

BEACON Center for the Study of Evolution in Action
An NSF Science and Technology Center
Strategic and Implementation Plan
(updated November 2018)

EXECUTIVE SUMMARY

The BEACON Center for the Study of Evolution in Action is an NSF Science and Technology Center founded 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 partner institutions of 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 the synergistic 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.

In this updated Strategic and Implementation Plan, we present **Goal Statements** for six areas: Education, Human Resources, and Diversity (EHRD), Leadership and Management, Knowledge Transfer, Integrative Research, Ethics, and Research Output. For each goal, we have identified two to six **Optimal Outcomes**, and we measure our progress towards these outcomes using Specific, Measurable, Attainable, Relevant and Time-Bound (**SMART**) **Targets**. For each Optimal Outcome, we also identify potential **Barriers** to Success, and the **Mitigating Actions** we are taking to overcome these barriers. For each Mitigating Action and additional specific **Actions** relevant to each Outcome, we identify who serves as a **Point of Contact**, and the **Due Date** for the action.

Summary of Goals. 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 collaborators who will support the sharing of knowledge and application of new technology on real-world problems. BEACON's **Integrative Research Goal** is to produce transformative, synergistic research through an inclusive collaborative culture that crosses disciplinary and institutional boundaries and is embedded throughout the Center's activities. BEACON's **Ethics Goal** is to practice and promote ethical and responsible research by implementing cross-disciplinary and multi-institutional ethics programs that will inform and guide all participants of the Center. BEACON's **research output goal** is to disseminate widely an increasing quantity of original and highly regarded scientific research on evolution in action.

BEACON's first five years produced remarkable achievements that have often exceeded the goals of our original strategic plan. Nonetheless, important lessons were learned about ways to improve our operations and new knowledge transfer directions became relevant, with implications for our structure and strategic plan. Some were reflected in our earlier annual updates to our strategic plan, and others were captured in the revised strategic plan for the second five-year period. In the current revision, we have made only minor changes.

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

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

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

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

EDUCATION, HUMAN RESOURCES, AND DIVERSITY PLAN

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. We are approaching this goal in two ways: by educating a diverse new generation of interdisciplinary scientists and engineers, and through education and outreach to the K-16 community and the general public. BEACON will contribute to 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.

EHRD Optimal Outcome 1: Multidisciplinary Ph.D. graduates and post-docs placed in faculty positions in line with averages across engineering, computer science, and biology. BEACON provides multidisciplinary training for graduate students and post-docs, and works to increase their visibility in biology and computer science disciplines. BEACON graduate students come from many departments, colleges and partner universities, each with their own disciplinary requirements and benchmarks. BEACON does not supersede these, but operates instead as an interdisciplinary enrichment program.

We are accomplishing this outcome through an integrated **sequence of courses** to prepare graduate students for this new multidisciplinary research. These courses are now available at all five partner institutions. In the fall semester, new engineering and computer science students take evolutionary biology, while biology students take a course in computational science; each group learns evolutionary theory and application from the perspective of the other. These courses have been taught at MSU every year since BEACON's inception (CSE 801 – Computational Science for Evolutionary Biologists; ZOL 890-601 – Evolutionary Biology for Non-Life Scientists). These courses are also offered simultaneously at multiple partner institutions (UI, UT, UW) using distance learning technology. In line with broadly training our graduate students and maximizing the impact of these courses, we continue to respond to user and consortium needs. BEACON graduate students and postdocs serve as co-instructors or teaching assistants for both courses, and gain valuable professional development experience.

The spring semester course (Interdisciplinary Research Methods with Evolution in Action) brings computational and engineering students together with biology students. As part of the course, students form multidisciplinary teams, under the joint supervision of computer science and biology faculty. Graduate students learn to use state-of-the-art tools to conduct their research and to facilitate long-distance collaboration across partner institutions, and often their research leads to publications.

To facilitate the placement of a new generation of interdisciplinary scientists, BEACON must not only train these individuals but also promote them within traditional fields. We are accomplishing this goal by nominating BEACON students and scientists for awards and leadership positions within traditional disciplines (evolutionary biology, computational biology, computer science, engineering, etc.), and also by increasing BEACON-sponsored participation within society meetings (e.g., the annual Evolution meetings) and by hosting society

workshops/meetings at BEACON or co-organizing such meetings at other locations.

We provide resources and training in professional development for our graduate students. The BEACON Congress now includes a day-long retreat for our graduate students and postdocs. Graduate students are also taking advantage of programs across our campuses such as the FAST Fellows (Future Academic Scholars in Teaching) program at MSU.

