John M. Carroll *Editor*

Innovative Practices in Teaching Information Sciences and Technology

Further Experience Reports and Reflections

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Editor
John M. Carroll
College of Information Sciences and Technology
Pennsylvania State University, University Park
Pennsylvania, PA, USA

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Contents

Teaching as Innovation

John M. Carroll

Abstract Innovative teaching can be achieved in many ways—leveraging what students already do, know about, and think about; relying on student engagement, self-regulated activity, and collaborative activity; and embedding teaching discourses in the values, practices, and institutions of the domain. Teaching innovation is especially critical and appropriate in computer and information sciences: *critical* because of the need to enroll and graduate more students and stronger students in these areas and *appropriate* because these areas broadly depend upon and consist of continuous innovation. This book describes and reflects on a diverse collection of innovative teaching practices across the faculty of the College of Information Sciences and Technology at Pennsylvania State University.

Keywords Teaching practice · Innovative teaching · Information sciences and technology

Teaching may be the original and most important innovation in human history. Sharing elements of knowledge and skill with others, guiding and inspiring them to assimilate and make sense, to practice and apply, to appropriate and re-appropriate, and to criticize, reinterpret, and extend, is the very essence of human progress and essential to human existence. And to the converse, whatever insights and techniques are not shared are not discussed and debated, are not applied and explained, and ipso facto never have impact; they never make a difference.

The key activities that comprise teaching are all about innovation. Young children are easily motivated to learn in order to make sense of and participate in everyday community activity (Dewey, 1938). It isn't *so* different for more developed humans. What is different is that they have already learned enough to be intentional about their motivation. They have more articulate ideas about what makes sense and how

J. M. Carroll (✉)
College of Information Sciences and Technology, Pennsylvania State University, University Park, Pennsylvania, PA, USA
e-mail: jmc56@psu.edu

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they wish to participate. This can make adults more discerning, more capable, and more focused learners, but it can also make them skeptical about engaging with teaching and learning merely because another adult encourages them to do so. Exciting students about knowledge and skill requires continual innovation in teaching. For only when learning makes sense, when it addresses issues and questions people understand and value, and when it matters to their communities and societies can teaching soar.

Innovative Teaching

Motivation to learn is the essential prerequisite; it opens students to teaching. But the subsequent interactions of teaching must continue to strengthen and enhance motivation. No one now thinks of teaching as merely pouring knowledge into a student's (presumably empty) head with the Nurnberg Funnel (a scary German legend about teaching in the Middle Ages, and the title of my first book on learning, Carroll, 1990). But we do sometimes imagine that the key vehicle of teaching is a well-structured slide presentation. It is of course an important idea to organize content deliberately, but structure per se is not a sufficient goal. Imparting knowledge and skill to students must raise and address significant questions so as to engage, provoke, and develop their minds and their imaginations. That's teaching. An organized presentation of content can play a role in this but is never sufficient.

What else is required for innovative teaching? I am confident that there is not a single recipe for engaging students and helping them learn. That is one reason why there should be more books (like this one) in which teachers describe and reflect on how they achieved teaching innovations. Four of the most general and powerful ideas about innovative teaching are enumerated immediately below. For the most part, these are ideas I first encountered empirically as a young IBM researcher carrying out studies of office workers trying to learn to use then-novel word processors (Mack et al., 1983). I later developed the concept of *minimalist instruction* based on that work (Carroll, 1990, 1998). Subsequently, and for the past 30 years, I have been a university professor. Initially, I tried teaching with well-structured slide presentations, but eventually I adopted my own ideas (Carroll et al., 2015, 2016; Carroll & Rosson, 2005; Du et al., 2012; Rosson & Carroll, 2013).

1. *Learning should be* meaningful *to students; it should leverage students' prior knowledge and experience and issues and questions that students already understand.*

Learning is typically making new meanings by reshaping and extending what is already familiar. New information, interactions, and experiences are incorporated into what is already known; at the same time, existing knowledge and skill changes and develops to accommodate and better exploit new insights, new ways of seeing, and new ways of doing (Bruner, 1966; Piaget, 1985; Vygotsky, 1978).

The office workers we studied long ago at IBM Research used their knowledge of office objects and work process and their skills of typing with typewriters (remember, this was the early 1980s) to scaffold their learning about word processors and the office work processes entailed by that technology. No one had to suggest this strategy to them, and in some cases the strategy caused them problems. For example, the Backspace command in a word processor does not just move the typing point backward; it *deletes the user's data* as it goes. This caused some alarm among our participants, and one might rightfully question the design of the Backspace command (which in many keyboards is now renamed Delete), but the behavior of our participants is a normal and robust example of how people leverage what they already know to make meaning in what they are learning.

