Design and implementation of a scalable authentic-research education program for Artificial Intelligence and Science

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Abstract

We report a program designed to bring authentic research experience to machine learning and science students at scale. Our design addresses common barriers to such efforts and should allow students and faculty from other universities to implement similar programs with ease. With support from a faculty member, students form a group. The group contains several teams working on independent projects in a consulting type of arrangement with research labs in natural sciences. Each team comprises students with complementary skills (in AI, science, and leadership). Labs provide the data, and the teams work on the discovery, design, and development of an AI solution. A student leadership team manages the student group. This team interviews applicants, forms other teams, sets up standards for operations, fosters collaborations, and ensures the continuity of multi-semester projects. To date, this group has run for three consecutive semesters and has engaged more than forty students, ranging from first-year college students to master’s candidates. This effort has resulted in over a dozen successful collaborations with academic and industry partners.

Machine learning education in classroom settings often revolves around the use of exercises that have already been explored thoroughly by more experienced practitioners, such as building a classifier for the MNIST dataset. This provides a controllable environment for educators with which they can administer these exercises on the scale of a classroom or cohort. However, while such exercises can be a beneficial introductory experience for students, the fact that solutions to these exercises have already been made and are readily available means that they are of limited value in providing students with more in-depth expertise in the field, as students are often only expected to replicate prior work done by more experienced practitioners.

A similar issue exists in the natural sciences, where the majority of labs are taught using a “cookbook approach”, in which an instructor is providing all the steps which students have to follow, thus not developing their own experience of the research process, which is a basis of science.
Studies evaluating approaches designed to submerge students into an active research process found a significant improvement in students’ science literacy [3], and graduation rates (both with any degree and with STEM degrees in particular) [5]. ‘Authentic research education’ (AREd) is one of the ‘flavors’ of the active learning education family (one can find such terms as ‘authentic learning’, ‘inquiry-based learning’, ‘authentic inquiry’, ‘research-like experience’, ‘authentic-research’, etc.) and is one of the hardest to implement. Spell et al. [4] surveyed hundreds of biology faculty members and found common themes in various definitions of AREd:

• Process of science: student is engaged in practices to build around steps and methods in traditional research.
• Novel questions: the answer to such questions are unknown, and may not even exist.

Many implementations of AREd (including those done by one of the authors of this manuscript before [7, 6]) are often non-scalable. Spell et al. [4] identified common barriers for AREd implementations. We generally agree with the finding, but will categorize them somewhat differently and will add an additional factor of “sufficient time for project execution”. Table 1 lists barriers that have to be addressed while designing AREd programs that can scale and thus lead to wider adoption of AREd methodologies.

| Student to qualified-instructor ratio | There is a need for highly qualified (in pedagogy, material knowledge, and research methods) instructor, and a low student-to-instructor ratio |
|--------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Lab/Data cost                        | Modern science is advanced - There is a need for advanced equipment, expensive consumables, etc |
| Skills and Knowledge                 | Students should have sufficient skills and knowledge to tackle AREd tasks |
| Project formulation                  | Finding a good project may require significant time and expertise |
| Time for execution                   | Execution of an authentic research project takes time, which often goes beyond the time ranges available in traditional courses |

Table 1: Barriers for scalable AREd implementations

Here we report a design and implementation note for the AREd program which has a solution to all 5 barriers. The program was designed and implemented in a form of a group "AI for Scientific Research" (AIfSR) at New York University, under the umbrella of Vertically Integrated Projects[1] - VIP for short. Note that VIP can be used for various pedagogy approaches, and one can find reports on other AREd programs relying on VIP machinery [8, 2].

