Forging Aspirant Undergraduate Scientists and Engineers into Stellar Researchers

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In the current research environment, the potential contribution (and guidance) of aspiring undergraduates is often neglected. Here, Ye Tao from the Rowland Institute discusses the opportunities and challenges to foster this next generation of scientists and proposes three guiding principles of successful undergraduate mentorship.

When Harvard decided to send its undergraduates home with days of notice at the beginning of the pandemic, Mr. Kai Trepka (Figure 1A), then a senior undergraduate researcher in my group at the Rowland Institute at Harvard, rushed to lab for a few last experiments that he had been dying to try out. Kai and I had collaborated for more than 3 years. In this time, he constructed a tube furnace and customized a thermal evaporator, mastered the whole suite of nanofabrication and material analysis techniques, developed new materials and physical models, and authored manuscripts that included a first-author article in the October 2020 issue of Matter. Watching Kai darting around in lab and delivering talks at conferences, one could not help but get the impression of an experienced, senior graduate student.

High-quality learning and research achievements, such as Kai’s, are common among undergraduate researchers in labs at the Rowland Institute. NKazi Nchinda (Figure 1B), a college senior in the neighboring lab of Dr. Nate Cira, is focused on discovering new microbial taxa through innovative uses of microfluidics and genomics and is currently collaborating with Adarsh Singh (Figure 1C), a remote-mentee of Nate, to computationally validate findings of a novel type of CRISPR/CAS9 bacterial immune system from an unusual organism, most closely related to gracilbacteria, that uses an alternative genetic code. On the other side of the globe at Nanyang Technological University, Laya Pothenuri (Figure 1D), a junior and my remote mentee, is busy conceptualizing and evaluating novel methods to turn locust infestations currently affecting her native country of India into a renewable resource, funded by a 2020 Young Explorer grant from National Geographic. Cal Miller (Figure 1E), now pursuing a PhD at the University of Colorado Boulder, designed and constructed from scratch a high-vacuum scanning probe microscope and used it to study non-contact friction over suspended graphene layers during 3 years of undergraduate research in my lab (Figures 2A–2C). Soy Choi (Figure 1F), a sophomore jointly advised by Dr. Hoa Thanh Le in my group and myself, is designing a glass-based submersible as a part of floating-mirror infrastructure that could soon help humanity avoid losing habitat and ecosystem services to thermal extremes.¹ And the list goes on...

What is it about Kai, Cal, and the other undergraduate students that consistently leads to high-quality research output? Could their success be fortunate statistical noise due to the small number and sizes of Rowland research groups, or perhaps to other particularities of our Institute, such as a clear guideline requiring a mentor-mentee ratio ≥0.5? It is my hope to take this opportunity to reflect on my own experiences against a backdrop of over a century of peer-reviewed literature on undergraduate research² to provide interested readers and colleagues a concise, three-bullet-point guide to foster the development of stellar undergraduate colleagues and maximize the quality of graduating scientists and engineers. Several papers examining ingredients in successful collaborations with undergraduates, some giving specific recommendations for mentors,³ have been published. Here, I summarize findings in an extensive literature, add my own brief perspective, and distill three guiding principles of successful undergraduate mentorship: (1) multi-year duration, (2) complete project ownership, and (3) a positive environment.

Multi-year Duration
Ten hours a week over 1 year has been repeatedly found to be the absolute minimum intensity and duration for an undergraduate research experience to positively impact persistence in STEM and objectively improve research skills.⁴,⁵ In fact, there is evidence of benefit in early intervention starting freshman year and continued increase in skill levels with program intensity beyond 2 years of sustained research involvement. This result is consistent with common experiences that specific technical and general communication skills in research work take years to develop and hone⁴,⁵ and that scientific identity is mediated through self-efficacy, which also takes time to build (Figure 2). An immediate implication

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of the finding is that mentors should focus outreach and recruiting efforts during early stages of the students’ undergraduate career. In the process, it is advisable to set clear expectations for a multi-year collaboration as a prerequisite for significant student learning and scientific productivity, goals of fruitful mentor-mentee relationships.