2. *Student roles in learning activity should include* self-directed reasoning and improvisation.

Learners should be creative and active participants, not just witnesses in their own learning (Dewey, 1938; Vygotsky, 1978). Thus, in leveraging what students already know and do in order to make learning more meaningful to them, teachers should always consider empowering students to *make meaning*, rather than just hearing or reading about meaning. A routine example is instead of reviewing the content of a reading assignment for the class, a teacher might pose questions about it or invite students to compare and contrast readings with respect to given themes and issues. The latter are *active learning* strategies (Bruner, 1966; Dewey, 1938).

3. *Students should be involved in* realistic activity*; applying knowledge in authentic contexts is the best way to encounter and acquire knowledge. Realistic activity is also* collaborative*; students should work and learn together, as people do in the real world.*

The context of learning is part of what is learned. When learning occurs in austere academic contexts, such as lectures or rote exercises, what is learned will be better remembered in lecture halls, but less accessible to learners in project-based work activity or in debates about societal values (Choi et al., 2023). But this is the opposite of what people need from teaching and learning. Since students typically know little about real contexts, such as work activity and debating values, it makes sense to incorporate realistic activity contexts with the events of teaching and learning whenever possible. This would allow students to learn how knowledge and skill can be useful as they first learn what it is.

Action-oriented teaching and learning is most effective when it is authentically embedded in the values, practices, and institutions of the subject domain (Lave & Wenger, 1991). For example, as an undergraduate student in mathematics (in the late 1960s), I proved many theorems, but I did this mechanically to work through problem sets, and I was careful never to talk to the other students. This is not how mathematicians work. They prove theorems strategically to build tools that enable further results and questions, and they talk to one another about what they are doing. In this sense, I feel that while much of my mathematics education was active learning, I did not engage mathematics authentically. At the end of my degree, I still had only the roughest idea of what it would mean to *do* mathematics. This is an inadequate educational outcome.

4. *Teaching should legitimize and* make constructive use of error and misconception*; errors are inevitable if students think on their own and are intrinsically motivating for students to diagnose and debug and to recover from.*

Much learning in the real world is driven by *breakdown*, Heidegger's term for things not working as expected (Koschmann et al., 1998). When one's knowledge and skill produce errors instead of results, one turns to learning and innovation. Breakdown can be uncomfortable, even paralyzing, but it can also be riveting and productive when it is experienced as presenting new challenges.

Students confront breakdown regularly because they are learners and necessarily exploring the boundaries of concepts and strategies. Teachers can help students experience their errors and misconceptions as actionable and useful, not as failures. They can convey to students that understanding and recovering from errors is an important path to learning (Jackson et al., 2022). This can help students to be more successful students and, throughout their working lives, to be better at managing and benefitting from breakdowns. Empowering and challenging students to think critically about the world as it is and to accept responsibility for the future is innovation.

Information Sciences and Technology

This book is about teaching innovation in the College of Information Sciences and Technology at the Pennsylvania State University, hereafter referred to IST. IST is an interdisciplinary college including artificial intelligence, data science and applications, human-centered informatics, information infrastructures and practices, and social and organizational informatics. The college was founded in 1999 with five faculty; it has grown to more than 80 full-time faculty and more than 2000 undergraduate students, nearly 300 graduate students, and more than 1000 online students.

The academic terrain of IST is an example of an *iSchool*; an international group of more than 120 universities now have iSchools, addressing "all aspects of research and teaching about information" (https://www.ischools.org). The iSchool movement coalesced in the early 2000s, a period when undergraduate enrollments in computer science were plummeting (Computing Research Association, 2013). In that context, iSchools sought to establish and address a broader vision of information as a lynchpin in human activity and in the future of universities. For iSchools, human concerns and possibilities are at the center of research and teaching about information technology, affording more integrated innovation of technology, social responsibility, and human experience. No surprise, faculty in iSchools typically represent a wide range of disciplinary origins and perspectives, computer and information science, psychology and sociology, philosophy, economics, and political science, as well as business, law and engineering, and people who themselves were educated in interdisciplinary programs.

Part of the vision of iSchools is that broader academic programs in information technology and innovative teaching by interdisciplinary faculties will attract and retain a larger and more diverse student population. The need and the opportunity for this are significant: five of the seven entry-level job categories with the highest projected need, highest growth rate, and highest salary for the United States are from general area of computer and information technology (Bureau of Labor Statistics, 2022). And this was *before* the 2023 boom in applications of generative artificial intelligence. All this suggests that the iSchool area will continue to develop.