[1]https://www.vip-consortium.org/
General group structure

In order to address common barriers listed in table 1 in a scalable way we involve:

- Students who study ML/AI, who had previous experience with the research process in science, and those who have had experience leading others.
- Students who went through the AI4SR program graduated but still would like to participate - groups’ advisors.
- Research labs in natural sciences often have unique datasets, but don’t have specialists to apply AI to them.
- VIP program administration at university helping with outreach, enrollment process, and other related tasks.
- Faculty member, serving as a facilitator of the group’s operations.
- Mentors who have industry experience in AI, and are interested in helping/mentoring a team (or teams) of students. At present group has one mentor who performs both roles: that of a mentor and of a faculty facilitator.

Teams and roles

In our model, the whole group is divided into small student teams which act as a small consulting company while working with a collaborating lab (Fig. 1).

Each student in the group (outside of student leaders) is assigned to a team for the semester. Each team is tasked with tackling one project. Teams are usually comprised of 3-5 students. Students are assigned based on their preference of which projects
they would like to take on, where the leadership tries to assign students to their most preferred projects. Tasks are set up in such a way that they are often self-contained, meaning the team does not need to rely on other teams to succeed, though there is sometimes potential for collaboration between teams depending on member expertise and task similarity. The group comprised three teams for the first semester and grew to eight teams in subsequent semesters.

Each member of a team is assigned to a role, with there currently being three roles: Coordinator, Researcher, and ML. The motivation behind assigning members to roles is that, at an undergraduate level, students are not expected to have all the necessary skills required to complete a research project. As such, role division brings together students with complementary skill sets that together are more able to tackle a research project.

**Coordinator role:** Coordinators have to manage the overall work of the team. It is their responsibility to handle logistics, communication, and planning of the team’s activities. Coordinators are also responsible for communication with the group’s leadership and with the team’s collaborator. Oftentimes these are students with management experience. Ideal candidates would have demonstrated prior leadership experience.

**Researcher role:** The tasks taken on by the group are oftentimes rooted in the natural sciences. As such, success at the task would require sufficient knowledge of its scientific background. Members who are assigned to the Researcher role are required to be able to bridge this gap between the scientific background of the task and the steps needed to work towards implementation. They are expected to act as scientific communicators who can survey the relevant literature and communicate the important details to other team members and any external audiences. This role is usually assigned to students with demonstrated skills in being able to survey, compile, understand and communicate scientific literature. Background in the sciences is desirable, though not strictly necessary, as we have observed from participating students in past semesters.

**ML role:** The role of the ML person is to implement the solution to the task. The ML person is responsible for all parts of the solution, including, but not limited to, data processing, model development, model evaluation, and code management. The ML person is also required to have sufficient knowledge of machine learning methodologies to be able to apply them properly to any given task. Crucially, this role is usually given to students who have background knowledge in ML but may not have enough practical experience. This role is not meant to teach students ML from the ground up but is an opportunity for them to apply what they’ve learned in the classroom in a real-world setting.

**Management**

The group is managed by a leadership team (Fig. 1) that consists of four students and one senior supervisor. Student leadership consists of one student leader for the group, and three student leaders for each role, collectively known as role leaders.

The group leader’s primary responsibility is the long-term strategic development of the group, including establishing collaborations for future semesters in advance. They are also responsible for the overall operation of the group, including communication between groups and leadership, scheduling, and outreach to the group’s collaborators.
Typically this position is given to a student who has displayed outstanding initiative and organization.

Role leadership consists of students who act as supervisors for that given role. They are responsible for the recruitment of new students into that role. Our system involved a centralized application portal, from which applications would be reviewed by leadership and student leadership would conduct an interview based on the role that the candidate is interested in or is the best fit for. Role leaders are also tasked with supervising students in their role, and intervening if any issues arise. Typically, these are students who have displayed a high level of aptitude in their role, to the point that they would be able to guide others in said role.

Given that leadership is ideally made up of students who have had prior experience, in the first semester it is possible to operate at a reduced capacity without student leadership. During this period, the group’s supervisor would identify students who are fit for those roles. We have found this approach to be beneficial as student leadership performs best when they have had prior experience working in the group as a normal member to build up the necessary experience.