Full and Immediate Project Ownership

In my lab, we capitalize on the causal relationship between project ownership and persistence in STEM by requiring that each student initiates and develops a new project on their own, typically around a framework developed by the PI and with as much support and advice as needed from mentors at the Rowland Institute and beyond. A typical student evolves with the project through three phases, roughly spanning 3 years. In the first phase, the student reads literature and designs, builds, and troubleshoots the experimental setups (Figure 2A). In the second phase, the student becomes an expert operator of their custom instrumentation and experimental procedures, enabling the discovery of new science and the demonstration of novel engineering concepts (Figures 2B and 2C). In the third phase, students are encouraged to formulate their own projects, leveraging their knowledge of the field, their unique instrumental capabilities, and their scientific curiosities. Throughout the multi-year process, students present in regular group meetings, receive constructive feedback, and are encouraged to present results at national and international conferences and draft first-author papers for peer-reviewed publication (Figure 2D).

A Supportive and Fun Environment

A recent study shows that negative lab environments and the inability to learn new skills are the leading causes of student attrition from research projects. While rigorous scientific expectation as colleagues and ample individual attention embodied in the duration and ownership guidelines go a long way toward ensuring that young researchers feel valued and valuable for the research enterprise, it has been fruitful in my experience to take a personal interest in their well-beings as young adults. It is essential that the scientific inquiry and discovery, which invariably involve human mistakes and failure, are allowed to take place within a physically and psychologically safe environment. Encourage students to try alternative procedures and embrace negative results as valuable forms of learning and avenues to unexpected high-impact discoveries, as long as it is safe, experimentally rigorous, and accompanied by good record keeping. It is productive to engage in extracurricular group activities that everybody enjoys (Figure 3).

Intervention before College

The preceding sections described the top three guiding principles for high-quality undergraduate research projects that are supported by literature and empirical evidence. They do not, however, provide a recipe for correcting the immense level of economic inequalities underlying academic achievement disparities in this country and elsewhere. In fact, following them may not even substantially increase the number of STEM graduates to levels needed to hasten our transition to a sustainable civilization. To substantially promote scientific and engineering literacy, a culture of equality and reason, intervention must happen by middle school. At the beginning of the summer of 2006, an analysis of the career progression from 1988 through 2000 of 24,500 middle schoolers was published. Strikingly, the study found that an eighth grader, who has the intention to pursue science, is 3.4 times more likely to eventually obtain a degree in the physical sciences or engineering compared to a classmate with the same mathematics achievement scores but lacking such career intentions.

That same month, as a freshman at Harvard and unaware of these findings, I was about to embark on an exciting summer undergraduate research...
experience at KTH in Sweden, funded by a Herchel Smith Undergraduate Fellowship. A decade and five research groups later, I came across the 2006 study around the time of starting my independent career. Reflecting back on my own trajectory, it dawned on me that, as much as I had thought my career choice was shaped by my various undergraduate research experiences, it was actually sealed much earlier, probably even before I stumbled upon and became fascinated by a college mechanics textbook at a family friends’ dinner party in ninth grade.

Recent studies have since conclusively confirmed that experiences and career intentions prior to college are the major predictors for choosing and persisting along a STEM career path. Pre-college intentions explain up to two-thirds of the variance in career choice, twice as impactful as good undergraduate research experiences, which since an early study have consistently been shown to reduce attrition by 10%–20%. From a mechanistic point of view, rigorous high school science and preparatory college courses expose students to the possibility of improvement through hard work, fostering the development of incremental beliefs, a growth mindset, and intrinsic motivations indispensable for persistence through the failures inherent in experimental research. Thus, the determination and confidence in one’s ability to improve through iterative, collaborative hard work allow the student to derive maximal technical benefits while satiating their curiosity through intellectual and emotional research ownership.

The implications of these findings are profound for addressing the current shortage of high-quality STEM graduates necessary for confronting multiple global challenges. Society can decide to massively fund and revolutionize pre-high school STEM education and/or efficiently improve the quality of undergraduate science and engineering training to levels beyond the typical models. While our laboratory is developing a proposal framework with...
the potential to achieve human resource development goals at both education levels, a full account with procedural and equity considerations is beyond the scope and space of this text and will be communicated elsewhere.

The Importance of STEM Education in the 2020s

The age of COVID is firmly established around the world. As inconvenient as the experience this year has appeared, available scientific evidence points to a convergence of threats that will likely continue to accelerate the disruption of global normalcy.1 Centuries of misuse of technologies have caught up with us, bringing humanity face to face with challenges at scales unprecedented in recorded history. Just as we need more scientists and engineers to help transition to a sustainable civilization, COVID has interrupted our efforts in labs and in the classroom. It is a time for reflection on what it means to be human, what it is that we seek in life, and how we, as scientists, engineers, and educators, can innovatively prepare and arm the world with the scientific knowledge and technical know-how that will determine the fate of humanity over the coming decade.