**Accomplishments**

*What was done? What was learned?*

What are the major goals of the project?

With the first direct detection of gravitational waves, the advanced Laser Interferometer Gravitational-wave Observatory (aLIGO) has initiated a new field of astronomy by providing an alternate means of sensing the universe. As the most sensitive and most complicated gravitational experiment ever built, aLIGO is susceptible to a variety of instrumental and environmental sources of noise. Of particular concern are noise features known as *glitches*, which are transient and non-Gaussian in their nature and thus difficult to model. A robust characterization of glitches is paramount in the effort to achieve the gravitational-wave detection rates that are allowed by the design sensitivity of aLIGO, though this proves a daunting task for members of aLIGO alone due to the sheer amount of data.

The (recently renamed) Gravity Spy project aims to address this problem through the convergence of four science areas: gravitational physics, human­-centered computing, machine learning (ML), and citizen science. Specifically, our goals is to leverage citizen science and machine- and human-learning techniques to design a socio-­computational system with which to analyze and characterize aLIGO glitches and improve the effectiveness of gravitational-­wave searches.

To address this overarching objective, each group in this interdisciplinary endeavor aims to answer field-specific goals. In the case of gravitational wave physics, this project strives to provide an efficient, reliable, and comprehensive system for aLIGO glitch classification. In addition, this project looks to improve aLIGO detector characterization and can help create lists of times that have poor, non-astrophysical data (known as data quality vetoes) by which we can improve searches for gravitational waves. Finally, this project can lead to the discovery new aLIGO glitches that arise as the detector evolves. The isolation of these glitches in the data and removal of their causes within the detector will improve the detector performance and aid the search for gravitational waves.

For the field of human-­centered computing, this project attempts to utilize citizen scientists for a non-­routine task, i.e. developing novel classifications for phenomena such as aLIGO detector noise, in a new and innovative way. This includes designing tasks to leverage the distinctive strengths of both humans and machines, while maintaining human engagement and learning.

This project will also lead to new methodologies within citizen science and machine learning by implementing new routines to ‘train’ volunteers and integrating machine learning into the citizen science process. Specifically, we aim to develop a unique tool to combine active machine learning and citizen-science input to create an adaptable hybrid noise-rejections system for data-rich projects. Through this tool, Gravity Spy will investigate learning algorithms that include multiple annotators, i.e. the people who label the glitches, who have varying expertise and skill. Finally, this project sets out to test and compare performance of different machine learning classification algorithms, such as simple Support Vector Machine (SVM) models and complicated Deep Neural Network models.

Through the cutting-edge research in gravitational-wave physics, machine learning, citizen science, and social science, Gravity Spy will leverage the strength of both humans and computers in a symbiotic relationship to develop a superior classifier for aLIGO detector noise, while pushing the research frontiers of each individual research group.

**What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

**Major Activities**

In order to achieve the overarching, interdisciplinary goals of this project, the first step was to create a platform with which to learn how each discipline viewed their role within the project, the specific goals each discipline looked to accomplish, and the necessary steps needed to integrate each discipline into a fully-functioning system. In addition, the group set up and managed many platforms for communication, including yearly face-to-face meetings, weekly working calls, and a shared software repository. The major activities for each discipline over the first year of the Gravity Spy project are as follows.

