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INTRODUCTION

Teaching Real Science to Real Students: On Being a Thoughtful Science Teacher and Doing a Good Job

The category of people who call themselves science teachers—and I include myself among them—is filled with thoughtful individuals who sincerely want to do a good job in teaching science to students. As science teachers, we want our students to solve problems, think critically, and have a depth of understanding about big scientific ideas and important science practices. We also take seriously our responsibility to the scientific community to ensure that generations of hard-won knowledge gets passed along to the future with fidelity. Many of us cannot resist cultivating in our students the same sense of wonder about the world that we ourselves feel when we are engaged in science. And we think long and hard about the reasons why first-rate science teaching is not happening everywhere and for all students.

For most, teaching science means ensuring that students gain a deep understanding of the big ideas that have helped human beings to shape the world in which we now live. For many, teaching science also means trying to level the playing field so that students in resource-poor communities have access to the same learning opportunities as those in more well-off places. In some schools, the reasons for learning science are intimately linked to community issues of environmental justice, while in others science is framed as simply one component of a well-rounded education. In some elementary and middle schools, science is highly-valued as a vehicle for literacy and mathematics instruction, while other places emphasize the creative aspects of scientific inquiry and attend to the ways in which scientific knowledge is generated in the first place. In many cases, the grades that students earn in science classes become a currency that can be later exchanged for class rank, college credit, and future employment.

Out of necessity, real science and school science are not always the same thing; science is a vast and sprawling enterprise, and transforming it into school science is part of an effort to make scientific knowledge accessible and understandable to young minds.[1] Science embodies a way of thinking about the world that uses empirical evidence as the basis for knowing, yet it is often taught in schools in ways that compel students to rely on the authority of teachers, or at least a "right" answer written down somewhere. Real science is messy and uncertain, with lots of false starts, dead ends, and noisy data. By contrast, school science is often neatly divided into textbook chapters, sub-topics, and bite-sized bits of information that can be efficiently assessed by teachers. Real science is as much concerned with asking questions as it is with answering them, while much of school science still focuses on recalling facts and solving problems. The exceptions of course, are in classrooms where teachers have made room for students' own thinking, where the spirit of inquiry thrives.

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Though thousands share the job description of "science teacher," many have very different experiences in their work lives, and the range of issues faced by teachers in schools reflects the diverse nature of their employment. Even just within the United States, the variety in these situations is breathtaking. Here are a few examples of the types of schools and contexts in which science teachers work—informed by real examples of places I have encountered in my own research and practice as a teacher educator:

- A school that is sufficiently resourced, with functioning laboratory spaces and annual departmental budgets for ordering supplies, that also has an underlying cheating epidemic driven by high-stakes testing.
- A middle school in a high-poverty urban neighborhood that has a robust science department led by a team of charismatic and collaborative teachers, who continue to find ways to make every student want to learn science.
- A rural school that struggles to hold onto its agricultural science program in the face of a changing population with little experience or prospects in farming.
- A magnet school that focuses on science and technology, where the degree of teacher autonomy is rivaled only by an exhausting range of instructional quality.
- An elementary school where teachers gladly trade autonomy for confidence in their own teaching by using science kits; where a small minority of teachers modify directions and repurpose the materials to give their students a more authentic experience with scientific inquiry.

There are science classrooms within walking distance of one another that might as well exist in parallel universes, because the work of science teaching and learning is so different in each. Yet the underlying mission for every science teacher—even taking into account the local curriculum and state standards—can be stated quite simply: in teaching science, how do I meet my students where they are?

