

# **Influence of an upper-division quantum capstone course on students' post-graduation careers**

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As new quantum technologies are being developed in a rapidly evolving quantum industry, the need for employees with bachelor's degrees continues to increase. At the University of Colorado Boulder, an upper-division physics capstone course called Quantum Forge (Q-Forge) was developed to help meet this need by preparing students to work in the quantum industry through participating in an authentic industry project with a partner company. This capstone course began in the 2022–2023 academic year, and we investigated the experiences of the first cohort of students throughout their time in the course. One to one and a half years after graduation, we follow up with these students to explore how the course has influenced their career trajectories and shaped their engagement with current and future work. We find that, while finding a job of interest was challenging for the students, they continue to perceive Q-Forge as a positive influence on their career prospects and current jobs.

## I. INTRODUCTION AND BACKGROUND

The potential of emerging quantum technologies has generated significant interest across the United States and internationally [1, 2]. Quantum companies are currently exploring a wide range of potential applications that not only focus on quantum computing, but also quantum sensing, quantum communication and networking, and products to enable other quantum technologies [3].

As the quantum industry continues to grow, there is an increasing need for a qualified workforce to support its development and long-term sustainability, which creates new career opportunities. These opportunities include roles accessible to individuals with bachelor's degrees. The anticipated demand for bachelor's level employees has extended beyond physics to include a range of related disciplines. Many individuals with degrees in physics may ultimately become "engineers" within the quantum industry, highlighting the need to prepare students with not only the skills of a physicist, but skills that can be applied to a range of job types [3, 4]. Educators have thus begun developing courses, minors, and entire degree programs to help educate the new quantum workforce [5–9].

In order to have in a career in the quantum industry, students must have relevant skills and knowledge, including knowledge of quantum mechanics, laboratory skills, and professional skills, such as the ability to work on a team and manage projects [3, 10]. Teaching these skills is a important responsibility for university educators, and there are many different methods of helping students to acquire this critical knowledge [5, 6].

There also exist a number of challenges to providing this education at the undergraduate level. These include the need for instructors with the necessary knowledge and skills to teach these courses and infrastructure at the university to support them. The interdisciplinary nature of the quantum industry and, therefore, quantum education, is also a challenge that must be addressed by institutions of higher education [5, 11].

At the University of Colorado Boulder (CU), one way of addressing the need to educate students for the quantum workforce was the development of an upper-division quantum capstone course for physics and engineering physics students. This two-semester course, offered annually, was modeled after the concept of a senior design capstone course in engineering disciplines, and is called Quantum Forge (Q-Forge) [12–14]. In order to study the impacts of this course on the students, we conducted extensive research to understand the perspectives of the first cohort of students throughout their year in Q-Forge [15–17]. Most recently, we conducted interviews with these same students from the first cohort of Q-Forge approximately a year after their graduation to understand their perceptions of the course's impact on their careers.

Our research question for this work is: how has Q-Forge affected students' careers a year after taking the course?

While the students engaged in Q-Forge were meant to be those who were interested primarily in a career in quantum industry after graduation, the goals of our participants were

varied and will be discussed in Sec. IV. Nevertheless, we aim to investigate the effects of Q-Forge on students' paths toward their desired career, whether it is in quantum industry or not.

## II. COURSE CONTEXT

CU is the lead institution of an NSF Quantum Leap Challenge Institute called Quantum Systems through Entangled Science and Engineering (Q-SEnSE). One of the explicit goals of Q-SEnSE is to "[emphasize] education, training, and workforce development as part of its overall mission to advance quantum information science and technology in the U.S." Q-Forge is one aspect of achieving this goal, aiming to provide benefits to both students and industry partners [18–20].