We continue to raise the prominence of BEACON within the computer science community by sponsoring BEACON booths, where we highlight BEACON participants, accomplishments and opportunities, at the two largest conferences in the field, the ACM's Genetic and Evolutionary Computation Conference (GECCO) and the IEEE's Conference on Evolutionary Computation (CEC) (biennially a part of the World Congress on Computational Intelligence) since 2012. The resulting high visibility in the community may be a factor in the decision of a genetic programming pioneer to donate to BEACON the funds to create the John R. Koza Endowed Chair in Genetic Programming at Michigan State University, now held by Dr. Wolfgang Banzhaf. Since 2015, BEACON has also sponsored booths at the ALife Conference and its sister conference, the European Conference on Artificial Life (ECAL), which are held in alternating years. In 2017, BEACON also had booths at the Evolutionary Multiobjective Optimization conference, which BEACON will host in 2019, and at the EvoStar Conference (which includes EuroGP, the European Conference on Genetic Programming).

We will measure our progress towards this outcome by tracking the *number of BEACON graduate students and post-docs receiving offers of positions that integrate their interdisciplinary training*, to include positions as tenure track faculty, postdoctoral researcher, industrial researcher, K-12 STEM education specialist, faculty administrator, science communication specialist, or advocate/political activist.

EHRD Optimal Outcome 2: Exceed national norms for diversity at all levels in 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. This accomplishment transcends the perfunctory goals of just increasing the number of diverse participants, to the demonstration of a more thoughtful culture that embodies diversity within its research lab opportunities, grant submissions, broader impacts efforts, educational outreach activities, formal mentoring training/support, fellowships, and direct student support funding.

With over 600 members, BEACON participants are: 53% White, 24% Black, 10% Asian, 5% Hispanic/Latino, 1% Native American, and 7% two or more races/ethnicities. Currently 37% of participants are self-reporting as URMs, which is well above the National Norm (30.8%). BEACON's strategic efforts to increase overall female participation across all levels has resulted in 43% of BEACON participants being female, higher than the National Norms of 32.8%. Finally, 6.4% of BEACON participants self-reported as having a disability, also exceeding the National Norms (3.3%). Furthermore, a BEACON grad student has recently assumed the top leadership role in the MSU SACNAS group, so we are not only working to enhance diversity of our members but also to support their development as leaders.

The subsequent “stretch goal” of sustaining these numbers will be reached by ensuring our environments supports and advances inclusive participation throughout BEACON and with our collaborative partners. Individuals with disabilities are a continued priority within our strategic efforts. To address the challenge of under-reporting, BEACON continues to develop a Disability Action Plan, which is tasked with establishing a climate of safe, inclusive, and adaptive environments for individuals with disabilities to thrive. BEACON is revising and updating 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 Native American Initiatives.

We continue to collect data on the *numbers or percentages of faculty, post-docs, graduate students, undergraduate participants, that are from underrepresented demographic groups*, including women, underrepresented ethnic groups, and people with disabilities. We regularly solicit feedback from the *External Advisory Committee* to get an objective assessment of our progress towards this goal.

EHRD Optimal Outcome 3: Increased literacy in evolution and the nature of science.

BEACON’s focus on *evolution in action* and pragmatic applications of evolutionary science puts us in a unique position to overcome common misconceptions about evolution and to demonstrate both its scientific significance and its practical and economic utility.

BEACON is developing tools and materials for education, such as the ongoing redevelopment of Avida-ED, development and implementation of evolutionary games (both within the gaming community as well as in museum exhibits) in addition to new and creative outreach activities. We have worked with multiple public learning institutions and outreach, including the US Science and Engineering Festival, MSU Museum, the Texas Natural Science Center, and the Seattle Aquarium to offer these interactive exhibits, learning opportunities, and undergraduate research opportunities. All tool and material development goes through a rigorous process of vetting by content and grade-level specialists and we are working with educational research partners to evaluate and assess the effectiveness as identified in our goals.