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There are many books about teaching science that are full of lesson plans, activities, science demonstrations, and collections of tips and tricks. I love those books, and have leaned heavily on them in my teaching, but this is not one of them. Rather, this is a book about the intellectual work of science teaching, undertaken by teachers for the purpose of shaping the subject matter they know and love for the specific students they teach. It is a connected set of essays orbiting loosely around the idea that the decisions made by good science teachers help light the way for their students along both familiar and unfamiliar pathways to understanding. Deeply embedded in the genome of this book are the principles and ideas from the Next Generation Science Standards, as well as ongoing research in science education and science teacher education.[2]

As a job, science teaching has been needlessly constrained by widely-held, impoverished conceptions about teaching, which view it as the controlled delivery of information from teacher to student. It is my conviction that the world of ideas needed by thoughtful science teachers is much broader than this. The purpose of this book is to enrich the intellectual ecosystem of science teachers as they consider daily how to be a good teacher to all of their students. Because my own work is primarily with new teachers, many of these essays are also about learning to teach science, and how one needs to take competing aims into consideration in order to make decisions in the classroom that lead to the outcomes we want. Occasionally those decisions may involve acts of what U.S. Congressman and civil rights activist John Lewis often calls "good trouble," in which teachers consciously push back against systems and practices that harm students, and challenge long-held institutional or cultural norms that place barriers in the way of students' academic achievement and passion for science.[3]

I spent the first decade of my career as a science teacher in suburban, rural, and urban public-school classrooms, teaching mostly chemistry and physics, along with occasional earth science, biology, or algebra class assignments. Serving twice as a science teacher in the U.S. Peace Corps, first in Kenya and then in Papua New Guinea also gave me a different and more global perspective on science teaching. It also made me rethink my identity and privilege as a white male in teaching subjects that offered access to valued knowledge for students who were often marginalized in schools. Then for the next dozen years, I became involved with university-based science teacher education, where I work today, mostly with students preparing to be secondary science teachers in diverse classrooms. It is no small coincidence that the range of contexts I have experienced in my work informs the central theme of this book: that the main intellectual work of science teachers is figuring out how to make connections between their subject matter and their students. I will argue for the remainder of this book that doing a "good job" as a science teacher requires a thorough knowledge of one's students, a flexible and ever-deepening understanding of the science, and a continuing attention to ways in which the science can be made accessible to students so that they might learn it.

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This book is organized into three sections, and the chapters all draw upon real-life science teaching to provide examples of what high quality science teaching looks like. The first section, titled "Student Ideas Are the Raw Material of Our Work," develops the theme that students' prior knowledge ought to be considered a resource rather than an obstacle, and that the intellectual work of good science teaching is thinking about ways to connect the content with what our students bring to learning. Chapter 1 explores the intersection between culturally relevant pedagogy and science teaching through the lens of valuing student ideas. Chapter 2 focuses on the practice of eliciting student ideas so that they may be used productively in the classroom. Chapter 3 is a short but necessary chapter addressing the need for respect and wonder when encountering new student misconceptions. This chapter suggests that when students are sincere about odd ideas, we are being given a gift that will help to teach them. Chapter 4 presents the case study of a teacher, Mr. Teague, who demonstrates what it means to really value students' ideas through the practice of *not* answering his students' questions.

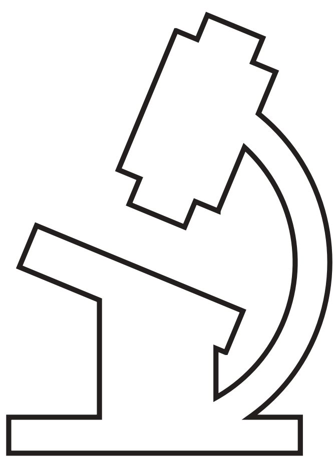
The next section, titled "Real Science, Real Students," addresses the day-to-day issues that occur in science teaching, approached from the perspective of reconsidering the commonplaces of the classroom, such as asking questions, planning, labs, demonstrations, safety, and field trips. Chapter 5 makes a case for the use of essential questions in science class as a way to provide a rationale for units, and connect the science content to real-world issues. Chapter 6 reconsiders the use of laboratory activities, and offers a different view on how science teachers might approach them from the perspective of engaging in model-based inquiry. Chapter 7 continues this discussion about models by examining the role that simulations might play in science learning when they are thought about as models themselves. Chapter 8 takes a fresh look at what safety goggles have to teach us about scientific practices, and Chapter 9 looks at what field trips and guest speakers still have to offer science teachers in an age when their use is becoming increasingly scarce. Chapter 10, which originally appeared in *Rethinking Schools*, tells a story that combines all of the themes in this section, when a field trip to tap maple trees in a city park led to a surprising confession.

