biology Teachers</td>
<td>Other</td>
<td>1313 Dolley Madison Blvd, Suite 402, McLean, VA 22101</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>15 Data Carpentry</td>
<td>Other</td>
<td>The Carpentries c/o Community Initiatives 354 Pine Street, Suite 700 San Francisco, CA 94104</td>
<td>Tracy Teal</td>
<td>Education</td>
<td>Y</td>
</tr>
<tr>
<td>16 Biological Sciences Curriculum Study (BSCS)</td>
<td>Other</td>
<td>5415 Mark Dabling Boulevard BSCS Building Colorado Springs, CO 80918</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>17 Concord Consortium</td>
<td>Other</td>
<td>25 Love Lane Concord, MA 01742</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 Society for the Study of Evolution</td>
<td>Other</td>
<td>4475 Castleman Avenue St. Louis, MO 63110-3201</td>
<td></td>
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<tr>
<td>19 Society for Systematic</td>
<td>Other</td>
<td></td>
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<tr>
<td>Biologists</td>
<td>Other</td>
<td>Education</td>
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<td></td>
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<tr>
<td>American Society of Naturalists</td>
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### 7. Summary table

<table>
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<th></th>
<th>Description</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>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.</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>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)</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>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</td>
<td>$1,504,079</td>
</tr>
<tr>
<td>4</td>
<td>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)</td>
<td>422</td>
</tr>
</tbody>
</table>
8.8. Media publicity

Press Releases


Media Coverage

- 8/31: PC Magazine: Ready for an AI platform that can make decisions on its own? https://www.pcmag.com/news/363155/ready-for-an-ai-platform-that-can-make-decisions-on-its-own
• 2/27: Communications of the ACM: Can neuroevolution change machine learning?
• 2/13: For the most complex technology problems, Stevens researcher turns to nature
  https://www.stevens.edu/news/business-gandomi-research-18
• 2/6: DMNews: Inside the system: Humans in the AI loop
• 2/5: Science Daily: Online tool speeds up evolution education
  https://www.sciencedaily.com/releases/2018/02/180205113043.htm
• 1/11: Science Magazine: Artificial intelligence can “evolve” to solve problems
• BBC Television: The first year of life (featuring Kay Holekamp)
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.

**Africa:** BEACON support helps Kay Holekamp and her collaborators train Kenyan graduate students, educate Masai women and students in local elementary schools in a rural area in southwestern Kenya, and give many talks each year to lay audiences in both the USA and Kenya. BEACON also facilitates maintenance of the field infrastructure needed to continue Holekamp’s very successful NSF-funded international REU training program for American undergraduates in Kenya. Current BEACON support also facilitates a collaboration that is helping to advance the career of an impressive young Ethiopian scientist, Dr. Gidey Yirga. Finally, BEACON support allows Holekamp’s group to continue working closely with film and print media in the USA and abroad. For example, author Sy Montgomery and photographer Nic Bishop have recently published an illustrated book for 5th-8th graders, featuring Dr. Holekamp and her long-term work with spotted hyenas entitled "The Hyena Scientist" as part of their Scientists in the Field series.

**Asia:** Two faculty members from China (Professor Lihong Xu, Tongji University and Meng Yao, East China Normal University) visited BEACON for extended periods in 2016-17, each funded primarily by the visitor's host institution or a grant from their government. During the reporting period, Prof. Xu's student, Chunteng Bao, spent time as a visiting scholar in BEACON, working with Goodman on developing a new non-dominated sorting algorithm (with a paper recently accepted) and on a novel multi-objective optimization algorithm employing separate diversity and convergence archives. Goodman continued to collaborate with last year’s visitor, Leilei Cao, on decomposition-based evolutionary multi-objective algorithms for dynamic optimization problems. Work continues with Prof. Xu and his group on the Greenhouse Control project. Goodman and Erik Runkle (MSU) and MSU grad student José Llera visited China in November, 2016 and Goodman visited again in November, 2017, to continue that collaboration with the project’s many members in China. Prof. Xu’s team is working with an experimental greenhouse at Tongji University’s Jiading Campus and a much larger one on ChongMing Island near Shanghai to test control algorithms developed by the team. Dr. Yuanping Su is also a visiting postdoctoral scholar at BEACON, working with Goodman, 2018-19.

To facilitate continuation of the extensive collaboration going on between 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. Goodman has visited to work with faculty members from Shantou University and Guangzhou University of Technology each year since, and visited again in November, 2017. This joint work has already resulted in numerous publications. Prof. Hailin Liu, Guangdong University of Technology, a collaborator on the project, was a visiting scholar at BEACON from May, 2015 through June, 2016, and returned to continue that visit in October, 2016. His Ph. D. student, Chaoda Peng, is a visiting scholar working with Goodman 2018-2020.