The group supervisor is a senior staff or faculty member that guides the group. Their role is to provide guidance to the group and student leadership where necessary. They also handle any administrative tasks that student leadership does not have the authority to handle. Crucially, in the beginning, their role will be much more hands-on as students are still becoming accustomed to the workings of the group. The role becomes less involved as more experienced students can take up the work needed.

One planned addition to our group is that of role-specific advisors. These are experienced individuals and past students who can provide the expertise that students can make use of in approaching their given tasks. This would provide an additional vector by which students can learn, by providing experienced mentors whom students can learn from and leverage their expertise.

**Principles for project formulation**

We ask teams to look for projects among scientific labs in chemistry, physics, and biology, specifically in those labs that don’t have yet AI/ML techniques used as part of their routing operations.

There are many scientific labs where AI/ML/advanced statics is widely used already and those are not the targets for the teams.

Specific areas for project formulation depend on the team. The team has the freedom to find collaborators, define a project, and decide where a project will go. Depending on the skills of the team, they may decide to look for opportunities in one of the science areas they are most comfortable with (biology, chemistry, physics). Alternatively, they may consider any science, but focus more on the type of techniques they have expertise in (deep learning, classical machine learning, time series analysis, unsupervised learning, etc).

In some cases, when we invite new students to join an existing project, we make an effort to match their skills to the project at hand.
The relationship between a team and collaborating lab resembles one between a consulting company and a client. Students of the team do not become part of collaborating lab research group and only interact with collaborators to understand the processes in their lab better, figure out how AI/ML can help them, and then deliver and evaluate the efficiency of a solution.

There are several reasons why we mostly work with scientific labs and not typical commercial data science companies

- This allows us to naturally include students from various fields (not only computer science students)
- Available time. Students in college usually don’t have more than 4-6 hours per week to contribute to something on regular basis. Scientific projects are great fits for the limited number of hours per week, as the timescale for project completion in academia is usually noticeably longer than in industry.
- Scientists are more eager to share unique data having real value. This is rarely the case with commercial companies
- Developing AI applications in the field of science helps further the state of knowledge in the field, which is fulfilling experience for students. One can read about currently existing efforts to bring AI to Science in US national labs [9] to learn more.

There is also a reason why we do not work on openly available datasets. Even a good standard ML solution (not a highly advanced one) is a good solution compared to the absence of any solution. This is in contrast with various projects on openly accessible data sets, where many solutions were already implemented, and to achieve significant impact a significant amount of expertise and time commitment is required.

The principles above allow students to work on projects that have an impact on the real world. We work with scientists whose immediate work would become better immediately in case a good solution is implemented. This is in a contrast with a typical situation of a student coming to a research lab where he/she could contribute only to a very small often non-significant part of an already existing project (a similar situation is with interns in commercial companies).

**Group Operations**

**Weekly meetings**

Weekly meetings are required for each team to work collaboratively, exchange ideas, merge individual works, and plan for future steps. Weekly meetings usually have a flexible time length depending on the team’s progress and team members’ preferences, ranging from half an hour (most of the work is completed individually) to three hours (the team prefers to work collaboratively).
Reporting work and progress tracking

Besides weekly meetings, each team also has weekly short catch-up meetings with the leadership team to report the project progress and receive feedback. The catch-up meetings tend to be fixed in 15 minutes to ensure work efficiency in both individual teams and the leadership team.

To effectively monitor team progress, each member of the leadership team is assigned to 2-3 teams for close progress tracking. The team assignment is based on the development stage of teams. For example, for teams at the stage of defining a clear task, the Research Lead will be assigned to monitor this team since research-based work is intensively needed, whereas teams in the process of developing a solution would ideally be overseen by the ML lead.

Meetings with collaborators

Coordinators in each team will set up meetings with collaborators whenever the team achieves certain accomplishments or the team needs more information from collaborators. Meetings with collaborators are infrequent (normally monthly), and at least one of the members of the leadership team will join the meeting. Meetings with collaborators also occur at the beginning and the end of the semester for reporting progress purposes.