In the final section, titled "Science Teacher Learning," the focus is placed on the ways in which novice and veteran science teachers alike improve their teaching practice. Chapter 11 draws upon the legacy of Michael Faraday to create parallels between making observations in science, and learning from watching other teachers teach. Chapter 12 which originally appeared in *Phi Delta Kappan*, deals specifically with the challenges of mentoring student teachers and novice teachers in science classrooms, and offers practical advice for doing so. Chapter 13 is a thought experiment on teacher expertise, situating teacher learning about the practice of differentiating science instruction within the mastery traditions used in martial arts. Chapter 14 concerns the perennial issue of the need for teachers to learn new science, and grapples with the dilemma of deciding what to do about gaps in our knowledge once we have identified them. Chapter 15 moves beyond individual teacher learning to the larger debates about the purposes of school science, and concludes with a closer look at the ways in which real science intersects with the framework of mass public education, examining the tension between school science realists and reformers.

The book ends with a brief and heartfelt plea in the afterword for capable individuals with talents in science to consider science teaching as a career. It is my sincerest hope that this appeal is copied, passed around, and acted upon, because regardless of the reason, our profession is still short-handed and could always use a few more thoughtful science teachers, willing and able to teach real science to real students.

Notes

1 For an extended discussion of this idea, see Popkewitz (1987), and also Cuban (2013).
2 Both The Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (National Research Council, 2012), as well as the Next Generation Science Standards (Achieve Inc., 2013) are important documents for understanding the consensus reached over the past four decades about science education both in the United States and around the world. However, just as the decoding of the human genome led to a new set of problems about understanding the relationship between genome and living organisms, so too does the publication of these standards documents lead to a need to better understand how the desired outcomes of science education are related to the daily work of science teachers. Some believe that if only we have well-designed curricula that reflect these standards, science education will improve. There is truth in this, but I focus my efforts here on a vision of science teachers as autonomous professionals who make continuous decisions for their students' learning, and the curriculum is but one component of this complex job.
3 This is a common refrain from Congressman Lewis, and he has frequently used the phrase as a hashtag (#goodtrouble) on social media (Mettler, 2016). When I was a teacher at Trenton Central High School in New Jersey, one of my physics classes was unexpectedly interrupted by a surprise visit of Congressman Lewis to our school, and I first heard him speak the phrase "good trouble" in telling his life story to our students that day. His recollection of sidestepping the advice from his parents to stay out of trouble is recounted in his book *Walking With the Wind: A Memoir of the Movement* (Lewis & D'Orso, 1999).



PART I

Student ideas are the raw material of our work

1

AIMING FOR CULTURALLY RELEVANT SCIENCE TEACHING

An Argument for Meeting Our Students Where They Are

Raising her hand during a class discussion on genetics, a tenth-grade African American girl in Teresa's eighth-period biology class asked, "Is there a reason that people with darker skin are more inclined to have high blood pressure and things like that?" Having been involved in undergraduate research projects on this topic both in genetics and sociology and earning top grades through all of her courses as an undergraduate, Teresa was readier than most student teachers to answer this question.

Her cooperating teacher, however, was not. This question landed as unwelcome because of the way it interrupted the planned and orderly transfer of information from the teacher, through PowerPoint slides, to the students. "Well, typically in black culture," she began, "they eat a lot of soul food…"

This was more than Teresa could bear. As a Latina—though if pressed she preferred to identify as Dominican—she had experienced this type of racism before, and now felt it even more keenly on behalf of the handful of students of color in this primarily white class. And though it felt risky because of her status as a student teacher, she decided it was necessary to interrupt her cooperating teacher and cause some good trouble.