**Europe:** Lenski continues to collaborate with researchers in Grenoble and Paris, France, to characterize genetic changes in the long-term evolution experiment with *E. coli*. This collaboration led to a paper analyzing changes in the genomic features of bacteria that evolved...
ongoing work on using multi-objective evolutionary optimization for solution of land use problems is continuing, with Jonas Schwaab having worked at BEACON as a visiting scholar from ETH Zürich from October, 2015 through August, 2016. In 2017, his BEACON collaborators, Erik Goodman and Kalyanmoy Deb, met in Berlin with Schwaab and his faculty supervisors: Adrienne Gret-Regamey from ETH Zurich and Sven Lautenbach from the University of Bonn. They plan continue to collaborate with Deb and Goodman and their graduate student Amin Khiali-Miab, on this work. The first conference publication was done at GECCO 2017 and two journal publications have already been accepted, with another journal paper in preparation in fall, 2018.

Kalyanmoy Deb is also working with international collaborators in Denmark 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. Deb is also working with Sweden (University of Skovde and Volvo Car Company, Skovde) on improving the assembly line of a production system using multi-criterion optimization. A group of six researchers visited Deb at MSU for one week in December 2016 to discuss the research activities.

North America: Deb and Goodman also collaborated with a visiting faculty member on sabbatical from CINVESTAV (Mexico City), Prof. Gregorio Toscano, on techniques for visualization of results from many-objective optimization. A review paper surveying existing techniques has been prepared for publication, and work continues on papers describing new methods jointly developed during Toscano’s visit. In September, 2017, Lenski presented BEACON-related work in a pair of talks at McMaster University (Hamilton, Ontario), and this coming December, 2018, he will speak at an international conference on “Perspectives in Genomics” (Cancun, Mexico).

Shahryar Rahnamayan (University of Ontario Institute of Technology, Canada) visited MSU on a grant from his own university to work with Deb on evolutionary dynamic optimization, parallel evolutionary methods, visualization and opposition-based optimization methods, from August 2014 to July 2016. Goodman served as an external Ph.D. examiner for one of Rahnamayan’s students in 2017.

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)
X. BUDGET

Attachments:

1. Current Award Year: Summary budget table reflecting NSF funding for whole Center (headquartered at MSU), followed by additional sheets for individual sites (NCAT, UI, UT, UW)
2. Unobligated funds: statement of funds and plans for use
3. Requested Award Year: Proposed total budget, and individual budgets for each subcontract
4. Center Support from all sources
5. Breakdown of Other NSF Funding
6. Cost Sharing
7. Additional PI Support
2. Unobligated Funds

We anticipate carrying over $564,985 into the next funding period, which is 11.3% of our total award for the current period. These funds will be used to continue funding for graduate students and postdocs, and to continue the support of research and education projects that are already underway.
### 4. Center Support from All Sources

<table>
<thead>
<tr>
<th>Award Source</th>
<th>Current Award Year</th>
<th>Requested Award Year</th>
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<td><strong>Award Source</strong></td>
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<td>Other NSF</td>
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<tr>
<td>Industry</td>
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<tr>
<td>University</td>
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</tr>
<tr>
<td>Other: Undergraduate Research support</td>
<td>$385,049</td>
<td></td>
</tr>
<tr>
<td>Other: Tri-Society support of education &amp; outreach activities</td>
<td>80,000</td>
<td>80,000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$6,504,079.00</td>
<td></td>
</tr>
</tbody>
</table>

*Other NSF:* In 2016, BEACON received an NSF supplement in the amount of $169,030 for “Supplemental Funding for Workshops for Developing Professional Skills for the Biotech Industry” to begin in academic year 2016-2017. This program is ongoing and some funds remain unspent.

*Industry:* Reported funds are from joint projects with Ford Motor Company, General Motors, and Dow Chemical Company. We do not yet know what funds will be contributed in the next funding period.

*University:* Institutional commitment by MSU: $550,000 per year.

*Undergraduate research support:* Collectively in 2018, BEACON spent $290,522 and secured $385,049 in leveraged funding to support 247 students. These funds supported 167 undergraduates, 30 high school students and 50 middle school students in robust STEM learning/research opportunities. Amounts contributed from each partner university are as follows: MSU, $134,584; NCAT: $115,000; UI: $2,900; UT: $127,500; and UW: $5,065. We cannot yet know how many funds will be available for these efforts next year.