The contributions from members of the LIGO Collaboration at Northwestern University’s Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and California State University, Fullerton consisted of data preparation and project infrastructure, designing the Gravity Spy user interface and workflows, and a first effort at using Gravity Spy results to improve aLIGO detector characterization. In order for citizen scientists to visualize aLIGO glitches in an accessible way, a pre-existing spectrogram-generation software was redesigned to fit the specific needs of Gravity Spy. This included the rewriting of the software in Python, defining new colormaps and thresholds on glitch properties, and redocumenting the code in an iPython notebook. Following this, the generation of large, labeled datasets of glitches to ‘train’ initial ML algorithms proved a daunting task, as the state of the detectors during the first aLIGO observing run was a fluid process. These *training sets* were created first by morphological classifications from the Gravity Spy team, and bolstered by initial machine learning results. Over many iterations, a robust training set was generated, and will be used with the first iteration of the Gravity Spy public launch. In addition, preliminary steps were designed to streamline the processing of Gravity Spy data back to the aLIGO collaboration. These steps included the setup and maintenance of a single server to host, process, and deliver data in an effective way. In addition, these members led the design and development of the Gravity Spy website, which is the direct interface between the project and human volunteers. This project was built using the Zooniverse Lab utility, and included tutorials, background material in gravitational-wave physics, FAQ pages, and multiple workflows for various user skill-levels. Site functionality was maintained during beta-testing of the project, and extensive feedback from many beta-users was implemented into the site. Furthermore, LIGO members of the Gravity Spy team addressed questions and fostered hundreds of conversations on the Gravity Spy talk forum. Lastly, initial infrastructure has been designed to feed the categorized glitches into Hierarchical Veto, an existing algorithm for removing poor data quality from LIGO data, in order to target those specific glitch classes and identify auxiliary channels in LIGO that may be able to veto them.

In order to answer the important question of training volunteers in non-trivial morphological classification, collaboration members from the School of Information Studies at Syracuse University designed training regimes for volunteers. To design these regimes, the team reviewed literature on human learning of image classification to design an effective training approach for volunteers. To document a user’s experience with the Gravity Spy website, the team developed system requirements in the form of user stories (i.e. short descriptions of a user’s ideal interface, including their desired system functionality and their reasoning for participation in citizen science). The Syracuse team interviewed one “super user” of the beta site to understand the process of identifying novel glitch classes, providing insight to the wants and needs of users that partake in the project. Gravity Spy also requires the tracking of volunteer classifications to assess the performance of individual users. Using these assessments, images can be fed more effectively to volunteers for classification and the retirement of images from the project will be optimized. The Syracuse team developed an approach for tracking volunteer performance to accomplish such a task. Lastly, the Syracuse team planned experiments to assess approaches for training and motivating volunteers to participate in the Gravity Spy project, and identified data collection needs to support human-centred computing research.

The Zooniverse team, based at the Adler Planetarium and Oxford University, implemented many features to heighten the user experience on the Gravity Spy site and integrated the many components of the Gravity Spy project into the Zooniverse infrastructure. These include:

* Prototyped and tested several versions of the human-classification task, including creating the survey task tool which was ultimately used
* Designed, developed, and launched the first stage of Gravity Spy, including the classification interface, discussion forum, and content pages
* Implemented the ‘tutorial’ functionality to provide clear instructions to volunteers participating in Gravity Spy
* Implemented the ‘field guide’ functionality to support providing deeper-dive content information about the different glitch classes
* Implemented the ‘skip summary’ option to increase efficiency in the classification task
* Implemented improved ‘collections’ functionality to support more sophisticated discussions of images and collections of images within the discussion forum
* Implemented an improved data export for the Gravity Spy team to more easily obtain the raw classification results
* Helped in the design and planning for the training interventions for the human-classification task
* Created the initial foundation for the code infrastructure to support the training interventions for the human-classification task
* Developed the infrastructure and provided support for the Northwestern LIGO team to directly upload data into Gravity Spy
* Developed the infrastructure to include ‘gold standard’ glitch data (i.e. expert-classified examples of glitches), which provides feedback to volunteers and data for the human-classification task
* Developed the infrastructure for feedback to be provided to volunteers based on whether they correctly or incorrectly classify gold standard glitch data
* Developed the initial infrastructure to be able to track different cohorts of volunteers participating in experiments within the Gravity Spy interface