"Oh my gosh! That's not why!" she said, "Increases in things like high blood pressure are often associated with stress. I have read several studies where it shows that because of the higher incidence of stressors in the lives of minorities, you see strong correlations between highly stressful lives and high blood pressure, and that usually has to do with institutionalized racism, and the possible stresses you'd endure being a minority in this country." She also described to her students the ways in which limited access to supermarkets and fresh food in many minority communities represented another aspect of systemic racism. After a momentary pause—and having nothing further to add—Teresa's cooperating teacher simply continued the genetics lesson.

Teresa told me what happened later, when a few of the students of color had approached her after class. "One of the girls came up," Teresa said, "and she was like, 'That was really cool. Nobody ever talks about *us*.' And she said '*us*' like that."

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In her book, *The Dreamkeepers: Successful Teachers of African American Students*, education researcher Gloria Ladson-Billings identified teachers whose African American students were deemed successful by both the school administration as well as the students' families.[1] Such an assets-based approach turned decades of educational research on its head by looking at what was worthy and good, rather than what was wrong, in the education of black students. In this research, Ladson-Billings looked for commonalities across eight very different teachers, whose classroom practices varied a great deal. With the help of those teachers, she ultimately developed a theory to explain the successful teaching she witnessed, giving it the name *culturally relevant pedagogy*.

A large part of the practice of science—and I include educational research under that umbrella—is the development of models to explain observed phenomena. Models have *explanatory power* to describe how different parts of a system relate to one another, and they also have *predictive power* that can help us reason about what might happen with other inputs or in different circumstances. Consequently, the quality of a model is judged by how well it explains the data, makes predictions, and fits other accepted explanations about the way the world works. Scientists tend to think that a model is on to something when it starts becoming generalizable; offering coherent explanations for other phenomena beyond what it was originally intended to explain. Models are often dynamic, and undergo revisions over time in order to better explain or predict a wider range of observations. Sometimes they are overhauled entirely when anomalous data makes the model no longer plausible. This point is important because it reminds us that models serve the data, and not the other way around.[2]

All of this is to offer a reminder that Ladson-Billings' theory of culturally relevant pedagogy is such an explanatory model, because what her Dreamkeeper teachers had in common was:

- They all had high academic expectations of their students,
- They all offered students regular opportunities to sustain themselves culturally; that is, students were validated in the classroom as cultural individuals, and
- They all sought to develop their students' sociopolitical consciousness so that students could critically analyze the factors that supported social inequalities.

The consequences of understanding the theory of culturally relevant pedagogy lay in its predictive power, with the underlying idea being that when other teachers of African American students engage in these practices, this model predicts their students are more likely to experience success in school.

Teresa's response to her student's question exemplifies all three of these aspects of culturally relevant pedagogy. Rather than witness her students be forced to accept a simplistic and wrong answer, she was prepared to offer a more detailed and sophisticated explanation with deeper connections to the content; which she expected them to understand. And rather than permit the airing of insensitive tropes about black people in a science classroom and allow that action to impact the ways her African American students thought about themselves, Teresa intervened to make sure that her students did not have to accept a caricatured view of themselves and their culture as a price for access to learning about genetics. Finally, Teresa encouraged her students to transform the lifeless knowledge being delivered to them into a tool for understanding and acting on their world. By reframing the issue from an individual matter to a systemic problem, Teresa was raising her students' awareness of the ways in which scientific knowledge matters to human beings organized in society. In a very clear way, Teresa was demonstrating the authentic relationship between scientific knowledge and her students' lives in the world beyond the classroom.

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In my experience, teachers coming into contact with the phrase *culturally relevant teaching* for the first time tend to focus on the root words—culture and relevance—in an effort to make sense of what it might mean for their own pedagogy.

The term *culture* has a common meaning that is often used in reference to the everyday practices—including language, cuisine, and artistic expression—that constitute the ways in which people behave and think. In the field of anthropology, the concept of culture serves as a way to think about the set of rules that guide the habits, behaviors, and norms of a given group of people. From a psychological perspective, culture is the set of perceptual filters that help people interpret the world through an existing framework of understanding.