Teaching innovation was a founding commitment of the IST faculty. In the early years of IST, many faculty gathered for a lunchtime meeting about innovative teaching. This was never a top-down directive, but it was encouraged by the enthusiasm of Larry Spence, our Director of Teaching and Learning in the college, by faculty peer interactions, and by insights and results in classes. When I interviewed for a job in IST in 2003, I experienced it as having a culture of teaching innovation, a shared value. It is a special possibility of an academic faculty to create such a culture, and I am grateful and proud to have participated in it. I joined IST partly because of this culture. I still recall my surprise that several faculty members I met on my job interview (including Larry Spence) were familiar with my prior work on learning (which was not the primary research area I was presenting at my interview) and wanted to talk about innovative teaching.

This book focuses on the innovative teaching practices of a single iSchool faculty. Thus, this collection of experience reports is more a faculty case study than the sort of convenience survey one generally sees in an edited collection. I couch the distinction this way because, in discussing this project with several colleagues, it seemed one reaction was to question the validity of concentrating on a single faculty. I think this is a serious point, but it needs to be considered in the context of standard practices, which often hinge on over-sampling members of the editor's professional network. Thus, even though the authors of the typical edited collection appear to be a diverse group, in some senses they are handpicked (by the editor) to be likeminded.

Moreover, I think that focusing on a single faculty case study allows recognition and acknowledgment of the thesis that teaching innovation is an issue of faculty culture, not merely a matter of individual instructor choice and initiative. I think this is also a serious point regarding what teaching innovation is, how it emerges, and how it can be sustained. The typical approach of reporting and examining teaching innovations course-by-course or instructor-by-instructor and sampling widely across universities and countries does not address this question.

This Book

This book is the second of two. In 2014, my IST colleagues and I (including faculty, staff, and students) published the 18 chapters of *Innovative Practices in*

Teaching Information Sciences and Technology: Experience Reports and Reflections (Carroll, 2014). Like that previous book, the chapters of this book are experience reports and reflections on teaching practices of IST faculty, staff, and students. Each essay describes specific pedagogical challenges and goals that a particular instructor addressed through her or his personal educational vision and values. We have tried to keep these reports succinct and concrete, in some cases pointing to other publications and web resources. The objective was to be inspiring, but more importantly to be grounded enough that other faculty could do something, emulate, adapt, and appropriate a technique or approach in their own courses.

The first five chapters address perennial challenges for teaching in IST. In the chapter "The False Promises of Application-Driven Learning: Mathematical Thinking in Today's Rapidly Evolving Technology Landscape," Sarah Rajtmajer observes that although IST undergraduates have selected a degree program with foundations in mathematics, they can still experience math anxiety. Based on her experience teaching a required math course for IST undergraduates, Rajtmajer shares strategies and perspectives. She argues that framing math as justified only by its applications can deprive students of the opportunity to overcome their anxiety and cultivate self-efficacy.

Shomir Wilson seeks to enable broader use of class discussions in the chapter "Professor in a Strange Land: An Expat Metaphor for Classroom Discussions". Wilson suggests that faculty embrace the generational gap between them and their students; the instructor is an "expat" immersed in a class consisting of people who understand, use, and experience technology differently. The metaphor converts what might be just a communication challenge into a collaborative resource, legitimizing the expertise students bring to the class and motivating their opportunity and responsibility to contribute perspectives.

Learning a programming language is learning a huge number of details that can obscure more general structures and concepts of the language. In the chapter "When Less Is More: A Java Introductory Course," Fred Fonseca describes his efforts to simplify initial presentation of language details more rigorously in order to help students keep general structures and concepts in mind as they learn.

Chris Gamrat addresses the related issue of introducing technological concepts to new and prospective IST students. In the chapter "Teaching Information Technology Without the Technology: An Unplugged Approach to Introducing IT Concepts to First-Year Students," he shows how paper presentations of technologies like social network analysis, programming, and cryptography can be effective and easier to manage.

In the chapter "Scenario-Based Design with ChatGPT: A First-Year Seminar Experience," John Carroll describes enrichment for a first-year seminar, a type of course primarily concerned with orienting new students to resources and opportunities of the campus and student life. This chapter discusses how IST method and tool content suggested new activities for first-year topics such as academic integrity and allowed students to carry out more meaningful course projects.