Avida-ED. Our digital evolution education software Avida-ED is now moving forward with the next major step in its development and dissemination. A multi-case national classroom assessment study of Avida-ED showed that students not only increased their understanding of evolution, but also their acceptance, which is a novel and promising result. As a follow up, we conducted our first controlled study of the use of Avida-ED in two sections of an introductory biology course at MSU, and are beginning more detailed national studies. We continue to develop new model curricula and offer pedagogy workshops and talks on Avida-ED at national professional meetings (Artificial Life, Bioquest, Society for the Study of Evolution, National Association of Biology Teachers, National Association for Research in Science Teaching, Society for the Advancement of Biology Education Research). Pennock’s spin-off HHMI grant allowed us to hire a dedicated programmer, and we completed recoding Avida-ED 3.0 as a cross-platform browser-based application, which was released in 2017. We are now working on version 4.0, which will allow students to investigate mechanisms connecting evolution and ecology. The HHMI grant also covered a graduate student who is helping to develop and test new model exercises tailored to the learning goals of gateway biology courses at MSU. A second

Avida-ED grant (Pennock, Smith, Mead, Lenski and Ofria) was also received in 2015 from the NSF IUSE program that is funding a five-year development, assessment and national dissemination effort. We have held six national train-the-trainers faculty development workshops, with about 18 participants each time, and will hold two more this year.

We have also taken over a number of outreach events that were been previously organized by the National Center for Evolutionary Synthesis (NESCent). These are now co-sponsored by BEACON and three scientific societies (Society for the Study of Evolution, Society for Systematic Biology, and American Society of Naturalists). All these efforts focus on increasing diversity and bringing educational materials to a national audience, continuing our outreach to the entire evolution education community. Goals of all our education and outreach are to deepen students' understanding of evolutionary mechanisms and applications (from evolution of anti-biotic resistance to evolutionary engineering), and to help them better understand the nature of science and learn to protect the integrity of the scientific process.

EHRD Optimal Outcome 4: An increased interest in evolution-related careers in both academia and industry. As a Science and Technology Center focused on interdisciplinary research dealing with evolution in action, we can provide programs and learning opportunities that show students options and prepare them for such careers.

BEACON is introducing students and teachers, especially from underrepresented groups, to the new opportunities afforded by BEACON's applied evolutionary tools and research programs. Examples of programs that support this goal are the Summer Research Opportunity Program (SROP) and the BEACON Research Experiences for Undergraduates (REUs) at Kellogg Biological Station and Friday Harbor Laboratories. BEACON also has education and outreach graduate RAs to interact with teachers and scientists to develop K-12 content.

We will measure our progress toward achieving this outcome using *pre- and post-program survey instruments* to assess the proportion of participants expressing interest in evolution-related careers. These surveys will be administered to groups participating in our programs. Our goal is to generate a significant increase in interest among participants in our programs.

LEADERSHIP AND MANAGEMENT PLAN

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.

External Advisory Committee Charter: BEACON shall appoint, with approval of the NSF Program Officer, an External Advisory Committee with membership exhibiting diversity in disciplines and in gender and race/ethnicity. The EAC will meet annually to provide guidance, oversight and advice regarding all BEACON activities, consistent with its vision, goals, and objectives. The EAC will be provided appropriate documentation about center activities, achievements and policies, and have the opportunity to interact with a broad cross-section of BEACON membership. The EAC will annually provide BEACON management a report including both formative evaluation for management and summative evaluation for use of NSF personnel and site visitors.

L&M Optimal Outcome 1. Increase in cross-disciplinary research and education. Historically, true interdisciplinary research and education has been hampered by field-specific terminology, methodology, and traditions, but especially by a lack of communication. BEACON is overcoming this barrier by facilitating communication among scientists, cross-training a new generation of graduate students, and encouraging the submission of interdisciplinary publications and proposals for funding. Technological systems for finding collaborators/mentors/students and tracking outputs and RCR training were put in place in December 2010 and refined throughout 2011, which greatly facilitates collaboration.

We have developed three measures to monitor our progress with this outcome:

- *Number of paper/conference submissions by BEACON authors.* In the short term, we aim to have 20 submissions/year on interdisciplinary research by BEACON authors; in the long term we anticipated at least 100 accepted peer-reviewed publications by October 2015. This long-term goal is already being met annually.
- *Number of students enrolled in cross-disciplinary courses.* Our goal is 10 students per academic year enrolled in the BEACON graduate course sequence. As described in the next outcome, we are also measuring *number of participants in BEACON-organized cross-disciplinary short courses.*
- *Number of funding proposals submitted.* Our goal is for 10 multi-disciplinary research proposals to be submitted to outside funding sources per year in the short term and 15 per year in the long term. BEACON has met the long-term goal annually since 2012.