Q-Forge seeks to provide students with a hands-on learning experience similar to what they might experience in either an industry internship or an entry-level job in the quantum industry. Accordingly, it promises that students will gain technical and professional skills, as well as knowledge useful for a future career in the quantum industry, and that students will experience industry culture by working with an industry sponsor. Q-Forge also aims to provide students opportunities for professional development that will prepare them to enter a career in the quantum industry [20]. Students must submit an application to enroll in Q-Forge, and priority is given to students who do not plan to attend graduate school.

Students in Q-Forge meet formally two times each week for check-ins with their entire class and the course instructor/TA. Students also have scheduled lab time for several hours once a week where they can work on their project together, although groups often choose to meet more often than this to accomplish their project goals. Toward the beginning of the year of Q-Forge, students engage in modules geared to helping them learn project management skills and technical skills that could be useful to their project. As the year continues, these formal modules are phased out and students spend most of their time in the course working on their projects. Throughout the first semester of the course, students engage in visits from, and tours of, local quantum companies to help familiarize them with the local quantum landscape. For more information about the Q-Forge course, see Ref. [17].

In the 2022 – 2023 academic year, which is the focus of this work, all students worked on a single project with one partner company. Students worked on a project that involved optimizing heat exchangers for one of their partner company's dilution refrigerators.

## III. METHODS

The participants in this study include four out of the five students who participated in the entire year of Q-Forge in the 2022-2023 academic year. These students all identify as white, and three of the four identify as men with one identifying as a woman. One student also identified themselves to us as autistic.

In order to ascertain how Q-Forge affected these students' experiences after the course was over, we invited all five students to participate in a longitudinal interview with researchers one year after their completion of the course. Interviews took place between September 2024 and February 2025. Interview questions focused on the students' jobs and/or careers after graduation, how the Q-Forge course influenced their work after graduation, which skills students learned through Q-Forge that have transferred to their work after graduation, and how they perceive the culture of their current place of employment with respect to that of academia. In this work, we focus only on the first two of these categories of interview questions. Student responses to the other categories will be shared in future publications.

Analysis for this work was conducted by reviewing the transcripts from these interviews and identifying relevant sections where students' answers addressed our research questions through an open coding process. A narrative analysis was then performed which allowed us to consolidate each student's answers into a cohesive story [21]. This allows us to share the unique perspective of each student, since there are many differences in student thoughts based on unique life circumstances. Each student was then given a descriptor based on their current career so that the students' jobs are easily identified throughout.

#### A. Limitations

While obtaining participation from four out of our five original participants allows us to share a great deal of information about the course's impacts on these students after graduation, we recognize that not conducting an interview with our fifth original participant limits our ability to make claims about the cohort as a whole.

Furthermore, Q-Forge is a unique course that takes place at only one well-resourced institution situated geographically within an area with access to a number of quantum companies. Certainly, a course like Q-Forge may impact students differently within the context of a different institution or different geographical situation, and the work presented here can only speak to what the impacts of such a course might be on future students.

Finally, we present here only a subset of the analysis that will be conducted on these data and our conclusions within this work do not describe completely the thoughts and opinions that were shared with us in these longitudinal interviews. Future work will detail additional conclusions that can be made from these data.

### IV. RESULTS AND DISCUSSION

In this section, we present a student-by-student analysis of these course impacts. Section V will contain a synthesis of these impacts and how we might expect Q-Forge to influence students going forward.

#### A. The Researcher: Reese

Reese is a white man who had, at the end of Q-Forge, planned to apply to jobs in a variety of physics-related industries including quantum and aerospace. Reese was deeply concerned with working for a company with coworkers that he enjoyed working with and in a role that involved hands-on work.

After completing his year in Q-Forge and graduation with a bachelor's degree, Reese continued to work in the research group that he had participated in as an undergraduate. When asked if this aligned with the goals he had for after graduation, Reese stated, "I like just kind of making new stuff that's never been done, or it's better than everything else, and stuff. Like, leading edge technology."

Because Reese felt that he had gained independence and responsibility within this research group, his continued work in his undergraduate lab allowed him to feel that he had met his goals for after graduation despite not having found a permanent role in a quantum or aerospace company.