The next four chapters address emerging challenges for teaching in IST. Machine learning applications have become pervasive through the past decade, and many college students without strong backgrounds in computer science and mathematics are interested in learning how to use machine learning. In the chapter "Hitting the Sweet Spot: Designing an Accessible Introductory Machine Learning Course for Informatics Students," Amulya Yadav and Hangzhi Guo take up this challenge, developing a use-oriented approach to an introductory course in machine learning.

Lizhen Zhu and James Wang describe the challenge that most data science education occurs in graduate programs, leveraging and integrating existing expertise of students. In the chapter "Unleashing the Problem-Solving Potential of Next-Generation Data Scientists," they discuss developing a project-focused, writing-intensive course for upper-level undergraduates in which students experience all phases of a data science project.

In the chapter "Providing Iterative Cybersecurity Hands-on Learning Experience: Reflections on Teaching Cyber-Defense to Second Year IT Students," Peng Lui critically reconsiders hands-on cybersecurity labs and describes course development that iteratively improved learning dependencies throughout a sequence of labs. This approach supported sequential mastery of advanced cybersecurity skills.

Another emerging challenge for teaching in IST is explainable Artificial Intelligence. In the chapter "Learning About Explainable AI with Very Little Programming For 4th Year Undergrads (or Younger)," Jonathan Dodge, Antoinette Diawuo, Enyan Dai, and Rupak Das describe the development of an undergraduate course designed to be "accessible to fledgling data scientists." For example, they minimized course dependencies on programming, mathematics, and human-computer interaction.

The next four chapters address embedding the classroom in the world. Dan Welch, in the chapter "Traversing the Software Development Life Cycle: Reflections on Teaching Object-Oriented Programming to Third Year IT Students," leverages the software development lifecycle as a template for teaching and learning software concepts and skills. Students enact the process model to learn about it and to learn about the structures, techniques, and tools that comprise it. For example, version control is employed throughout the course.

Guoray Cai's chapter "Blurring the Boundaries of Teaching Modes to Improve the Experience of Professional Learners" notes that a by-product of the COVID pandemic was instructional development focused on various modes (face-to-face, synchronous remote, asynchronous, and hybrid). Cai describes how teaching modes can be more seamlessly combined for Penn State World Campus students (whose default mode is asynchronous) to produce better outcomes.

In the chapter "Semester Projects on Human-Computer Interaction as Service and Outreach, undergraduate and graduate," Frank Ritter and Sarah Stager argue that course projects can be more engaging and useful to students if they are more real, for example, having specific social and economic impact, in addition to providing students opportunities to integrate and apply course concepts and techniques.

Mahir Akgun examines the role of knowledge creation in learning in the chapter "Knowledge Integration and Knowledge Building: Engaging with Different Perspectives to Create a Place for Knowledge Building in a Learning Environment." Based on experience with a visual analytics course, he argues that incorporating knowledge building into learning activity supports a more dynamic, collaborative, and stimulating environment.

The final four chapters address management and development issues for courses and curricula. In the chapter "Single Point Rubrics: An Opportunity in Graduate Education," Edward J. Glantz and Ralph J. Osmolinski critically review grading rubrics, explicit models for allocating credit that provide transparent subgoal guidance to students in carrying out assignments and help explain grading outcomes. They focus especially on using rubrics in graduate courses.

David Hozza, in the chapter "Entering the Cybersecurity Workforce: Certification vs. College Degree," describes the emergence of the cybersecurity profession and current challenges to train sufficient numbers of qualified cybersecurity professionals to meet the needs of industry and government.

In the chapter "Teaching as a Practice of Cultivating Relationships," Priya Kumar, Yao Lyu, and Ananya Reddy, a faculty member, a graduate teaching assistant, and an undergraduate student, respectively, describe teaching as relationship building. They illustrate four principles of relationship-rich education through their personal teaching and learning experiences.

Rosalie J. Ocker and Lisa Lenze, in the chapter "Achieving Consistent and Relevant Learning Outcomes on a Common Course," discuss the redesign of an undergraduate core course in database design and development. The course is required for most programs in the IST college and is taught by a wide range of faculty each year. Ocker and Lenze's project sought to create a common course design that would satisfy diverse students and faculty across programs in IST.

I joined IST in 2003. I was a bit past mid-career. I believe I had always tried to be innovative in my teaching, but I appreciated and was inspired and encouraged by the collegial validation and support for this in IST. I think it helped me to become more innovative and to keep trying to be innovative more than I might have done on my own.

Though I was motivated to organize this book by a sense that many of my colleagues were innovative teachers, I have ended up impressed at just how innovative they are. Strategies like leveraging what students do, know about, and think about, relying more on discussion and activity than on lecture and description, employing collaborative learning, designing course activities that are authentic to real-world domains, and using signature projects and practices are not exceptional or radical practices in our college; they are teaching norms. This is quite exciting. It was not what I experienced myself as a student, nor is it what I saw when I first became a faculty member.