L&M Optimal Outcome 2. Increase in cross-institutional research and education. In addition to increasing collaboration across disciplines, BEACON will work to increase collaboration across the five partner institutions. The primary barrier to collaboration is the difficulties inherent in long-distance communication. The BEACON Center is equipped with videoconference facilities, and BEACON has established a culture of collaboration to encourage sharing of Center resources.

Progress toward this outcome will be measured in the following ways:

- *Number of inter-institutional paper/conference submissions.* In the short term, we aim to have 20 submissions/year by BEACON authors from multiple institutions; we anticipate at least 100 accepted peer-reviewed publications over the first five years, and at least 30 submissions per year in the next five years (with at least 150 accepted). BEACON made steady progress toward this goal in the initial years, exceeding 30 annual submissions every year since 2013.
- *Number of inter-institutional courses and workshops.* Three courses were introduced in the first year. Our original long-term goal was to offer an average of one additional course to be offered every other year. However, inter-institutional courses present a large range of logistical problems (especially since some of BEACON's partners are on the semester system while others are on the quarter system). BEACON received two NSF funding supplements for "Materials and Workshops for Cyberinfrastructure Education in Biology" (led by Drs. Titus Brown and Tracy Teal). This funding has allowed BEACON to partner with SESYNC, NESCent and others to offer intensive cross-disciplinary short courses not only at BEACON institutions, but also around the world. This series of workshops led to the founding, under the leadership of Dr. Tracy Teal, of a new not-for-profit organization called DataCarpentry.org to offer these workshops and to train the trainers to allow the workshops to be widely offered. Dr. Teal serves as the organization's Executive Director. While initially supported by BEACON and the NSF supplements, the organization has now received financial support from the Gordon and Betty Moore Foundation, in a grant administered through BEACON. We believe that these short courses are meeting some of BEACON's most fundamental goals, and will do so very effectively over the long term.
- *Number of students in BEACON's cross-institutional, cross-disciplinary courses.* The original goal was 20 students per academic year in the short term, and a cumulative total of 100 across 5 years. As with the above goal, we revised this goal to more closely match the numbers of new students enrolling each year, and to account for the fact that an increasing number of new graduate students already have an interdisciplinary background in biology and computer science (e.g., students who were involved in BEACON undergraduate research). Our current goal is 10 students per academic year in these courses, and a total of 100 students per year in the cross-disciplinary short courses organized by BEACON faculty.

L&M Optimal Outcome 3. Increase in new funding sources (cross-disciplinary and cross-institutional). BEACON research funds are intended as seed money to stimulate new thinking, encourage new interdisciplinary and inter-institutional research, and to generate pilot data for new proposals for external funding.

We will measure this outcome through *number of submissions*, with a goal of 20 proposals submitted per year, and *award dollars*, with a short-term target of \$5 million per year and a long-term target of \$10 million per year. BEACON began meeting the long-term target in 2011, and has received over \$10 million in external funding every year since then. The primary barrier to continuing to achieve this outcome is the *pre-existing* lack of communication across disciplines. One consequence of this barrier is that researchers are not aware of research and funding opportunities in other disciplines. Sessions are held at BEACON congresses to allow participants

to brainstorm research problems; congresses have been held every summer since 2010 and have resulted in many new collaborations and projects.

L&M Optimal Outcome 4. Increase in new participants. BEACON's initial strategic plan emphasized a goal of adding participants to BEACON. However, BEACON's success in that regard exceeded all expectations, exceeding the targets for 2015 during 2012. While a large membership is desirable, it also represents a dilution in available resources per participant, which has a negative impact. Adding participants is no longer a significant goal—rather, we seek to increase the interdisciplinarity, diversity and academic distinction of our participants, as addressed by other elements in this strategic plan. We will continue to encourage students and postdocs to advance through a succession of BEACON institutions (e.g., grad students at one institution doing a postdoc at another).

To attract stellar new participants, BEACON implemented the Distinguished Postdoctoral Scholars program in early 2012, a competitive fellowship that brings in one new interdisciplinary postdoc a year, for a two-year fellowship. BEACON also developed a Faculty Affiliate Program to attract diverse faculty at other institutions, appointing one new Faculty Affiliate per year with an initial two-year grant of \$100,000. These programs have now been phased out in anticipation of our decreasing funding levels in our final years of STC funding. However, two of our Faculty Affiliates and their laboratories are still active in BEACON. BEACON now has a Student/Postdoc group to address student concerns, give students representation on BEACON committees, create a sense of community and attract and retain students. Finally, the BEACON website is regularly updated with press releases, blog posts, and announcements about ongoing research and opportunities.

