<u>Personal, Background, and Future Goals Statement</u>

Ronak Ramachandran | UT Austin | NSF GRFP 2025

I started studying quantum computing out of complete disbelief. I was watching a NOVA documentary, and one of the professors being interviewed was waving his hands about how quantum mechanics implied there were parallel universes. Shocked that PBS would spread science fiction as fact, I paused the documentary and spent the next few hours trying to get Google to agree with me that it was all a load of pseudoscience. Unable to understand the papers I was seeing well enough to decide if they were true, I took free online courses, read books, enrolled at UT Austin, attended Dr. Scott Aaronson's research meetings, and founded a quantum computing organization just to find people to talk to about it. Along the way, my mindset must have shifted completely, because by the time I was a sophomore listening to Dr. Aaronson explain Hugh Everett's many worlds interpretation during his course in quantum information science, I not only liked the idea; it seemed like the only natural way to interpret the math.

Fueled by a desire to understand the fundamental rules our universe obeys, I am now doing research in quantum complexity theory and quantum query complexity, because I believe these fields are where many of the most surprising roadblocks to our understanding lie. Complexity theory attempts to classify problems by the resources they need—time, space, randomness, entanglement—while query complexity classifies problems by how much of the input you need to read to solve a problem. Both can have surprisingly wide-reaching implications in seemingly unrelated fields, from the foundations of logic [DL79] to the physics of black hole horizons [HH13].

I care deeply about the truth and doing the best I can to spread it. That translates to an addiction to getting to the bottom of things—that is, research—and a love for finding the best way to communicate what I learn with people who care—that is, teaching. Being a professor feels like the ideal role for me; it strikes the perfect balance between discovering new information, mentoring people who share my enthusiasm for research, and teaching courses to curious students.

Intellectual Merit

<u>Coursework:</u> I knew I wanted to research quantum computing very early in my undergraduate career. During the pandemic, I started attending Dr. Scott Aaronson's weekly research meetings, noting unfamiliar terms and researching them after each meeting. I took his courses, first Quantum Information Science, then Graduate Quantum/Classical Complexity Theory, then Quantum Information Science II.

These courses gave me strong foundations in quantum information, but to see the whole picture more clearly, I needed to learn the physics that motivates it. I took Quantum Physics I and II, despite advisors warning that the courses would not advance my degree. Most interesting to me were some recent applications of quantum information and complexity theory to quantum gravity, the catchall phrase for attempts to resolve apparent discrepancies between general relativity and quantum mechanics. To wrap my head around the unfamiliar notation used in relativity, I decided to take an introductory course taught by Dr. Richard Matzner, a prominent relativist who led the Binary Black Hole Grand Challenge Alliance.

<u>Undergraduate Research:</u> I began reading about how lower bounding the complexity of Harlow Hawking decoding could resolve the black hole information paradox [HH13] and how the Anti-de Sitter / Conformal Field Theory (AdS/CFT) correspondence raised the possibility of a sense in which geometric volume corresponded with algorithmic complexity [BFV19]. In my excitement over quantum gravity, I decided to attempt to extend one of Dr. Aaronson's recent results in the area [AP23]. With the help of both Dr. Aaronson and his collaborator, Dr. Jason Pollack, I initially tried to resolve an open problem they posed, but after months of failed attempts, I began exploring different formulations of the problem than what Dr. Aaronson and Dr. Pollack had first considered. I used insights from topological graph theory to prove a few simple theorems about the relationship between the crossing number of bulk graphs and the 2D surfaces within which they could be embedded. I presented posters of my work in quantum gravity, first at the College of Natural Sciences Undergraduate Research Forum, **winning a $200 Rising Researcher award**, and later at **Quantum Information Processing (QIP) in Taipei, the top conference in my field.** The project is still open for significant progress, and I may return to it at some point during my PhD, but after defending my undergraduate honors thesis in 2023 [PR23], I wanted a project that could have more immediate impact on our understanding of quantum computation.

<u>Graduate Research:</u> That opportunity came during my first year as a PhD student when Sabee Grewal, another one of Dr. Aaronson's students, raised the idea of exploring variants of QMA, the class of problems with solutions that can be efficiently verified by a quantum computer, to build evidence supporting the hypothesis that QMA(2), that is, QMA with two unentangled provers, is equal to NEXP, the class of problems with solutions that can be verified in exponential time. I decided to join the project, and together with Sabee Grewal, Vishnu Iyer, Simon Marshall, and guidance from Dr. Aaronson, we proved that giving QMA verifiers small amounts of additional power results in variants of QMA that become as powerful as NEXP, adding to a long line of research [A18][JNVWY21] giving **evidence for the strength of quantum computers by proving that small modifications make them surprisingly powerful**. We put out a preprint [AGIMR24] and recently submitted the result to QIP for review.

I also started a new project in quantum query complexity with Justin Yirka, another student of Dr. Aaronson's, seeking novel separations between two quantum query models. We **devised a novel algorithm for inverting a permutation** using only O(sqrt(n)) queries to an in-place oracle, an improvement over the O(n) lower bound conjectured by Fefferman and Kimmel in 2018 [FK18], and we **demonstrated a separation for a unitary problem** requiring Ω(sqrt(n)) in-place queries but only one standard XOR query. We are currently working with Blake Holman and John Kallaugher from Sandia National Labs to apply a recent generalization of the adversary method due to Belovs and Yolcu [BY23] to try to prove a similar separation between the two oracle models for a decision problem. Along the way, we have become familiar with a wide range of techniques for lower bounding the running times of quantum algorithms. Equipped with this knowledge, I feel better prepared to tackle similar questions.