Lastly, the team at Northwestern University’s Image and Video Processing Laboratory (iVPL) contributed by developing and implementing ML algorithms to classify images of aLIGO glitches used in the Gravity Spy project and a Bayesian crowd-source classifier algorithm for tracking user responses and skill level. The group applied support vector machines (SVMs) to training sets provided by LIGO collaborators, testing the training set against itself with techniques such as cross-fold validation to obtain the optimal values for tunable hyper-parameters of the model. The team proceeded to design a convolutional neural network algorithm and apply this algorithm to the training sets. This model is more appropriate and scalable for big data scenarios. The group then experimented with different deep neural networks for different fusion levels (i.e. using multiple renderings of the same glitch as input data to ML), and tested these algorithms on the training set. These advanced ML algorithms will be used and interfaced with Gravity Spy during year two of the project. In conjunction with the Syracuse team, the iVPL team developed a complimentary crowdsourcing classifier that takes the ML results and citizen labels of images as input and decides the retirement of images, future images to be shown to an individual user, and whether an individual user is to be promoted to more advanced workflows.

**Specific Objectives**

See above.

**Significant results**

In the first development year, the Gravity Spy team launched two Beta versions of the Gravity Spy website. Beta-testing of the website culminated in the discovery of multiple new and substantial glitch categories from aLIGO’s first observing run, including glitches which would later receive the names Paired Doves and Helix. During beta-testing alone, the website had over 1200 registered users and over 37,000 glitch classifications, fostering hundreds of conversation threads on the website’s talk forum. Furthermore, public launch coinciding with the commencement of aLIGO’s second observing run in late August/early September 2016 will see the creation of the first Zooniverse promotion-based volunteer training regiment.

**Key outcomes or Other achievements**

See above.

**What opportunities for training and professional development has the project provided?**

As this project is interdisciplinary, it has been invaluable in opening all members to new ways of thinking as well as developing a robust set of communication skills. Specifically, this project has affected its members professional development in the following ways.

At Syracuse, the project provided training and professional development for one post-doctoral researcher, Tae Kyoung Lee. Dr. Lee participated in all of the activities of the project: literature reviews, developing research plans and an experimental design, developing the system architecture and preparing publications. At the end of June 2016, Dr. Lee left the project to take a position as an Assistant Professor at University of Utah. Additional, in July 2016, a new doctoral student joined the project, Mahboobeh Harandi. Ms. Harandi has started participating in project meetings and reading the literature. In the rest of the summer, it is planned for her to engage in participant observation in various citizen science communities to develop an understanding of their functioning.

In the Northwestern CIERA group, Post-Baccalaureate Research Fellow Scott Coughlin advanced as a software developer by leading the design and implementation of the underlying algorithms of the project. In addition, Coughlin also gained experience by becoming the system administrator of the local Gravity Spy server. Through this process, Coughlin became more familiar with database software such as MySQL and understanding the inner workings of web servers. In addition, Doctoral student Michael Zevin designed initial ML algorithms for glitch classification and contributed to the various coding necessities of the project, which provided him further background in python coding and implementation of ML. Zevin oversaw the design of the Gravity Spy website, which has provided the opportunity to hone communication and outreach skills through a citizen science infrastructure. Zevin presented multiple talks and posters on Gravity Spy, further promoting his science communication skills. Both Zevin and Coughlin took on leadership responsibilities within Gravity Spy by organizing and running the weekly meetings and by taking the role of primary collaboration editors for the Gravity Spy Methods paper (in prep). Finally, the Gravity Spy project enabled the teaching of rudimentary Python coding to a team of four summer students (2 undergraduates, 2 high schoolers). Summer students also participated in the active discussions during the weekly Gravity Spy meetings, promoting communication skills within a scientific working group.

For the Northwestern iVPL group, doctoral students Neda Rohani and Sara Bahaadini applied State Vector Machines to do initial classification. Afterwards, they started reading the literature of deep neural networks as needed for big data scenarios. They learned different packages used in deep learning area such as “theano”, “lasagne” and “keras”. Designing different neural networks helped them improve their coding skills in Python. They will submit a conference/journal article reporting their work. All these skills are invaluable in the pursuit of a PhD in machine learning. In addition, the project allowed doctoral student Emre Besler to model a classifier that accomplishes the task of fusion of Machine Learning results and citizen labels. He made a survey of different fusion methods in literature and with the help of Rohani and Bahaadini, developed an algorithm that processes ML and crowdsourcing data, and gives decisions about the images and the citizen scientists accordingly. Besler coded the whole algorithm in MATLAB, which helped him develop his knowledge of data processing. He will submit a conference paper regarding the fusion methods and the results in the future.