Whole group presentations

We have 2 whole group presentations within a semester: a mid-term group presentation and a final group presentation. During the presentation, the coordinator of each team will give a 5-7 minutes formal presentation to explain their project and show their team’s progress to all members of our group. After each presentation, other members are encouraged to ask questions or contribute novel ideas to the team’s current tasks. The group presentation not only helps students organize their thoughts and practice their presentation skills but also connects every team member and allows them to exchange ideas.

1-minute ‘sales pitch’

We encourage our team members to prepare a 1-minute “sales pitch” for the project they are associated with. In the short elevator pitch, students should briefly introduce their project and describe what they have done. The practice of a 1-minute “sales pitch” enhances students’ presentation skills and allows them to better present their work during job interviews. It also improves their understanding of the project and its importance.

Interviewing new members

As mentioned above, we build teams with complementary skills. Some students have already developed expertise in machine learning, some in understanding research processes, and some in communication and/or leadership. To make an efficient “unit” we
carefully compose teams. We interview all the applicants to make sure people have ex-
pertise sufficient to serve well in one of the roles in the team and to explain to students
what to expect. Some students have expectations that don’t fit our model of operations.

Evolution of roles

If the role does not evolve with time some students may lose excitement. Some students
may serve as group leaders with significant influence on how the group operates. Such
leadership roles allow students to guide/direct/help other students.

Some students (after graduation for example) may choose to become advisors. Such
roles would allow them to continue to contribute to interesting projects and feed back
into the group on the best practices they see in the industry.

Tools and Practices

We aim for students to develop skills and practices which are directly transferable to
industry. So there would be no need for them to re-learn things later.

We use

• Slack, for text communications
• Shared Google or Microsoft drive for data/documents sharing
• Microsoft OneNote to keep track of progress, in a way that everybody on the
team can see progress reported every week by another member of the team
• Zoom for online weekly meetings
• Agile methodology of development
• Python and R as main programming languages. With solutions delivered to col-
laborating lab as a Python/R package or as a Python/R-based dashboard

Setting up collaborations

After a team with an area specialization is formulated, if the team has no collabo-
rators, students seek collaborations by themselves. Team members look for potential
collaborators (usually university professors) online, usually through researching exist-
ing literature, and shortlist suitable potential collaborators. The coordinator in the team
will then send out collaboration requests. If the potential collaborator is interested in
working together, the team will schedule a meeting to introduce our group and discuss
the details of the collaboration.
Example projects

Image Semantic Segmentation

The project focuses on a dataset of luminescent microscope images of human sperms generated from a lab at the University of Groningen. The goal is to segment and count the quantity of sperm cell heads in microscopy images. The segmentation will reduce the image complexity, which is helpful for the researchers in labs to analyze the fertility or pathology of the sperm cells. We proposed the use of a U-net++ model for image segmentation, achieving a 0.77 Dice score. A web app was developed around the model for researchers in the lab to upload new microscope images to be segmented.

Spectroscopy of Nanodiamonds

Nanodiamonds are broadly used in the bio-medical industry as a fluorescent marker. The project is a collaboration with a lab at The University of Groningen. Many different fluorescent nanodiamonds for industry usage are produced and offered to the bio-medical industry. In the process of testing the products, the lab needs to validate the quality of the nanodiamonds by observing their spectrum. Several tasks are addressed in this project. 1. Visualization: The spectra with splines is fit and visualized; 2. Fitting: Automatically find optimal numbers of Gaussian curves to use and fit the spectrum; 3. Image Annotation: Label diamonds in a pile with the corresponding temperature based on the different spectrums produced under different temperatures; 4. Identification of environment: Predict under which condition is the spectrum generated.