This book is not a claim that my colleagues and I are more innovative than other faculty. Rather, it is an acknowledgment that the culture of teaching and learning in a faculty is more than the practice of any faculty member. This collection of reflective essays on teaching practices is a vehicle to begin exploring that proposition and, more specifically, to reflect on and extend innovative teaching in IST, to continue to learn from one another, to help one another achieve more. This book is a vehicle to share a collection of innovative practices and experiences and IST's continuing culture of teaching innovation with other colleagues. It is a celebration of innovative teaching.

Acknowledgments I am grateful to my innovative teaching colleagues for encouraging the concept for this book (and its predecessor) and for working to develop and share that concept. More personally, I hope this honors the memory of my former colleague Professor Larry Spence who did more than anyone to establish the culture of innovative teaching and learning in our college.

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Part I
Meeting Students Where They Are: Perennial Challenges

The False Promises of Application-Driven Learning: Mathematical Thinking in Today's Rapidly Evolving Technology Landscape

Sarah Rajtmajer

Abstract Undergraduate curricula in informatics programs typically include several courses in mathematics. In my time teaching mathematics in IST, I have noticed continual and increasing calls from colleagues and administrators to prove to students the relevance of these courses through application-driven lesson plans and preferential treatment of topics with well-understood connection to today's technologies. This chapter offers a counterpoint to these calls. I suggest that the treatment of foundational mathematical concepts as a means to well-defined and highly circumscribed ends perpetuates math anxiety and undermines flexibility of mathematical reasoning critical to highly dynamic IST careers. The examples I provide center around a course on discrete mathematics. However, the message is general.

Keywords Discrete math · Math for information sciences and technology · Math anxiety

Introduction

By the time they reach mid-career, today's students of information sciences and technology (IST) will be engaging with technologies they did not learn about and could not have imagined as undergraduates—technologies, perhaps, powered by AI and quantum computing—recently in the realms of science fiction. A premise of this chapter is that the primary goal of an IST curriculum should be the provisioning of a rich set of skills and a growth mindset which students can draw upon throughout their careers as they learn, work, and innovate in a rapidly evolving technological landscape.

S. Rajtmajer (✉)
College of Information Sciences and Technology, The Pennsylvania State University, University Park, PA, USA
e-mail: smr48@psu.edu

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At the center of such a skillset, I argue, is mathematical reasoning. Some examples of mathematics in IST are ubiquitous: number theory for cryptography, set theory for password security, and relational algebra for databases. We pull out these examples when our students ask us “why they need to learn this.” But if we are being honest, we know that public key cryptographic algorithms will be replaced soon (NIST Announces First Four Quantum-Resistant Cryptographic Algorithms, 2022) and passwords even sooner (Goodfellow et al., 2016). It turns out that deep learning has its foundations in algebra (Dweck, 2016). That is convenient for instructors tasked with teaching linear algebra and fielding students’ questions about real-world utility. I wonder, what did they say before AI? And what will they say next?

My message brings together two challenges which on the surface appear unrelated: natural tensions between theoretical and applied mathematics and students’ experiences of stress, anxiety, and lack of confidence in mathematics. My experience in the classroom is that these challenges are intertwined and mutually perpetuating.**I argue that overemphasis on the application of fundamental mathematical concepts to specific exemplars within today’s technology landscape situates mathematics as a means to an end, encourages memorization rather than imagination, and undercuts students’ confidence in their ability to engage with mathematical reasoning more broadly.** This will backfire, I fear, when students are faced with new ideas and new technologies down the road—an inevitability in the rapidly changing fields of IST.

This chapter will share suggestions for instructors in undergraduate-level mathematics classes for IST majors to mitigate math anxiety and promote a growth mindset (Dowker et al., 2016) through engagement with historical context, philosophy, puzzles, and games.

Math Anxiety

Decades of research in education and psychology have explored stress, anxiety, and lack of confidence in mathematics—so-called math anxiety (see Ashcraft, 2002 for an overview). School-age children have been the focus of much of this work, although researchers have suggested that large subsets of the general population at all ages are impacted.