At Cal-State Fullerton, undergraduate student Isa Patane has begun a project to take the output categorization from Gravity Spy and use that to tackle one of the major goals of the project, “to help create lists of times that have poor, non-astrophysical data (known as data quality vetoes) by which we can improve searches for gravitational waves” In particular, Isa will use the Gravity Spy categories as an input to the Hierarchical Veto algorithm, already in use for LIGO, to better target specific glitch classes. In preparation for this, Isa learned Python programming (through Codecademy) and Unix in order to understand the data preparation framework set up by Coughlin and Zevin (Northwestern). Isa has now begun setting up infrastructure to feed the categorized glitches into Hierarchical Veto.

**How have the results been disseminated to communities of interest?**

Results were disseminated to the associated scientific communities in a variety of ways. At least one member of the Gravity Spy team participated in the weekly aLIGO detector characterization meetings and would occasionally give updates and reports. Members of the aLIGO detector characterization team, both inside and outside the Gravity Spy collaboration, participated in the discussion forums on the Gravity Spy site, providing immediate feedback to user questions and comments on their analysis. Coughlin introduced Gravity Spy the the aLIGO collaboration at the LIGO conference in March 2016. Zevin presented a poster on the Gravity Spy project at Northwestern’s Computational Research Day in April 2016, and was awarded 1st place in the poster competition. In addition, Zevin gave a presentation showcasing the methodology of the Gravity Spy project at the summer 2016 AAS meeting. Smith and Zevin helped disseminate information on Gravity Spy while running the LIGO booth for several hour-long blocks at that same meeting. Coughlin will introduce the Gravity Spy full public launch at the LIGO-Virgo Collaboration conference in August 2016. In addition, the group has been asked to take part in a piece about the Gravity Spy project in Symmetry Magazine.

Outside of the physics community, results about citizen science have been disseminated through discussion with the researchers and developers of the Zooniverse project. The project has resulted in one conference submission describing the approach for tracking volunteer performance on the offered training tasks, and has been reported in the local press. Lastly, an article reporting the methodology behind the ML Deep Neural Networks algorithm and its results using data from the first observing run is in preparation.

**What do you plan to do during the next reporting period to accomplish the goals?**

During the next year, the Gravity Spy team proposes to accomplish the goals listed above in the following manner.

CIERA collaborators plan to further integrate the results of the Gravity Spy project with aLIGO detector characterization, in addition to their work in building and advancing the Gravity Spy Zooniverse website and its machine-learning algorithms. The CIERA team will also carefully help maintain and evolve the Gravity Spy project as aLIGO progresses through future observing runs. Finally, the team hopes to improve upon the automated process of transporting glitches from the aLIGO group to the Gravity Spy project and back to the aLIGO group.

Maintaining the Gravity Spy project and website

* Updating the classification workflows as new glitch categories arise in upcoming aLIGO observing runs
* Participating in and maintaining the talk forum on Gravity Spy
* Adjusting workflows parameters (e.g. for retirement, user promotion, etc.) based on feedback from initial users
* Implementing user feedback on the general structure and flow of the Gravity Spy site

Integrate Gravity Spy results with aLIGO detector characterization

* Low-latency output of Gravity Spy glitch images and ML confidence to incorporate into aLIGO daily detector characterization summary pages
* Improve the speed and method of the delivery of questionable glitches from the Gravity Spy project to experts within aLIGO detector characterization
* Making training sets and machine learning confidence scores from Gravity Spy available and easily accessible to other groups within the aLIGO collaboration

Software Development

* Continued development of iPython notebooks explaining the science and processes behind the Gravity Spy project
* Total automation of all software aspects of the Gravity Spy project (i.e. all steps of the project from the rendering of glitches as spectrograms to providing results to the aLIGO detector characterization group from the Gravity Spy project)

Syracuse collaborators will work on the second phase of the project, namely design and development of a system that enables volunteers individually and as teams to develop new classes of glitches, with support from the machine learning classification and possibly from analysis of other data channels from aLIGO.