Classification of trajectories of nanodiamonds within macrophages

This project deals with the trajectories of nanodiamonds within macrophages. The collaborator, Dr. Mzyk, is interested in determining the types of diffusion occurring within these trajectories. After careful investigation, the Mean Squared Displacement (MSD) of trajectories is determined as the feature of trajectories for the classification task. The model training from the synthetic dataset of trajectories achieves 99% of accuracy, and the model is packed with a python package accessible to the lab researchers. Since the model is trained from a synthetic dataset, further investigation is required to make the model more robust to a real dataset.

Vaccination Response Prediction

Given demographic and pre-vaccination information on patients who have received a flu vaccine, the task of the project is to predict vaccine efficacy on an individual basis. The researchers in the collaborator’s lab, had previously trained an ML model through linear regression, but the model did not perform very well, so the team used the previous model as a baseline and developed a better performance model with higher accuracy, precision, recall, and F1 score. For research purposes, the lab requires multiple models with True Positive vs. False Positive rates at different classification thresholds. As such,
the next step for the team is to develop an application generating different models based on the decision thresholds.

Development stages

The entire authentic research process took almost four semesters. The team adjusted the focus each semester based on feedback and progress. The management staff evolved from a single key administrator to a management team of students. At its best, eight projects were going on at the same time. This section will show how the research project evolved from a small, single management team to a community.

Semester 1

• *Divide the recruited people into teams, the supervisor follows up the whole process, and different projects are carried out at the same time.*
  Depending on the background of the students and researchers recruited, they are divided into 3 groups to work on 3 projects, and someone within the group is mainly responsible for communication and management. The supervisor of the whole project monitors the progress of each project.

• *Collaborate with large groups to market our group so that more potential students and researchers learn about our program.*
  We exposed ourselves to many target students through the school’s research department’s website. Many students who are studying AI and ML fields applied, and students who are interested in these fields reached out to our leadership team.

• *The most experienced person at the beginning of the project will lead the whole group and ensure the operation of the whole group.*
  The faculty member is managing everything - team operations, looking for collaborators, etc (with only a few attempts by students to find collaborators)

Semester 2

• *Advertise early and recruit new Candidates.*
  Information about the group was given to the school in advance to help promote the program, while some of the students from the previous semester stayed behind to continue the work at hand. We ended up with 5 teams of 18 people.

• *Based on the performance of the group, student leaders are selected to lead the group.*
  After the first semester, based on the progress of the group, the background experience of the participants, and their group performance, students are selected based on their skills and invited to join the group’s leadership.

• *Try to get the participants to communicate with the outside world and identify potential problems and collaborators.*
We involve students in finding collaborative labs, and the supervisor helps students to communicate with potential collaborators and build collaborations.

- Collect feedback from participants and ask them if they want to continue participating in the program. A Google form was created to collect information about the participants’ experience in the research process, including group communication, group achievements, and whether they wanted to stay in the program. For those who wanted to stay, we also asked whether they wanted to continue with the original project or whether they wanted to be exposed to other projects.

Semester 3

- Continue to use established methods from previous semesters. Define the main responsibilities of each participant in the project.
  We continued to work with school organizations and received more applications than before. We also contacted students who were interested in staying based on the feedback we received. We ended up with 29 participants in 8 groups and 4 student leaders.

- Refine selection criteria based on feedback from the first semester.
  In previous semesters, there were cases where students had weak backgrounds and little knowledge of what they needed to know. Some students relied heavily on the supervisor’s guidance. This semester we raised our acceptability criteria and looked at the candidate’s independent problem-solving skills during the interview.

- Delegate more administrative tasks to the student leadership team, creating an enterprise-like hierarchical management model.
  Reliance on the senior supervisor is reduced, and the student leadership is expected to take on more management tasks. The leadership team was involved throughout the semester in interviewing, monitoring the progress of the project, and mentoring teams.

- Create a shareable database for the leadership team to share and manage data
  Each semester there is a record of participant information, and collaborator needs. We use Google Docs and Google Sheets as management information-sharing tools. The group uses Onenote to record the main content of related projects and weekly progress reports.