L&M Optimal Outcome 5. Effective support of Center operations by Management team. To determine whether Center participants feel the Management Team is effectively supporting Center operations, Drs. Patricia Farrell and Marilyn Amey conducted the second formative organizational evaluation throughout 2012, a more in-depth evaluation in 2013, and a follow-up survey in 2014, all of which generated many concrete recommendations for improvement. Some of these were already being addressed by the management team, but others have resulted in new programs, revised procedures, etc. Ongoing evaluation is continuing in Phase 2 to ensure progress, including a Social Network Analysis completed in 2016 to understand the flow of information and resources among BEACON partners. In 2017, the focus of the evaluators has turned to BEACON's legacy, in an effort to identify the key aspects of BEACON that should be maintained post-STC funding. In 2018, the evaluators studied the career paths of BEACON alumni and the role of BEACON in stimulating interdisciplinary research.

L&M Optimal Outcome 6. Center is perceived by NSF as exemplary. BEACON has the potential to become an exemplary STC. We will *track the number of public mentions made by NSF* about BEACON. Our goal is two significant mentions per year, which has been easily met each year so far. The Director will take the lead in ensuring that NSF is continually kept informed of significant BEACON accomplishments. In 2016, the Director reported on BEACON's accomplishments in broader impacts to the Association of Public and Land Grant Universities. We will also position BEACON to continue to thrive after the second phase of NSF funding, making clear the full value of this substantial investment.

KNOWLEDGE TRANSFER PLAN

Industry has made extensive use of biologically-inspired computing tools, including artificial neural nets, genetic algorithms, genetic programming, agent-based modeling, differential evolution, swarm computing and artificial immune systems. Sample areas of application of evolutionary tools include data mining and symbolic regression, control of dynamic systems, combinatorial optimization for 2- and 3-D layout, plant floor scheduling, vehicle routing, and single- and multi-objective optimization for product design. BEACON's **Knowledge Transfer goal** is to develop effective mechanisms and pathways to facilitate intellectual exchanges among BEACON partners and industry that will support the sharing of knowledge and generation and application of new technology. While BEACON's initial knowledge transfer plan envisioned establishing a membership-type Industrial Affiliates Program, the experience of the first three years of BEACON operation revealed:

- 1) Several companies are interested in sponsoring BEACON projects to explore or demonstrate the applicability of BEACON technologies to their real-world problems, and some have already begun to do so,
- 2) None of these companies is interested in joining a consortial program such as an Industrial Affiliates Program. Instead, each is free to arrange the type of relationship (contractual or otherwise) that suits their purposes and is acceptable to BEACON (generally through one of its member universities).
- 3) Some companies do not wish to publicize their involvement in a particular area of research as they view it as information that is of use to their competitors. They may be willing to provide challenge problems and either proprietary or "sanitized" data to BEACON researchers, but may not want to be joint authors on publications using that information.
- 4) Similarly, some companies may wish to make use of BEACON-developed tools, but not to acknowledge that use to their competitors. Therefore, BEACON must use evidence such as willingness to continue participating in joint research with BEACON as evidence of the benefit being obtained by industry, and to use more generic measures such as number of downloads as evidence of the general usefulness of the tools created by BEACON.

Therefore, BEACON revised its Knowledge Transfer Plan in 2013 to eliminate the Industrial Affiliates Program and to focus instead on relationships with individual companies or other organizations, reformulating measures to take into account the lessons above.

Although BEACON had generated a generic Intellectual Property agreement designed to govern the operation of an industry/university consortium, at this point, this generic agreement is not being used. Of course, BEACON's existing agreement governing treatment of Intellectual Property among BEACON's member universities remains in place. BEACON's Industrial Affiliates Manager, Prof. Betty Cheng, was renamed its Manager of Industry Relations.

KT Optimal Outcome 1. Establishing collaborative research relationships with industrial sponsors. Reaching an agreement on contracts and grants involving research sponsorship and development of intellectual property can be challenging, but some BEACON participants have had previous success in this area, and can work to overcome a given company's inhibitions

concerning collaborating with universities by advising Center participants who are considering collaborations with industry.

We will track our progress toward this outcome through three measures:

- a) the *number of external industry/government laboratory collaborations with BEACON through its member universities*. Our goal is to add one significant industrial collaboration per year during the renewal phase,
- b) the *number of joint grant proposals submitted with industrial partners*. Our goal is to submit at least one per year,
- c) the *number of publications submitted that arise from industry-provided challenge problems and data* (per Optimal Outcome 2 below) or are submitted jointly with industrial partners. Our goal is to submit at least two per year.