Nevertheless, Reese's position in his undergraduate lab was time-limited and he was no longer able to maintain his role there after August of 2024. Since that time, he has been looking for a job in physics industry using LinkedIn, Handshake, Indeed, and Google.

Reese identified networking as a primary challenge of his in his job search. Reese emphasized,

I've been trying to network, but it's hard... it's like, just, something that's not natural to me. So it's something, like, I struggle to, like, know what to say.

Reese emphasized that he felt being able to network more effectively would have made it easier for him to get a job in his desired field.

He also felt that he faced challenges as an individual with an engineering physics degree rather than a strictly engineering degree. Reese stated,

It's hard to, like, convince these guys that, you know, I'm better than these mechanical engineers with, like, fluid dynamics or differential equations, because I can derive them not just follow the rules.

Reese noticed that while he felt that he had the ability to learn the skills he needed on the job, it was hard to convince interviewers that he would be a better fit for an engineering job than a candidate with more specific engineering experience. Understanding more about the role of the physics bachelor's degree in the workforce (i.e., outside of preparation for graduate school) is a key area for future research [22, 23].

When asked about the role of Q-Forge in his future career, Reese stated that Q-Forge helped him develop his problem-solving skills and be able to approach new types of tasks that he had not seen before. For instance, Reese said,

Putting me in a whole different kind of environment. Like just being uncomfortable with something that [I] don't really know a lot about.

Like, we had to do all this background reading about thermodynamics... So that made me, kind of, more confident rising to the occasion to solve the problems that I want- or need to solve.

Due to the open-ended nature of Q-Forge, Reese was able to explore solving hands-on problems that were different from the types of problems he might have seen in his more traditional coursework. Through this process, he was able to see that he is capable of coming up with solutions to open-ended problems, which led to additional confidence in a future job where these types of tasks might be commonplace.

Despite the value of this experience with real-world problem solving, Reese continued to have trouble finding a job that would be a good fit for him after his graduation from CU. This shows that simply providing students with experience on an authentic project is not necessarily enough to prepare them for a job search, although it may well prepare them adequately for the type of work they will be doing once they do get a job.

#### **B. The Graduate Student: Jasper**

Jasper had always planned to further his career as a physicist by going to graduate school, and during his longitudinal interview was working as a Teaching Assistant (TA) and Research Assistant (RA) in his graduate program. Jasper also identified to us as a white man.

Jasper's work in his graduate program aligned well with his articulated goals throughout Q-Forge. When asked about how he was feeling about his current job as an RA, Jasper replied,

It's in a very similar field to what I worked on in undergrad, and sort of what I'm interested in working on broadly. And the group here is really great. Like, everyone's really nice. And the PIs are great. They both know so much stuff.

Jasper also articulated that he was enjoying being a TA for undergraduate students. As many teachers do, he enjoyed seeing students learn something for the first time.

I just really enjoy helping students get to that point where they learn something new, and they're like, whoa, I understand things in a new way.

While Jasper noted that graduate school was challenging for him, he also made it clear that he was enjoying teaching, his research group, and his program as a whole. In fact, Jasper confirmed that he had picked the university that he went to based on his research group, stating,

When I was kind of first looking around and visiting the grad schools [the PI] and everyone else in the group made a really nice impression. And I was like, wow, this really would be great to work with them. And I'm so glad to have chosen to come here and then gotten through the, like, parts of the process to be able to work with them.

Jasper had gone through his application process to graduate school earlier in the year than his peers began their job searches due to the application timeline for graduate programs. While he didn't experience challenges with his job search in the ways that some of his peers did, his next steps after graduation with a bachelor's degree were also much more traditional, leaving less room for unexpected challenges.