*Tri-Society Support:* Funds are from the American Society of Naturalists, The Society for the Study of Evolution, and the Society for Systematic Biology, and are available annually.

### 5. Breakdown of Other NSF Funding

- In 2016, BEACON received an NSF supplement in the amount of $169,030 for “Supplemental Funding for Workshops for Developing Professional Skills for the Biotech
Industry” to begin in academic year 2016-2017. This program is ongoing and some funds remain unspent.

6. Cost sharing

The budget for BEACON’s renewal grant does not include any cost sharing from the university, as none was required for the reward. Therefore, we have none to report in this section.
7. Additional PI Support from All Sources

<table>
<thead>
<tr>
<th>Award Source</th>
<th>Current Award Year</th>
<th>Requested Award Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cash ($)</td>
<td>In-kind</td>
</tr>
<tr>
<td>NSF</td>
<td>1,256,064</td>
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</tr>
<tr>
<td>Other Federal Agency</td>
<td>150,000</td>
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</tr>
<tr>
<td>University</td>
<td>192,500</td>
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<tr>
<td>Private Foundations</td>
<td>546,000</td>
<td></td>
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<tr>
<td>International</td>
<td>17,537</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>$2,162,101</td>
<td>162,101</td>
</tr>
</tbody>
</table>

These amounts are approximate annual amounts from total awards, based on the following information:


Lenski, R. E. MSU Hannah Professorship Endowment. Total Award Amount: $130,000 per year.

Lenski, R. E. CNRS/France. Evolution in Action with Living and Artificial Organisms. 1/2015-12/2019. Total Award Amount: €15,000 per year ($17,537 as of 9/17/18).

Ofria, C. NSF. The evolutionary origins of multicellularity and development in experimental populations of digital organisms. 8/2017-7/2020. Total Award Amount: $683,920.


Pennock, R. T. Howard Hughes Medical Institute 52008102. LEVERS: Leveraging Engagement and Vision to Encourage Retention in STEM. 2014-2019. Total Award Amount: $2,500,000.
APPENDIX A

BIOGRAPHICAL INFORMATION FOR NEW FACULTY MEMBERS

None to report.
BEACON Executive Committee
PI’s, Institutional & Industrial Linkages, Crosscutting Themes, EHRD, Diversity
Lenksi, Ofria, Pennock, Holekamp, Goodman, Cheng, Punch, Pierre, Getty, Kerr, Foster, Miikkulainen, Graves

BEACON Director
Goodman
Deputy Director Ofria
Management Team
Managing Dir. (Whittaker), Ed. Dir. (Mead), Diversity Dir. (Brown Clarke), IT (Schmidt), Business Mgr (James). Accounts Mgr. (Zubek)

EHRD Steering Committee
Chair: Getty. Education Dir. (Mead), Diversity Dir. (Brown Clarke), Assessmnt. (Libarkin) & Mentoring (Jackson) Leads; Partners’ EHRD Coordinators

Diversity Steering Com.
Chair: Pierre. Diversity Dir. (Brown Clarke), Leads from Partner Universities

Industry Relations
Mgr: Cheng

MSU VP Research & Grad Studies

External Advisory Comm.

Diversity Initiatives: A Universal Responsibility Permeating the Center
Genomes, Genetic Architectures & Evolvability
Thrust Group 1
Leads: Waters (Bio) & Banzhaf (Comp)

Behavior & Intelligence
Thrust Group 2
Leads: Holekamp (Bio) & Pennock (Comp)

Ecological Communities & Collective Dynamics
Thrust Group 3
Leads: Dyer (Bio) & Adami (Comp)

Evolutionary Applications
Thrust Group 4
Leads: Barrick (Bio) & Deb (Comp)

Cross-Cutting Themes: Biological Evolution (Lenksi)
Computational Evolution (Punch)
Multidisc. Training (Ofria, Mead, Hintze, Adami); Education/Outreach (Getty)
RCR/Future Faculty/Pdoc Devel/Mentoring (Pennock/Jackson); BEACON Fellowships (Torng)

Team Members
Michigan State University
Mgr: Miikkulainen
Ed. Coord: Wilke
Div.Proj. Liaisons

U. Texas Austin
Mgr: Miikkulainen
Ed. Coord: Wilke
Div.Proj. Liaisons

Univ. of Washington
Mgr: Kerr
Ed. Coord: Swalla
Div. Proj. Liaisons

N. Carolina A&T
Mgr: Graves
Ed. Coord: Graves
Div. Proj. Liaisons

University of Idaho
Mgr: Foster
Ed. Coord: Soule
Div. Proj. Liaisons

Internal Assessment Team
Farrell-Cole, Amey
Multi-Disciplinary Training
O’Rourke, Pennock
The BEACON Congress took place 8 – 11 August 2018 at the Kellogg Hotel and Conference Center at Michigan State University. The leadership of BEACON provided the advisory committee with their annual report, with responses to our report from last year, and with information on their progress over the year.