Analyze year 1 outcomes

* Profile participants
* Plan surveys and interviews to understand participant engagement in and learning from the system
* Examine volunteer activity in Talk (ditto)
* Track interaction of research team with volunteers and effects of the interactions
* Experiment with different recruiting messages
* Experiment with different volunteer training regimes

Design and implement systems to support discovery of new glitch classes

* Create user focus groups to understand needs of advanced users to discover novel glitch classes
* Gather requirements for new glitch classes from aLIGO
* Design system functionality to support clustering
* Plan experiments and data collection to analyze clustering performance

The Northwestern iVPL group will work on some advancements regarding novelty detection and the capabilities of the crowdsourcing classifier. More specifically, the algorithm will be modified in a way that it can detect and create new glitch classes when there is indeed an image that belongs to a new class, instead of labeling all unidentified images as “none of the above”. Furthermore, clustering techniques will be introduced to the different classes of citizens and the decisions will be taken accordingly.

Analyze year 1 outcomes

* Image classifier output
* Crowdsourcing classifier output

Design and implement clustering algorithms to detect new glitch classes

* Study literature of clustering algorithms using deep neural networks
* Design a deep neural network to support clustering and detect new glitch classes
* Introduce a novel algorithm for the clustering of the citizen decisions and modifying the crowdsourcing classifier accordingly

Finally, the Cal-State Fullerton members will work on updating and improving the golden set of glitches and the field guide for new glitch categories that are identified by volunteers. Particularly, new types of glitches that are found in the second observing run of aLIGO need to be addressed and implemented into the Gravity Spy project (we expect new glitches to arise because the interferometers will be operating with increased power, and with new hardware and configurations).

* Undergraduate Patane and Smith will use the Gravity Spy categories to create vetoes for times of poor data quality in LIGO, and help to identify the sources of certain classes of glitches
* They will work with Zevin and Coughlin to create a budget of LIGO’s glitches so that the categories can be seen as “pie pieces” and work can be prioritized (in the LSC) toward identifying causes for and fixing the most numerous types (in addition to the types most strongly affecting LIGO’s flagship astrophysical searches)
* Smith and Patane will engage (further) with the Gravity Spy citizen scientists through “Talk” and communicate insights back to the LSC detector characterization group and vice versa

**Impact**

*What is the impact of the project? How has it contributed?*

**What is the impact on the development of the principal discipline(s) of the project?**

*Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research and/or pedagogical methods in the principal disciplinary field(s) of the project.*

The project is inherently multidisciplinary and so makes contributions to multiple areas of research.

For the gravitational wave community, this project has revolutionized the way the community thinks about categorizing and finding new glitches during the scientific observing runs. A consistent problem with detector characterization is the combination of a lack of personpower with the overwhelming amount of glitches that occur in the detectors. This project provides the solution to this problem and will free the detector characterization team to do more intensive follow ups of glitches instead of trying to find new ones. In addition, this project inherently bolsters labeled sets of glitches for the training of machine learning algorithms, which will in turn provide a more complete classification analysis of glitches from the aLIGO datastream. The other innovation this project provides gravitational wave physics with increased public awareness and interest, complementing the public excitement over the monumental discoveries of the past year.

For the Computer-Supported Cooperative Work (CSCW) community, the contribution is to the knowledge base around online communities, and citizen-science communities in particular. We are exploring ways to scaffold the classification task (i.e., to provide support for a new volunteer) in order to provide training to new volunteers. If this approach is successful in retaining volunteers and improving the quality of their contributions, it will contribute to our understanding of learning and motivation in this form of online community. The work will also have practical value, as the approach will likely be of interest to other citizen science projects.

A particular innovation in the current planned approach is using machine learning to select training images, rather than using only expert-classified images. As a result, volunteers being trained can make real contributions to the project even during the training period, potentially increasing the efficiency of the project. However, this improvement comes at the possible cost of providing inappropriate materials for training if the machine learning classification is incorrect. Exploring the tradeoffs between efficiency and training effectiveness will be another contribution to our understanding of citizen science in particular and to learning in online settings more generally.