KT Optimal Outcome 2. Industry-provided challenge problems (i.e. “Real World” problems) and data with feedback. Instead of working with “toy problems,” BEACON aims to work on real problems with real data provided by industry. In early stages of a relationship with a company, rather than working with proprietary data, we will ask that the company provide “sanitized” data that will allow us to provide a real solution to a real problem, without requiring the company to disclose any proprietary information. We will measure our progress by the *number of instances that challenge problems, data, and feedback are received from industry partners*. Our goal was to receive two challenge problems from industry by October 2011, a total of at least five by October 2013, and two per year in following years. These goals were met to date, including, at MSU, 5 challenge problems from automotive companies, one from the Air Force/BAE, and an autonomous vehicle challenge from Northrup Grumman. Partner University of Idaho has received one in traffic/disaster management. BEACON’s Manager of Industry Relations will help overcome potential industry partners’ skepticism about the benefits of providing such challenge problems by showing demonstrable results from prior collaborations as part of ongoing communication with industry. However, this numerical goal shall be reduced by one for each instance of a signed contract or grant under KT Optimal Outcome 1 above, because more rapid progress on that outcome supplants the need for instances of Optimal Outcome 2.

KT Optimal Outcome 3. Spinoffs formed. Another optimal outcome of successful knowledge transfer to industry will be the formation of companies based on BEACON work. Our measurement of success will be the *number of spinoffs formed*. The target is to form the initial spinoff(s) within the first 10 years of the Center’s existence. Deciding when IP is suitable for commercialization and knowing how to get started are the main barriers to this goal, and BEACON can point people to appropriate resources (e.g., incubator offices) and organize seminars as part of the BEACON Congress meetings. The initial session designed to make BEACON members aware of how to collaborate with industry was organized in summer 2013 by the Manager of Industry Relations, as a sandbox session at the BEACON Congress. Several BEACON members described their industrial relationships, how they were initiated, and advised attendees on pitfalls and approaches to avoiding them.

INTEGRATIVE RESEARCH PLAN

BEACON's **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.

IR Optimal Outcome 1. New research collaborations and proposals. We track the *number of interdisciplinary/multi-institutional research publications and proposals*: Over 40% of BEACON publications are interdisciplinary and about 35% are inter-institutional as of 2018. Our goal is to at least maintain these impressive numbers throughout the second phase of BEACON funding. Similarly, approximately 2/3 of research proposals are interdisciplinary and about 1/3 are inter-institutional. Our goal was to raise these numbers from their previous levels to match those of our publications, and this goal was met as of 2016.

Building and coordinating research across geographically dispersed teams can be quite difficult. The Thrust Group and Cross-Cutting Theme Leaders will work continually to ensure more face-time and fewer emails among participants, to allocate travel funds for building relationships among participants, and to coordinate seminars between partners. Engaging graduate students and post-docs in interdisciplinary research can also be challenging, as these trainees tend to be closely connected with a single lab and unaware of training opportunities outside of their advisers' disciplines. BEACON students and post-docs will be required and encouraged to spend time acquiring skills in laboratories outside their disciplines. Faculty advisors in BEACON will play key roles in assisting these participants in finding opportunities.

An important tool in facilitating integrative research was the Toolbox workshops, developed originally at the University of Idaho (<http://www.cals.uidaho.edu/toolbox/>). These workshops encouraged researchers to communicate about the philosophical basis of scientific research, help collaborators identify and examine research assumptions, and are ultimately designed to increase mutual understanding in interdisciplinary research. The PI and principal developer of the ToolBox instruments, Michael O'Rourke, moved from University of Idaho to Michigan State University, in Fall 2012, and has since partnered with Robert T. Pennock, a BEACON co-PI, to extend the scope of these workshops into ethical issues by linking them to Pennock's Scientific Virtues Project (see Ethics Optimal Outcome 2 section below).

IR Optimal Outcome 2. New paradigms for research in organic and digital domains. BEACON is pioneering the study of evolution in action using a model that joins biological evolution, digital evolution, and evolutionary applications, to their mutual benefit. In contrast, traditional "disciplinary" scientific meetings typically feature one of these areas, but not the others. BEACON will seek to organize meetings or new sessions that expose each of these audiences to the relevant work of the others.

We will measure our progress by tracking *the number of new sessions at scientific meetings or scientific meetings hosted at BEACON* (BEACON participants will submit proposals to scientific societies for workshops or symposia or to organize conferences related to Evolution in Action by October 2013 – goal met), *the number of new journals and societies*, and *new or increased funding for biocomputational research*.