The literature suggests that math anxiety is a phenomenon with both social and cognitive underpinnings (Tobias, 1993). Reflective of political and power structures underlying perceptions of intelligence, math anxiety is not felt equally by all. It impacts women and minorities more significantly (Nosek et al., 2002; Yu et al., 2024). Math anxiety is not only more pervasive and severe in women than in men but also believed to be more closely associated with performance in female students than in male students (Yu et al., 2024). Research thus far has failed to produce any evidence that sex differences in mathematics performance have biological basis, yet sociocultural context has perpetuated a notion that the male brain is more logical and

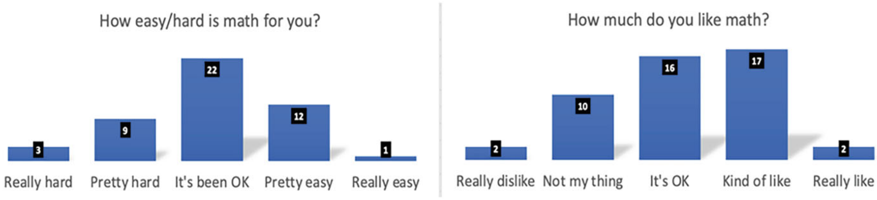

Fig. 1 Results of two-question in-class survey of IST 230 students

better at math (Mendick, 2005). This is a vicious cycle for women and girls—fearful that they will not understand and that they cannot do, they don't.

I have observed a surprising prevalence of math anxiety over several years as an instructor of a foundational (required) mathematics course for undergraduates studying IST—surprising, perhaps, because these students have self-selected into a technical major that leans heavily on mathematical foundations.

This semester, I made my first attempt to quantify this pattern among my own students. I administered a survey to my class of 47 students in IST 230—discrete mathematics on the first day of classes at Penn State. I asked them how hard they have found math in prior courses and how much they enjoy math. The results are in Fig. 1. Results were well-distributed but lower than ideal for students in IST. My goal, of course, is to have moved the needle on these answers by the last day of class and for students to feel that change well beyond this course and this program.

Figuring Out as Growth Mindset

As a woman with a PhD in mathematics and a faculty member in a College of Information Sciences and Technology, I have had the opportunity to teach both theoretical and applied math courses in traditional math departments and in the context of IST where I sit now. My experiences have reinforced the value of mathematical reasoning for both audiences, equally.

Studying topics in theoretical mathematics is an exercise in getting comfortable with discomfort—in figuring out. Consider the first topic we teach in IST 230, propositional logic. I show students a logical expression. It involves symbols like $\exists$ which is shorthand for "there exists" and $\forall$ which means "for all." Most students have never seen these symbols before and that fact alone is enough to cause some discomfort. But most will dutifully learn the translation of symbols to text and will recite those definitions readily on homework or exams.

Next, we string these symbols together into statements. For example, students are asked to understand whether the two statements:

$\neg\forall x\, P(x)$: "It is not true that $P(x)$ is true for all x."

and

$\exists x \neg P(x)$: "There exists an x such that $P(x)$ is not true."

are equivalent (they are). By the next class, they are looking at these four statements, and they are being asked whether the fourth is a valid conclusion of the first three premises:

Premise: $\forall x(P(x) \rightarrow S(x))$—$P(x)$ implies $S(x)$ for all x.

Premise: $\neg\exists x(Q(x) \wedge R(x))$—There is no x such that $Q(x)$ and $R(x)$ are both true.

Premise: $\forall x(\neg R(x) \rightarrow \neg S(x))$—Not $R(x)$ implies not $S(x)$ for all x.

Conclusion: $\forall x(P(x) \rightarrow \neg Q(x))$—$P(x)$ implies not $Q(x)$ for all x.

It looks intimidating, but they know that they can *figure it out*.

Our subsequent module on proofs is a great example of getting comfortable with discomfort and figuring out. Proof-writing is a notoriously hard topic where math anxieties peak. I tiptoe into these waters starting with proofs that, at first glance, seem easy enough. Here's one:

Theorem If $m \in \mathbb{Z}$ is even, then m^2 is even.

I teach students general techniques that they can apply. I teach them about *I teach students general techniques that they can apply. I teach them about*. I teach them that sometimes it helps to break down a problem into smaller parts, i.e., cases. However, these are all just tools that may or may not be helpful for their problem at hand. There is no step-by-step guide I can give to a student tasked with proving a theorem. They need to open their toolbox and pick one to try. And if that tool doesn't work as planned, they need to put it back and pick up another one.

It is precisely in this moment—when a student wrestles with a problem that scares them—that they sit in an opportunity for growth. If they can work through it, they now have one datapoint for their memory bank of a time when they looked at a daunting mathematical concept and figured it out. Next time they are in a similar situation, they are less likely to panic and more likely to start figuring.