The slipperiness of the way *culture* is used in everyday speech reflects common misunderstandings about race, ethnicity, and language. All too often, the term is used in the United States and elsewhere as a simplistic proxy to refer to the habits and practices of people who are non-white and non-English-speaking. In this way, some white teachers come to believe that they do not have a culture—only the "other" has cultural practices and beliefs—and that culture is something frozen in time, immutable.[3] Neither is in fact true.

The common way of thinking about *relevance* is in the connection of teaching to something that students are familiar with or care about. One of the reasons we aim for relevance in our teaching is that it serves as a scaffold for learning, providing landmarks for students so that they can recognize where they are. Relevance is valuable, but can be fleeting, especially when rooted in popular culture or if the connection is not particularly strong.

Relevance also relates to issues of childhood growth and developmental appropriateness, and I am reminded of one student teacher in particular who tried very hard to make his teaching relevant for his students.[4] He was quite interested in video games, and as a result many of the examples he used in class at the beginning of the year were drawn from whatever latest game he had played, his idea being that kids loved video games and that mentioning them in conjunction with science would foster their interest. However, his students were in 6^{th} grade in a low-income school, and not only were many of the games targeted at mature adults, they were also simply quite expensive. Instead of providing scaffolds for learning, his examples simply sowed confusion.

Relevance provides students with opportunities to connect new ideas to familiar old ones. When a biology teacher begins a unit on mitosis by asking students to raise their hands if they know someone who has had cancer, he is helping to make explicit connections between subject matter and students' lives. When a physics teacher starts a lesson on Hooke's Law by going around the room and asking where in their lives students have seen springs, she is priming the students to think about all the different places (screen doors, underneath cars, click pens, etc.) where the topic under study intersects with their lives.

In a way, the case for relevance in teaching is really an argument for authenticity, and the removal of barriers to learning. When topics of study are authentic, the degree of relevance to students is immediately apparent. The learning task has an immediate connection to the real world, even more so if it involves accountability to a real audience beyond the classroom. When we choose examples that are familiar to students, we avoid raising roadblocks between their current understandings about the world and what we want them to learn, permitting students to reckon with the science.[5]

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Recall that Ladson-Billings' model of culturally relevant pedagogy states that African American students of teachers who have high academic expectations of their students, regularly offer opportunities for students to sustain themselves as cultural beings, and work on developing their students' sociopolitical consciousness, can reasonably expect to experience success as measured by both their schools and their families. This model has been bolstered now by over two decades of empirical work since it was first published.[6]

When teachers sustain students' cultural identities, it means that students do not have to check their culture at the door as a prerequisite for learning science. Not only that, but teachers who encourage students to be fluent in more than one culture, more than one way of viewing the world, also find opportunities for language and culture to intersect with the content of the lesson.[7] Doing so can also provide an access to the culture of science.

For example, a physics teacher can take time to explore the Spanish word *velocidad* in a lesson on vector and scalar quantities, and help all students think about the differences between *speed* (which just has a magnitude) and *velocity* (which has both magnitude and direction). The Spanish *velocidad* does indeed represent a vector quantity, but has an everyday usage similar to *speed* in English. Spending a short amount of time on this distinction can help students clarify their understanding of physics, as well as helping them to develop conceptual fluency in two languages. Teachers who keep their eyes and ears open for clues about their students' lives outside of school are more likely to identify such teaching moments.[8]

For many teachers, the first step toward sustaining culture is just getting out of the way, and resisting the urge to prevent students from using familiar patterns of communication and engagement, and then leveraging those student resources for deeper learning.[9] I recall a visit to one of my favorite biology classrooms, when the students had aggregated their class data into a table on the whiteboard at the front of the room. I watched as one student took out his phone and snapped a photo of the class data set on the whiteboard. In many schools and classrooms, phones are subject to strict regulation, even as they form the nervous system for adolescent culture at all socioeconomic levels. The teacher in this class had intentionally created a classroom environment in which cell phones were permitted—skirting the edges of school policy—as long as students could justify their use for a scientific purpose. Drawing on both his generational and cultural identities, the student's natural impulse was to use his phone to take a picture of the data, and by encouraging the student to leverage this, the teacher created a space for culture to influence science learning.