Of all of the experiences Jasper had in Q-Forge, he singled out the opportunity to work on a team as the most influential and helpful for him in his current role. He stated,

Definitely the group work, I think, has been the most helpful for me. And I'm sure that other people have something to say about the science, too, because if you're in a more, like, quantum-y industry, then they'll be like, oh, it was great to be on the ground floor, like, knowing a lot of these things from the beginning. But for me, as someone who's in not that specific subfield, I think just the group work. And getting to know what a healthy group dynamic looks like has been really helpful to me.

Working as part of an authentic team was an important part of the Q-Forge experience for Jasper, and he highlighted this as valuable even above the science he learned. This is also one way in which Q-Forge differs from a traditional laboratory course.

#### **C. The Quantum Engineer: Nina**

Throughout her time in Q-Forge, Nina had been curious about a career in the quantum industry, but unsure if she wanted to pursue such a career in her future [17]. Nina identified herself to us as a white woman.

After graduating, Nina got a job with the industry partner that her team had worked with throughout Q-Forge. When asked if this aligned with her goals for her career, Nina stated,

I was a little bit torn between industry and sort of a more research role versus teaching. I wasn't sure between the two, and I think I'm happy where I ended up.

Nina's uncertainty about her future career continued into her job search after she completed Q-Forge, but after getting a job at the sponsor company, Nina felt that this did align with her desires for a job after graduation.

Her job search, however, was not necessarily a straightforward process. Nina said,

I applied to so many different places. I had a few interviews, not as many as places that I applied to. Mostly [for] engineering type jobs. I think the only other job offer I got was for [other job offer]. I sort of decided to just kind of wait things out until something came along. I was working at the restaurant, so I felt comfortable not going straight into industry or something related to my degree for the time being. And then

I was emailing back and forth with the people at [company], and a few of us would still come in after graduation, because we were trying to wrap up our project that we didn't finish. And then they offered me an internship.

Nina's traditional job search was largely unsuccessful, as she mentioned getting only a few interviews and only one offer that she ultimately decided not to take. Similarly to Reese, Nina struggled with getting a job using her degree when she first began to look. Nina's success in her job search came from her connections with her industry sponsor throughout Q-Forge, as they eventually offered her a job.

Also similarly to Reese, Nina mentioned feeling that Q-Forge prepared her for her current career by allowing her to learn how to work on an open-ended problem with no known solution. Nina said,

It was helpful during Quantum Forge that we weren't working on a project that there was an easy solution to in a textbook. And I think that helped, sort of, wrap our heads around that it's a new and growing industry where you get to come up with new solutions.

Nina felt that the open-endedness of this project helped her better understand the industry that she would ultimately be working in by teaching her that it is an industry where new solutions are important and valued. Q-Forge is potentially the only place in the CU physics curriculum where these students would have been exposed to such a real-world problem, and students clearly saw value in this.

#### **D. The AI Contractor: Owen**

Owen began his time in Q-Forge excited to eventually have a job in the quantum industry, but his interest waned over time as he became more interested in working on some of his own ideas and ultimately developing his own company. Owen identified himself to us as a white man.

After taking Q-Forge, Owen found a job as an independent contractor working to validate AI chatbot responses to physics and math questions. When asked if this job aligned with his goals for after graduation, Owen indicated that the job was not what he had been wanting to do after graduation, but that he did it to make the money he needed.

The job search, for Owen, was "maybe one of the hardest things I've ever had to do." Owen also specified that "I've had extremely limited success when it comes to applications."

Graduating with a bachelor's degree in engineering physics with specialized knowledge in quantum engineering did not necessarily set Owen up for success in his job search, similarly to Reese and Nina. As mentioned earlier, it is important for courses like Q-Forge to ascertain how to better support students in their ultimate career search if these courses aim to help more students get involved in quantum industry.

When asked about what he learned in Q-Forge that has ben-

efited him, Owen discussed some specific technical skills. He said,

I did a bunch of data analysis and programming for this project. That was the thing that I was mostly interested in, because, frankly, I wanted my future to be in data science and analytics, and so that- that stuff that I worked on is has definitely been very relevant to the direction that I want my career to go.