Can't all this happen in applied math too? Yes, of course. However, a subtle (but I argue, important) distinction when centering the importance of application is the focus on functionality rather than understanding. Applied math serves to solve a known problem with a known answer in a known way. Our implicit message to the student is this:

Someone (really smart) already figured out that this is the set of steps you take to solve this IST-related problem. You should commit these steps to memory and then use them when you see that problem come up again on the test or, ideally, outside the classroom.

Unfortunately, chances are that when that problem shows up again outside the classroom, it will look different than it did in class. The more time passes, the more likely that is to be true. But even today, most real-world applications of concepts of discrete mathematics in IST are far more nuanced and complicated than what we can show in the classroom (more on this in a moment). The set of steps the student memorized will not apply. Rather, we hope that the way of thinking we taught them will apply. So, if we agree on that, let us agree that building that way of thinking should be the goal from the start.

The conceptual concerns I've presented about application-driven mindset may seem overly academic, but they are manifested in tangible ways when compounded with practical realities. All math courses in IST try to cover a lot in a limited time. At Penn State, IST 230 is the one-semester course tasked with teaching students (all of) discrete math. The topics "covered" on this list would amount to at least four semester-long courses in an undergraduate mathematics curriculum, e.g., logic, set theory, number theory, and graph theory. This, of course, means we need to pick and choose where we spend more time and where we give just a light touch. Our teaching philosophy and our expected outcomes guide these decisions. For example, the logic and proofs I mentioned earlier in this chapter would likely be first on the chopping block in an application-driven course. Those concepts underlie all of programming, but, with limited time and an application-driven focus, you might be better off skipping those.

In-Class Strategies

If I've convinced you thus far that a more theoretical flavor is a worthy goal, you might wonder what steps take in the classroom to engage in this way. Here, I share some ideas, grouped according to high-level strategies that each instructor might interpret based on their classroom dynamics and teaching style.

Normalize Being Stumped

Use history to inspire Students might be surprised to learn that the world's greatest mathematicians spend much of their careers tackling problems that may take them years to solve or which they may never solve at all. Share with them, e.g., the inspiring story of Fermat's last theorem (Ribenboim, 1979). In 1637, Pierre de Fermat scribbled a note in the margin of a page of his copy of Arithmetica, an Ancient Greek text written by mathematician Diophantus of Alexandria (c. 250 BE). The note states that the following equation is unsolvable with positive integer values of x, y, and z, for all n greater than 2:

$$x^n + y^n = z^n$$

Fermat writes (translated):

I have a truly marvelous demonstration of this proposition which this margin is too narrow to contain.

After 358 years and the career-long dedication of countless mathematicians, Fermat's last theorem was finally proved in 1994 by Andrew Wiles, a professor at Princeton (Wiles, 1995). There are many stories about landmark problems and the mathematicians who devoted themselves to them of similar intrigue and magnitude in the history of mathematics. These anecdotes can serve to humanize and even glorify not knowing, figuring out or even never figuring out, and creativity.

Students might be intrigued to learn the notion of undecidability, i.e., some problems simply cannot be solved using the axioms of mathematics. One might present, for example, the 2015 finding that an important and long-standing mathematical problem underlying fundamental questions in particle physics and quantum physics is provably unsolvable (Cubitt et al., 2015). That example also gives students very tangible picture of recent and ongoing advancement of the field of math (vs. math as a relic of the past).

Use today for context In this vein, students might be surprised to know that there are many important unsolved problems still today. And, in fact, new problems continue to emerge as the field moved forward. This is the essence of research. I tell my IST 230 students about The Millennium Prize Problems,[1] seven open problems in mathematics with $1 Million prizes now attached to their solutions. Several times, students have followed up with me in the next class or in office hours to discuss them. They independently read those problems and, at least for a moment, perhaps thought this way their opportunity to make their million dollars.

In the classroom, one might consider devoting 20–30 minutes to let students experiment with an open problem themselves. One does not need to let the students know from the outset that the problem is unsolved but pick something relatively straightforward and let them work through the process of figuring out. Coloring problems work well at this level, I have found, and could be placed within a module on graph theory. You might ask students, essentially, to prove or disprove the four-color theorem (Gonthier, 2008)—that is,

Theorem Given any separation of a plane into contiguous regions, the regions can be colored using at most four colors so that no two adjacent regions have the same color.

Give each student four colored pencils and ask them to figure out whether this statement is correct or incorrect. Let them work in groups and bang their heads against it for a while. When it is time, they might be thrilled to know that the four-color theorem was not proved until 1976, despite more than 100 years of effort and many false proofs and counterexamples. Even then, it was proved only with the support of software.