Teachers can make these spaces with language as well. As a high school physics and chemistry teacher, I had frequent reasons to count to three, usually for demonstrations when I was about to drop something, switch something on, or light something on fire. Occasionally we might go up to five or six when counting off groups, something we do often in the university classes I now teach. The first time I do this with a class, I typically use Swahili and make my students count: *moja, mbili, tatu* with me. In any given classroom, there can be many different language resources among the students, and if we as teachers leverage these into a cognitively manageable activity like counting, we can get to learn things about our students that we might not otherwise know. I typically try to get students to suggest a language we have not yet used, and there are always surprises beyond the Spanish and French that many students already know; in my classes we have counted in Quichua, Pashto, Bengali, American Sign Language, Portuguese, Ibo, and many other languages. I try to pick a different one each time—and make the whole class say it with me. A student may never have heard their home language in a science classroom before, and my experience is that even this small gesture communicates that they do not have to leave that important piece of who they are at the classroom door as the price of admission for learning science.

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It also turns out that using relevant and authentic phenomena for investigation helps teachers see a role for their students' cultural resources in science class. Further, when we choose ideas that help develop students' sociopolitical consciousness, we give them an opportunity to critically examine and address issues of justice, fairness, and power—and science no longer seems disconnected from everyday life. For students who experience injustice, unfairness, and powerlessness in their lives, the answer to the question "When will we ever use this?" is self-evident in these classrooms.

It seems to me that some teachers are overly eager to apply the term "culturally relevant" to their teaching. Similarly, some education researchers and publishers will make claims about the "cultural relevance" of a particular teaching approach, professional development, or set of curricular materials. I often find these claims to be something of a stretch, and wonder if the appropriation of the phrase is primarily for the purposes of self-promotion or out of a desire to be perceived as progressive. This seems especially true when successful outcomes for black students—like the ones whose success was the phenomenon Ladson-Billings set out to explain—are nowhere in sight.

In sharing these ideas—and early drafts of this chapter—with preservice science teachers, one frequent comment was that a teacher like Teresa was more easily able to engage in culturally relevant teaching because of knowledge gained through her own life experiences. Certainly, navigating her own identity growth while making sense of how she was perceived by the dominant culture permitted Teresa to develop an understanding of how harmful stereotypes could be perpetuated in schools.[10] The self-reflective question raised by some preservice teachers in these conversations was: what happens when this is not the case? I found drawing an analogy to learning science content to be convincing in response. Just as a novice might recognize that they need to improve their understanding of biology, chemistry, physics, and earth science in order to be an effective science teacher, so too must teachers who grow up uncritical of the operation of the dominant culture recognize that they have some catching up to do if they are going to be good teachers to all of their students. Admitting one's ignorance, and taking ownership over the responsibility to learn, is a necessary first step.[11]

A teacher like Teresa—fighting to ensure that the science her students learn is less burdened by racism—is not necessarily seeking recognition for enacting culturally relevant pedagogy. Rather, she has internalized its underlying tenets as a consequence of wishing to do right by her students. She has high academic expectations, aims to sustain her students as cultural beings, and works to develop their sociopolitical consciousness not because she is following a formula to be a better teacher, but because she genuinely wants the science taught to her students to be correct and deeply learned. She also sees the laziness of status quo science teaching as actively harmful to students of color and white students alike because of the ways in which knowledge is passed along uncritically. And like the teachers who Ladson-Billings calls *Dreamkeepers*, she takes responsibility for the success of all of the children in her care because she sees her own fate as intertwined with those of her students.