In service of this outcome, BEACON, in 2012 and again in 2013, requested and received supplemental funding from NSF to organize workshops at BEACON and to coordinate their offering at multiple other NSF STC and Synthesis centers, under the leadership of BEACONites C. Titus Brown and Tracy Teal. These workshops train biologists in a variety of computational tools useful for study of genomics and evolution. Each of these workshops was oversubscribed—that is, more people applied than could be accommodated. The success of these workshops led to the founding of a new not-for-profit organization, DataCarpentry.org, with Dr. Tracy Teal as its Executive Director. In addition to initial funding from BEACON, the Data Carpentry organization has received a sustaining grant from the Gordon and Betty Moore Foundation, administered through BEACON. Between January, 2015 and November, 2016, Data Carpentry ran 52 workshops with a total of 1,100 trainees, in ten countries. EDAMAME (Explorations in Data Analysis for Metagenomic Advances in Microbial Ecology), a workshop aimed at training biologists how to analyze metagenomic microbial data, began in the summer of 2015 and has been repeated annually, led by Dr. Ashley Shade, with assistance from Dr. Teal. This week-long workshop is held at Kellogg Biological Station and has trained about 20 participants per year (the maximum that can be accommodated) in metagenomic analysis. To encourage other BEACON participants to spend time developing symposia for scientific meetings, short courses, etc., the Management Team and other BEACON faculty will ensure that assistance and support is provided by BEACON administration and by colleagues with shared or complementary interests. In order to try to increase multi-disciplinary and multi-institutional publications, the Education Director and faculty participants will encourage grad students and post-docs to participate in biocomputational courses and rotate through laboratories outside their own disciplines.

IR Optimal Outcome 3. Increase in publications related to evolution in action. We will track the *number of papers published by BEACON participants*. Our aim was for the *number of publications* by BEACON members to have increased over the baseline set in the first year of operation by 10% by October 2013 and by 30% by October 2015; the 2015 goal was already met by October 2013. Our revised goal is to increase our number of publications each year by 10% over the previous year. We will also track *the number of media references to BEACON*. In addition, we had also set the goal that by October 2013, at least one new multi-institutional/interdisciplinary result should be covered in a high-visibility outlet such as the New York Times or the Discovery Channel. BEACON research is now regularly featured in outlets such as the National Geographic website, NPR, Scientific American, and many other popular news sources.

Currently, the public media has a resistance to covering evolutionary topics. The Managing Director and the Education Director will work to emphasize the utility of studying evolution in action by facilitating communication with the public. Specifically, the Managing Director maintains a blog on the BEACON website featuring posts by students and postdocs describing their research in an accessible way, and uses social media (Facebook, Twitter) to publicize BEACON work. The Managing Director also assists BEACON faculty with producing press releases and works with the University Relations office to distribute the press releases and attract publicity. The Education Director coordinates with NESCent to help increase visibility for the Center.

To increase the coverage of biocomputation in the media, the Director, Managing Director, and Education Director will identify key individuals and venues through which to pitch biocomputational evolution in the popular science media. Science journalists may be invited to BEACON congresses.

IR Optimal Outcome 4. Development and dissemination of new curricula and resources to train multidisciplinary scientists in evolutionary biology and computational evolution. As part of BEACON's mission, we will develop new materials for training multidisciplinary scientists, including upgrading Avida and Avida-ED. We will distribute these materials within and beyond BEACON.

To measure our progress, we will track the *number of requests for information*. Our target was for downloads of Avida/Avida-ED to increase over the baseline set in the first year by 30% by October 2013, a goal that has been met. Beginning in August 2016, Avida-ED 3.0 switched to a browser-based platform, so we no longer measure application downloads. Instead we have begun to track web-page hits. In its first year Avida-ED 3.0 was accessed 14,331 times; during 2018, it was accessed 20,441 times. During 2010-2011, BEACON developed a research-based course and modules. By October 2012, internal dissemination among BEACON partners was achieved. Our ongoing focus is on external dissemination, and we will continue to track how many users contribute feedback, request information, or attend workshops.

ETHICS PLAN

BEACON's **Ethics Goal** is to practice and promote ethical and responsible research by implementing cross-disciplinary and multi-institutional ethics programs that will inform and guide all participants of the Center.