Incorporate Puzzles, Games, and Fun

The correlation between liking math and perceived aptitude was very high in the in-class survey I deployed this semester (referenced in Fig. 1). In fact, no student had more than a 1-point difference between their two responses. Hence, it might be true that helping students find math more enjoyable might also help to improve

[1] Here is the Millennium Prize Problem as webpage: https://www.claymath.org/millennium-problems/

confidence and reduce anxiety. This idea has also been suggested in prior work (Middleton & Spanias, 1999).

To this end, using puzzles and games in class is an intuitive idea. Discrete math, luckily, is ripe with these opportunities. There are also some wonderful websites that collect and categorize these games and wonderful volumes on recreation mathematics (Bogomolny, 2024). During the course module on Boolean logic, one might spend a class period having student teams create games with logic gates. With some guidance, teams can create tic-tac-toe or river crossing games, e.g., Ascher (1990). During the course module on probability, for example, one might reenact the Monty Hall problem (Gill, 2010) with real (small) prizes.

One source of a multitude of puzzles, stories, and fascinating ideas is Douglas Hofstadter's 1979 masterpiece Godel, Escher, Bach: An Eternal Golden Braid (Hofstadter, 1999). The work has been so influential, in fact, that there have been undergraduate courses at MIT, Stanford, Dartmouth, and elsewhere dedicated entirely to the text. Many of the concepts at the center of the book, e.g., logic and recursion, are central to discrete mathematics. But indeed, the book could no doubt fit in beautifully as a source of enrichment for any mathematics course in the IST curriculum. For student inclined toward art, music, literature, and philosophy, the book will be particularly meaningful. But it is also worth noting the focus of GEB on linking mind and machine. In that way, it is also germane to IST and promotes creative thinking about technology that I have heralded throughout the chapter.

Rethink Grading

Finally, I think it is important to address issues around grading, although, I myself have few answers yet in this regard. I have seen students' laser focus on grades undermine growth mindset and willingness to be wrong that I have argued we need to encourage. Worry about grades, of course, heightens anxiety. In retrospect, I wish that I had included a question on my class survey about grades in prior math classes. I assume that all three—past performance, perceived difficulty, and enjoyment—are closely intertwined for most students.

To some extent, students' focus on and anxieties around grading cannot be avoided if we are to engage with grades at all. However, we can redesign grading practices in IST-related math courses to better serve our learning objectives and send a clear message to students about the behaviors and skills we value. Specifically, traditional grading based on homework correctness, timed exams, etc., sends the message to students that having the right answer or, worse, being able to parrot the right answer quickly is the goal.

Certainly, there is a body of work we can lean on in this regard. Research in education has much to stay about the alignment between grades and standards to promote learning (O'connor, 2017). Future work should explore grading strategies that support the objectives I have laid out.

Conclusion

Looking back, many of the key moments I can pinpoint on my path to a PhD in math and a career in IST research involved fun and exploration, free from concerns about why I needed to know it or why it mattered in the real world and free from concerns about evaluation. I loved playing with the abacus my parents gave me as child and playing Math Blaster! on our first family computer in the early 1990s.

In high school, I had the opportunity to explore some wonderful college math courses at a nearby university. I could pick courses I was interested in and attend them, but I was not expected to turn in assignments or take exams. Because there was no evaluation and no pressure, I selected topics that really interested me despite how daunting they seemed. I took a class in string theory one semester. I understood so little, but nevertheless, I remember feeling a rush just sitting surrounded by those big ideas. A young woman, I assume a graduate student, taught the class. I was mesmerized by her.

I had a similar experience in 2004. I was a junior in college. Manindra Agrawal spoke to a packed audience. He and collaborators had recently published the first polynomial-time primality test (Agrawal et al., 2004). With a few classmates, I took a NJ Transit train from New York City to Princeton to see him speak. I could not understand the details of the proof, but I felt the gravity of the moment. I knew that I was witnessing history; more specifically, I saw that math is alive, it is dynamic, and it precedes technology rather than responds to it. Mathematics is almost never motivated by application. By the time you know what you "need it" for, it must be there. That is the business of mathematics.

Among these formative experiences, there are common threads: curiosity; freedom from evaluation; untethering from real-world application; self-motivation; self-confidence; and self-esteem. When we develop information scientists, data scientists, and AI and technology researchers, I argue, we need to teach them mathematics the same way we teach mathematicians—not from an origin of application but treating application as a possible or plausible destination. This is because, like mathematicians, we are laying groundwork for a world of possibility.

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