While what he learned in Q-Forge was not necessarily relevant to the job he currently has, Owen still felt that some of the technical skills he learned in Q-Forge would help him once he is in a role that is better aligned with his goals.

## **V. CONCLUSIONS**

For the students who completed longitudinal interviews, lasting impacts of the course were varied. Two students mentioned the importance of learning how to work on an open-ended, authentic project. One student focused on having learned a specific technical skill, while the other interview participant valued the teamwork skills gained throughout Q-Forge. This demonstrates the importance of a variety of different potential impacts from a course like Q-Forge, as students may value certain skills, knowledge, or experiences over others. Furthermore, a practical course like Q-Forge may be the only opportunity undergraduate students have to gain some of these experiences, as many are not offered in other places in the curriculum.

Despite the wide range of benefits students discussed having gained from Q-Forge, finding a job in their chosen field was difficult for three out of our four interview participants, with the fourth having chosen a more traditional path into academia rather than going into industry. This is an important insight for a course like Q-Forge that aims to help students prepare for a career in quantum industry. These results demonstrate the importance of increased career preparation for students involved in courses like Q-Forge as, in its current form, students are identifying that Q-Forge benefited them greatly in gaining skills applicable to a job in quantum industry, but that they are still struggling to get these jobs. Further helping connect students with jobs in the quantum industry through resume and interview preparation, as well as job search training can then allow the benefits of this course to fully manifest both by helping students get the jobs that they need and by helping to meet the workforce needs of the quantum industry as a whole.

## **VI. ACKNOWLEDGMENTS**

We would like to express gratitude to the students who cared about this project enough to complete an interview over a year after their graduation. Their experiences and reflections on this course are invaluable to our work. This work is supported by the National Science Foundation QLCI Award OMA 2016244 and PHY-2317149.