**What is the impact on other disciplines?**

*Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.*

Interactive learning systems

* The approach developed for tracking the performance of the volunteers during training is based on work in interactive learning systems, but extends those models to account for the uncertainty of machine learning selected training images. The resulting model could be of interest in the original field of interactive learning systems.

**What is the impact on the development of human resources?**

*Describe how the project made an impact or is likely to make an impact on human resource development in science, engineering, and technology.*

Syracuse

* The project has contributed to the training of a post-doctoral researcher and PhD student.

Northwestern CIERA

* This project has contributed to the academic and research training of post-baccalaureate researchers, graduate students, undergraduates, and high school students.

Cal-State Fullerton

* This project has contributed to the academic and research training of undergraduate students (at a primarily undergraduate and Hispanic-serving institution).

**What is the impact on physical resources that form infrastructure?**

*Describe ways, if any, in which the project made an impact, or is likely to make an impact, on physical resources that form infrastructure, Including physical resources such as facilities, laboratories, or instruments.*

N/A

**What is the impact on institutional resources that form infrastructure?**

*Describe ways, if any, in which the project made an impact, or is likely to make an impact, on institutional resources that form infrastructure,*

N/A

**What is the impact on information resources that form infrastructure?**

*Describe ways, if any, in which the project made an impact, or is likely to make an impact, on information resources that form infrastructure,*

Labeled glitch images, currently provided by the analysis of the Gravity Spy team and in the future provided by citizen scientist classifications, are an information resource that are of interest to other researchers because they offer large datasets with which to train classification algorithms.

Development of the Gravity Spy project has also resulted in a platform for teaching gravitational-wave physics and gravitational-wave searches to new members of the LIGO group at Northwestern, which could potentially be used at other institutions as well.

**What is the impact on technology transfer?**

*Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use.*

The Gravity Spy project is being implemented on the Zooniverse project builder platform, meaning that the techniques being developed for integrating volunteer training, user classifiers, and ML are potentially available to many other projects (which emcompases a wide variety of citizen-science projects) that use that platform.

**What is the impact on society beyond science and technology?**

*Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world.*

Even in its beta status, the project has engaged more than 1200 citizen science volunteers, providing them with an entrée into the field of gravitational-wave astronomy. This approach of directly connecting the public with scientific data has been shown time and again to increase interest in STEM fields, and inspire younger users to pursue STEM careers. Moreover, the volunteer training regime that this project introduces may lead to the creation of more citizen science projects for groups who believed that a research or “big data” project may be “too challenging” to have citizen feedback in.

**Changes/ Problems**

**Changes in approach and reasons for change**

None

**Actual or Anticipated problems or delays and actions or plans to resolve them**

The original project plan called for the system to go live in this summer, but the date has been moved back to correspond to the aLIGO’s start of data collection in the next engineering run. The exact date has yet to be set, but we are planning to be ready in September 2016. We intend to do a “quiet” launch in September and to have the public launch with a wave of publicity when the engineering run starts.

**Changes that have significant impact on expenditures**

Syracuse

* The Syracuse project plan originally called for hiring one doctoral student, but with NSF approval, these funds were used instead to hire a postdoctoral researcher.  However, owing to a delay in the postdoc starting at Syracuse and her success in finding a tenure-track faculty job earlier than anticipated, our expenditures for the postdoc were less than budgeted, leaving a small carry-over. These funds will be used to pay a second student to work on the project in the 2nd year.

Northwestern CIERA

* The Northwestern plan called for the hiring of one postdoctoral researcher, but instead the funds were used to hire a Post-Baccalaureate Research Fellow, Scott Coughlin.

**Significant changes in use or care of human subjects**

Syracuse

* As anticipated in our original IRB application, IRB approval for the project is being amended to include the planned experiments.

**Significant changes in use or care of vertebrate animals**

Nothing to report

**Significant changes in use or care of biohazards**

Nothing to report