Semester 4

- The Senior Supervisor is only involved in operations, and the students are responsible for the management. They only advise on important important matters that the student leadership cannot handle themselves.
  After two semesters of working together, the student leadership team became more familiar with the recruiting and meeting process. The senior supervisor
does not need to attend all regular meetings to supervise each group, the leadership team will report the progress of each group to the supervisor. The leadership team also takes the majority of initiative and pushes processes forward.

- **Try new promotional models and recruit more participants with other talents.**
  Our main publicity channel is the research group under the NYU Engineering department. Since AI/ML also involves a lot of math and data science-related knowledge, we asked students from this major to try to contact the respective departments to promote our group and recruit potential participants.

### Summary and conclusion

#### Authentic research

Does the program we present provides students with an opportunity to perform authentic scientific research?

First, we can look at the set of scientific process activities obtained in the survey of biology professors [4]: student-generated questions, hypothesis formulation, experimental design, data collection, data analysis, presentation/publication. Then we can also look at a more general model of scientific inquiry presented by Harwood [1]. There are ten activities through which a scientist moves/loops in no specific order: observing, defining a problem, forming the question, investigating the known, articulating the expectation, carrying out the study, examining the results, reflecting on the findings, communicating with others.

We can clearly see from the information given in the manuscript that experience in the AIfSR group gives students an opportunity to meaningfully participate in all such activities, on top of working with novel questions.

#### Addressing blockers

Let us review now how exactly we addressed the common AREd implementation barriers listed in table[1].

**Student to qualified-instructor ratio**

Given the fact that project management is handled by each team independently with only some aspects helped by more experienced students/mentors, we implemented a model in which one faculty member can support many students. In our current structure, we have 1 PhD-level mentor, 4 students serving as leads, and 24 students in individual teams. Thus currently student/instructor ratio is 29/1. It is worth noting that at the present stage the required involvement of the mentor is only a few hours per week (this number was greater during the first semesters), and thus there is a potential to significantly increase the student/instructor ratio.
Lab/Data cost

Data generation/collection is handled by research labs (using expensive equipment or by doing expensive ‘field data collection’). Thus there is no need for additional resources to be allocated for a team of students.

Skills and Knowledge

In order to allow students with limited knowledge to work on real authentic research tasks, and bring real benefits, we first team of students with larger knowledge than that of any individual student. Such a team may be thought of as a ”collective postdoc” or it can be looked at as a small startup.

Project formulation

It takes time and expertise to formulate a new project, which would be useful if solved, doable in a reasonable time and considering resources, not been addressed by someone else yet (or addressed only a few times in different labs). We rely on collaborating labs to provide us data they can think may have value, if ML/Stat methods are applied, and work together with them to implement a solution in practice when delivered. Such opportunities are unique enough, have a lot of ’freedom’ to formulate what and how should be addressed, don’t have a guarantee to be solvable, have real scientific value, and are approachable given students’ combined expertise level.

Time for execution

We found that projects may need multiple semesters to get to a meaningful contribution stage. By utilizing VIP program resources we have an opportunity for students to enroll for multiple semesters.

The student leadership team works to ensure continuity of the projects in cases teams have new members (the teams do in fact often change due to the nature of the agile student body).

Connection to industry

We aim for students to use industry-standard tools and practices, thus creating additional side benefits: students can apply those tools/practices in their later work, research labs receive modern solutions, and mentors from industry can help students use their regular tools/methods.

Conclusion

We believe such or similar programs may be implemented at many universities, and they would benefit all the parties involved: students, researchers in natural sciences, mentors, as well as faculty, and administrators at universities.
Contributions and Acknowledgments

Sergey Samsonau leads the efforts and is responsible for the initial idea, establishment of the AIFSR group, as well as group development. All authors actively participated in work on projects, establishing collaborations, management, and design of group operations. Sergey Samsonau, Lu Jiang, Hazem Lashen, and Jiamu Bai wrote the manuscript.

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