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- [1] National Quantum Coordination Office (NQCO) ().
- [2] enNational Quantum Strategy (accessible webpage) ().
- [3] M. F. Fox, B. M. Zwickl, and H. Lewandowski, Preparing for the quantum revolution: What is the role of higher education?, *Physical Review Physics Education Research* **16**, 020131 (2020).
- [4] C. Hughes, D. Finke, D.-A. German, C. Merzbacher, P. M. Vora, and H. J. Lewandowski, Assessing the Needs of the Quantum Industry, *IEEE Transactions on Education*, **1** (2022), conference Name: IEEE Transactions on Education.
- [5] C. D. Aiello, D. D. Awschalom, H. Bernien, T. Brower, K. R. Brown, T. A. Brun, J. R. Caram, E. Chitambar, R. D. Felice, K. M. Edmonds, M. F. J. Fox, S. Haas, A. W. Holleitner, E. R. Hudson, J. H. Hunt, R. Joynt, S. Koziol, M. Larsen, H. J. Lewandowski, D. T. McClure, J. Palsberg, G. Passante, K. L. Pudenz, C. J. K. Richardson, J. L. Rosenberg, R. S. Ross, M. Saffman, M. Singh, D. W. Steuerman, C. Stark, J. Thijssen, A. N. Vamivakas, J. D. Whitfield, and B. M. Zwickl, Achieving a quantum smart workforce, *Quantum Science and Technology* **6**, 030501 (2021), publisher: IOP Publishing.
- [6] A. Asfaw, A. Blais, K. R. Brown, J. Candelaria, C. Cantwell, L. D. Carr, J. Combes, D. M. Debroy, J. M. Donohue, S. E. Economou, E. Edwards, M. F. J. Fox, S. M. Girvin, A. Ho, H. M. Hurst, Z. Jacob, B. R. Johnson, E. Johnston-Halperin, R. Joynt, E. Kapit, J. Klein-Seetharaman, M. Laforest, H. J. Lewandowski, T. W. Lynn, C. R. H. McRae, C. Merzbacher, S. Michalakakis, P. Narang, W. D. Oliver, J. Palsberg, D. P. Papas, M. G. Raymer, D. J. Reilly, M. Saffman, T. A. Searles, J. H. Shapiro, and C. Singh, Building a Quantum Engineering Undergraduate Program, *IEEE Transactions on Education* **65**, 220 (2022).
- [7] J. K. Perron, C. DeLeone, S. Sharif, T. Carter, J. M. Grossman, G. Passante, and J. Sack, *Quantum Undergraduate Education and Scientific Training* (2021), arXiv:2109.13850 [physics, physics:quant-ph].
- [8] B. Cervantes, G. Passante, B. R. Wilcox, and S. J. Pollock, An Overview of Quantum Information Science Courses at US Institutions (2021) pp. 93–98, iSSN: 2377-2379.
- [9] A. S. Dzurak, J. Epps, A. Laucht, R. Malaney, A. Morello, H. I. Nurdin, J. J. Pla, A. Saraiva, and C. H. Yang, Development of an Undergraduate Quantum Engineering Degree, *IEEE Transactions on Quantum Engineering* **3**, 1 (2022).
- [10] F. Greinert, R. MÄCeller, P. Bitzenbauer, M. S. Ubben, and K.-A. Weber, Future quantum workforce: Competences, requirements, and forecasts, *Physical Review Physics Education Research* **19**, 010137 (2023), publisher: American Physical Society.
- [11] J. C. Meyer, G. Passante, and B. Wilcox, Disparities in access to U.S. quantum information education, *Physical Review Physics Education Research* **20**, 010131 (2024), publisher: American Physical Society.
- [12] A. J. Dutson, R. H. Todd, S. P. Magleby, and C. D. Sorensen, A Review of Literature on Teaching Engineering Design Through Project-Oriented Capstone Courses, *Journal of Engineering Education* **86**, 17 (1997), \_eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/j.2168-9830.1997.tb00260.x>.
- [13] R. H. Todd, S. P. Magleby, C. D. Sorensen, B. R. Swan, and D. K. Anthony, A Survey of Capstone Engineering Courses in North America, *Journal of Engineering Education* **84**, 165 (1995), \_eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/j.2168-9830.1995.tb00163.x>.
- [14] Home - ABET (2021).
- [15] K. A. Oliver, V. Borish, B. R. Wilcox, and H. J. Lewandowski, "The prettiest photos are the ones that have happy people in them": the use of photovoice in an upper-division physics capstone project course, in *2023 Physics Education Research Conference Proceedings* (2023) pp. 254–259, iSSN: 2377-2379.
- [16] K. A. Oliver, V. Borish, B. R. Wilcox, and H. Lewandowski, Implementation of the photovoice methodology in a project-based upper-division physics course, *Physical Review Physics Education Research* **20**, 010142 (2024), publisher: American Physical Society.
- [17] K. A. Oliver, V. Borish, B. R. Wilcox, and H. Lewandowski, Education for expanding the quantum workforce: Students' perceptions of the quantum industry in an upper-division physics capstone course, *Physical Review Physics Education Research* **21**, 010129 (2025), publisher: American Physical Society.
- [18] Quantum Leap Challenge Institutes (QLCI) | NSF - National Science Foundation (2019).
- [19] Home | Q-SENSE: Quantum Systems through Entangled Science and Engineering (2023).
- [20] Quantum Forge (2023).
- [22] S. B. Merriam and E. J. Tisdell, *Qualitative Research: A Guide to Design and Implementation* (John Wiley & Sons, 2015) google-Books-ID: JFN\_BwAAQBAJ.
- [23] enQuantum Education and Workforce Development | RIT ().
- [24] A. R. PiÅ±a, S. El-Adawy, M. Verostek, B. T. Boyle, M. Cacheiro, M. Law *FromPhysicsFoundationstoInterdisciplinaryFrontiers*(2025), arXiv 2504.13719[physics].