Ethics Optimal Outcome. Center participants will understand shared and discipline-specific practices of Responsible Conduct of Research (RCR) and will embody general scientific norms/virtues, including curiosity, honesty, objectivity, integrity, community, and transparency. The Graduate School at MSU currently uses a combination of online training and face-to-face mentoring through CAFFE (Center for Academic and Future Faculty Excellence). All partner universities have their own RCR training programs in compliance with NSF requirements. In previous versions of our Strategic Implementation Plan, we stated that BEACON would track the *percent completion of department- and university-specific RCR training requirements by participants*, to ensure that all participants complete training requirements. This tracking has proven to be extremely difficult to implement successfully, as each university, department, and program has their own requirements, their own tracking systems, and their own timelines. That is, although all the units require annual compliance of their students and postdocs, there is no single time of year when compliance can be checked across all the units. We had also stated that we would track the resulting *change in frequency of ethics violations*. As of November 2016, zero ethics violations by BEACON members have been reported. As a result, we are shifting our goal and our action items in this Optimal Outcome to focus on providing RCR training opportunities to BEACON members, rather than attempting to track external activities. We will now track the *number of RCR training opportunities provided* and the *number of people who attend BEACON RCR trainings*.

In 2013, Co-PI Pennock gave a series of presentations on the scientific virtues and their relationship to Responsible Conduct of Research (RCR) at the regular BEACON group meetings. These served as a pilot test of the virtues-based approach to RCR training that he is developing. Dr. Pennock and Toolbox project leader Dr. Michael O'Rourke are collaborating to develop and test Toolbox-style models that focus on the virtues that are central to the scientific character. Since 2013, they have offered several workshops every year focusing on curiosity, the purpose of science, honesty, courage, and humility to evidence for BEACON Congresses and Friday seminars. We continue to collect data from these workshops to improve our curriculum and to see how participants view this approach; in Fall 2017 a paper reporting on the very positive results was accepted for publication in *Science & Engineering Ethics*. In 2014 Pennock received a \$1 million Templeton Foundation grant to fund a national study of exemplary scientists to see how well this new ethical approach matches the values scientists actually hold, and those results will be published shortly. Pennock's book on the topic—*An Instinct for Truth*—will be published by the MIT Press in May 2019. Pennock and Michael O'Rourke have developed responsible conduct of research (RCR) training modules based on the core scientific virtues that combine this approach with O'Rourke's Toolbox structured dialogue model. They pilot test these workshops at BEACON and recently published data showing that participants strongly prefer this approach over traditional methods of RCR training. MSU is now funding them to test an extension of this approach for graduate students in the humanities. These projects aim to

transform the way we think about and teach RCR, and we are now looking to disseminate this beyond BEACON as a national model.

Faculty, students, and post-docs at MSU gather at a weekly BEACON meeting to discuss research progress and to have a social hour, every Friday at BEACON headquarters and are joined via videoconferencing by members at all partner universities. Graduate students, postdocs, and faculty members from all BEACON institutions give 30- or 60-minute presentations on their work. While participants in BEACON-funded projects are expected to give at least one presentation per funded year, all BEACON members are encouraged to present their BEACON-related work whether funded or not. We also regularly host visiting speakers from other institutions that present research of interest to BEACONites. Students and faculty at partner institutions participate in the research discussions by videoconference and are encouraged to replicate the social hour at their own institutions. Such activity encourages the development of a BEACON community. We will track the *number of BEACON seminars held each year*. These community-building activities in connection with the Scientific Virtues project help to foster shared norms and virtues.

RESEARCH OUTPUT GOAL

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

Research Output Optimal Outcome 1. Original research by BEACON members on evolution in action will be prominent in the evolution literature. Our progress toward this goal will be measured by *the number of publications in peer-reviewed journals, presentations at scientific conferences, and grant proposals submitted*. Our ongoing goal is 150 publications, 150 conference presentations, and 40 grant proposals submitted per year in the first two years. These goals were not met in 2011 – likely due to underreporting by BEACON members – but have been met annually since then. Our original goal was to increase these numbers by 50% by October 2015, which has been achieved already for conference presentations and grant proposals. At the beginning of phase 2 of BEACON funding, we set a goal to double the original numbers. However, our membership size has stabilized, and although we know that our members are quite productive, we have observed a continued trend of underreporting. Therefore, we are revising our goal to maintain the current levels of reported output.

Research Output Optimal Outcome 2. BEACON research output will be perceived as making an important contribution to the literature. We will measure our progress towards this goal by soliciting *feedback from the External Advisory Committee*, who will provide an objective view of our progress.