As in the previous years, BEACON continues to astound in the creativity of the research, their ability to attract additional funding, their productivity, and their cross-disciplinary novelty. The courses across the fields for students and other interactions across the universities and across the departments are of particular interest.

The advisory committee was impressed not only with the numbers of underrepresented minorities given BEACON opportunities, but also with the climate and culture affirming the importance of diversity to everyone. We are also very impressed with BEACON’s education efforts, at the universities and also at national meetings. The education efforts are led by professionals in the field. In this area in particular we are impressed that BEACON is developing how-to manuals on becoming as supportive in education and diversity as they have succeeded in being.

BEACON now has two more years to go; a major challenge will be keeping the benefits of BEACON at all the institutions once the NSF funding has ended. Michigan State University has guaranteed $1,000,000 a year for five years, until 2025, something that is unchanged even given recent challenges in funding at MSU. The adjustments in staffing and reallocation of summer salary supplements are already being planned for, so there will be no surprises for the year after BEACON. As we noted last year, the other partner institutions also have commitments for continuing support, in a number of cases through programs that are campus-based but affiliated with BEACON. The leadership hopes that joint projects from different universities will maintain the synergy of cross-university work. There are also concrete plans for the outreach efforts of BEACON to continue.

One of the strengths of BEACON has been an apparent and perceived balance among very different action plans. All of them look to be thriving in the annual report which we were
provided. But the plan for behavior and cognition was less evident than the others at the 2018 BEACON conference. It is also true that some of the research areas that might be done with a variety of organisms tend to be done with microbes or to a lesser extent, plants, not animals. This is not a criticism but is something BEACON leadership might want to look at as it considers funding requests in the remaining years.

Perhaps our biggest concern this year is in the actual study of what has made of difference. In the coming two years, we hope that BEACON will increase and generalize its study of whether its interventions are successful.

First, are the REU programs successful? BEACON has successfully engaged large numbers of undergraduates in research experiences. The quality and impact of these experiences should be assessed and compared to those of comparable populations. One approach would be to employ the SURE III, which is an NSF-funded Survey of Undergraduate Research Experiences (SURE III). The SURE-III Survey intends to collect quantitative data on the benefits of undergraduate research (Lopatto, 2004a, 2004b; see: https://www.grinnell.edu/academics/areas/psychology/assessments/sure-iii-survey). Data can be disaggregated and compared to other programs, which is not possible with locally developed questionnaires (which often lack validation).

Second are the interdisciplinary courses successful? BEACON has developed several innovative, interdisciplinary courses designed to build bridges across disciplinary boundaries. Currently, data are lacking on the efficacy of BEACON’s interdisciplinary courses. The evaluation of the interdisciplinary courses would benefit from (1) specification of measurable learning objectives (e.g., “understand” is not measurable); (2) collection of pre-post course data; (3) analysis of outcomes to determine impacts and limitations. Currently, data are lacking on the efficacy of the interdisciplinary courses.

Third, have the efforts towards diversity actually increased it in the field? BEACON serves as an important role model for enhancing diversity within the field of evolutionary biology and cognate fields. Given that BEACON has built strong and effective collaborations with the Society for the Study of Evolution, the Center could help facilitate rigorous documentation of the state of diversity within the discipline compared to other biological fields. Sponsoring data collection efforts (e.g., by funding individuals to encourage conference participants to complete surveys; raffle for prizes for completing web surveys) are often needed to obtain representative samples.

Fourth have the outreach activities made a difference? Outreach activities form an important part of BEACON’s mission. The past few reports have candidly acknowledged the difficulty of obtaining data on the utility, delivery, and impact of outreach activities. Innovative data collection methods should be considered, such as purchasing a large clicker set to take to outreach events and ask several questions of participants (by individuals who did not deliver the outreach). Such data sources have limitations, but they would provide a first step in assessing impact.
We recognize that some of these documentation efforts might be challenging, but hope that BEACON can make progress in all four of these directions.

Overall, it has been a pleasure to serve as advisors for such an outstanding program and we hope that BEACON leadership takes very seriously our recommendation last year to provide the community with a how-to become like BEACON short of cloning Erik Goodman.
APPENDIX D

MEDIA MATERIALS

None to report.