<u>Future Goals:</u> With this in mind, I am now making a foray into **quantum fine-grained complexity theory**, which I have made the focus of my research plan. I am grateful to have access to experts who can guide and support this new research direction. My advisor, Dr. Scott Aaronson, was part of the group that introduced the first version of QSETH [ACLWZ20], opening a new line of research into how quantum-specific conjectures can lead to new conditional quantum lower bounds. Inspired by that work, I sought out hands-on experience with the tools of classical fine-grained complexity at the DIMACS Tutorial on Fine-grained Complexity at Rutgers, a week-long workshop led by Amir Abboud, Karthik C.S., and Nick Fischer. In addition to reproducing existing results through daily problem sets, the workshop gave me the opportunity to learn about and attempt to solve open problems in the field alongside more experienced researchers. I was struck by how little is understood in the quantum setting and encouraged by how much potential there is for further advancement.

Broader Impacts

<u>Early Teaching Experience:</u> In addition to research, I have always prioritized education, teaching, and sharing knowledge. In early 2019, as part of a Future Teachers of America initiative, I would miss half of the school day three days a week to **provide extra help in math to struggling and special needs students** at our local elementary school. The following summer, I **founded a 4-week Python programming summer academy**, single-handedly creating a website, posting flyers around town, planning lessons, writing homework sets, and finally teaching programming to the students who signed up, all just because I had no other summer plans, and I liked doing it. Teaching is easy to like when you see the results; at the final showcase for the academy, I got teary-eyed watching one 10-year-old student proudly show her mother the choose-your-own-adventure game she had made from scratch.

<u>The Quantum Collective:</u> One of the proudest accomplishments of my undergraduate career was the growth and success of an organization I founded at UT Austin called the Quantum Collective. As a freshman, I was unable to find a single other student pursuing quantum computing research. To discover like-minded peers, I started a reading group and convinced my department to send out a mass email inviting interested computer scientists. The initial four members and I eagerly pored over the research papers we all brought to our weekly meetings, but without physicists, engineers, or mathematicians in the group, we were limited in what we could find and parse. Eager to bridge this divide, I **founded the**

Quantum Collective together with some members of the reading group. I began to set up the community I wished had existed when I first became interested in quantum computing. I split the reading group into introductory and intermediate sections to help bring new faces in. I created learning labs to give students a more structured classroom-like setting to learn the skills necessary to earn IBM's Qiskit Certification. In my final year, I set up a **research boot camp**, mentoring students through topic selection, research tools, writing, presentation skills, and more, culminating in a **mock research conference** where five teams shared survey papers and presented their posters and talks to friends, family, and some faculty judges over pizza. Throughout all this, we hosted guest speaker events open to the public that drew hundreds of attendees, ran **annual quantum hackathons** to send teams to international competitions, and gave educational **demonstrations of quantum physics and computing at Girl Day**, a UT Austin event where K-8th grade girls from across the state travel to UT Austin to engage in hands-on Science, Technology, Engineering, and Math activities. Eventually the leadership team grew from two to four to eight as we struggled to keep up with rising membership and multiple parallel initiatives. By the time I graduated, there were **over 700 people** in our online community from across disciplines, universities, and even countries. Now, as a PhD student at UT Austin, I participate in a more hands-off mentorship capacity while the next generation of students leads the organization to new heights. There is something indescribably rewarding about watching the organization continue to grow and attract curious and eager students into the quantum computing community.

Volunteering: As a PhD student, even with research steadily filling my schedule, I continue to find time to prioritize volunteering. About a year ago, I joined Tzu Chi, an organization united by a strong sense of service, generosity, and kindness. I attended public park clean-ups, pulled up weeds for the local community, and cooked healthy vegetarian meals to give away to students on campus, but the most rewarding experience with the organization was volunteering to **teach math to struggling and economically disadvantaged students** at Overton Elementary in Austin.

Last semester I also volunteered weekly at Perez Elementary School—a school where over 90% of students are economically disadvantaged—to **teach 5th grade students robotics through hands-on lessons with Lego Mindstorms.** After a rocky first lesson, the teachers at Perez taught us skills to manage behavioral issues, and I rewrote the lesson plans I had been given to make them more engaging, beginner friendly, and most of all, fun. Students became more focused and creative, and by the final lesson, they were working in teams to have their robots dance with each other, combining all the tools we had taught them over the weeks: sensors, motors, logic, loops, and even functions.

Teaching: Being a Teaching Assistant is more than just a job to me; it is a commitment to making a course worth the time and effort my students put in. As an undergraduate, I was a TA for CS331 Algorithms and Complexity Theory twice, and since becoming a PhD student, I have been a TA for CS 358H Quantum Information Science and CS 345H Programming Languages. I listen carefully to my students during office hours to identify and address the roots of their confusion, and I try to incorporate real-world motivations and entertaining relevant anecdotes into the lesson plans I write for my discussion sections. My students' **enthusiasm, high attendance, and consistently positive course evaluation feedback** reflects that this extra care and dedication is appreciated.

Conclusion

Research and teaching have been the two most important and fulfilling centerpieces of my life so far, and I would love to have the opportunity to continue to pursue both as a researcher, advisor, and professor in academia. The generous support of the NSF through this fellowship would be invaluable toward helping me realize that aspiration.

References: [DL79] DeMillo and Lipton. (1979). [HH13] Harlow and Hayden. (2013). [BFV19] Bouland, Fefferman, and Vazirani. (2019). [AP23] Aaronson and Pollack. (2023). [PR23] Pollack and Ramachandran. (2023). [A18] Aaronson. (2018). [JNVWY21] Ji et. al. (2021). [AGIMR24] Aaronson e. al. (2024). [FK18] Fefferman and Kimmel. (2018). [BY23] Belovs and Yolcu. (2023). [ACLWZ20] Aaronson et. al. (2020).