Notes

1 A friend gave me a copy of *The Dreamkeepers* (Ladson-Billings, 1994) just after I had been accepted into graduate school at the University of Wisconsin-Madison, and I was pleasantly surprised to see that the author was a professor there. After I read it, I immediately signed up for her class on Multicultural Perspectives in Education. The class was over-enrolled but she let me in anyway. Shortly thereafter I asked her to be my advisor, and I remain grateful two decades later that she agreed.

2 Models certainly serve to evaluate the validity of new data. As Kuhn (1970) notes however, it is more typical in "normal science" for anomalous data to represent edge cases or faulty measurements rather than signal the start of a scientific revolution in which old models fail and new models are adopted. Morris (2018) thinks Kuhn took

things too far (and had an ashtray thrown at him by Kuhn for telling him as much) because he conflated the models with reality itself.

3 Sleeter's (2001b) discussion of this phenomenon in teacher education explores its impact in detail. In much of her work (Grant & Sleeter, 1985; Sleeter, 1993, 1994, 2001a, 2015), Sleeter suggests strategies for resisting and countering the effects of the dominant culture of whiteness in teaching, curriculum, school structure, educational research, and teacher education, while also recognizing the cultural aspects of whiteness itself.

4 The work of Margaret Beale Spencer (2008) reminds us that even notions of what is "developmentally appropriate" have been tilted towards a conflation of whiteness with normality.

5 The removal of barriers to learning is also a central theme in the Universal Design for Learning curricular framework (Meyer, Rose, & Gordon, 2016).

6 Just to point to one tangible example, Claude Steele's work on stereotype threat (Steele, 2010) investigates the psychological mechanism through which expectations influence academic performance, and he demonstrates how specific positive affirmations of cultural competence serve to mitigate negative effects. There is a clear link here to Ladson-Billings' (1994, 1995, 2006, 2014) work on culturally relevant pedagogy.

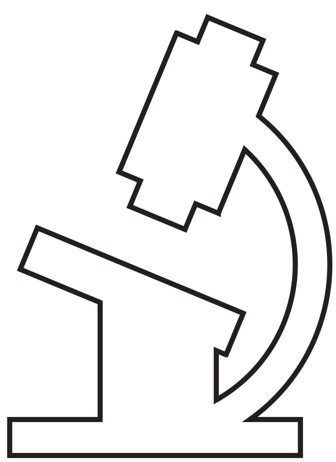
7 Banks (1995) terms this the content integration dimension of multicultural education.

8 I am surprised at a how often this idea seems to be interpreted through the lens of essentialism within the everyday discourse of teachers, as if there is one approach for teaching science to Black students, another for Latinx students, etc. My suspicion is that there are cognitive parallels between this sort of flowchart-inspired thinking and the largely discredited folk beliefs about "learning styles" that remain endemic among education professionals (Willingham, Hughes, & Dobolyi, 2015).

9 There is a rich scholarship in science education on this point. See for example: Bang, Warren, Rosebery, & Medin, 2013; B. A. Brown, 2006; B. A. Brown & Spang, 2008; Hudicourt-Barnes, 2003; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001.

10 This is an example of what Du Bois (1903/1993) called a "double consciousness." It is also a good argument for recruiting more teachers of color into the workforce (Villegas & Davis, 2008).

11 This is the central thesis of Gary Howard's (2006) book, *We Can't Teach What We Don't Know: White Teachers, Multiracial Schools*.



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2

ELICITING STUDENTS' IDEAS

Student Ideas as the Raw Material of Science Teachers' Work

None of the students could resist running their hand over the black bear pelt laid out on the table as they took their seats surrounding it. Before Tom could even say hello to the class, people started asking questions about the bear. "Was this caught up here?" one student asked. "What kind of bear is this?" another called out.

Tom, a master environmental educator working at the New Jersey School of Conservation, patiently answered each question, but purposefully did not go into too much detail. He had a question of his own he wanted to ask first. "So," he said addressing the students seated around the bearskin, "What do you know about bears?"

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Good science teaching starts with the premise that student ideas are the raw material of our work. In order to shape those ideas, we need to know what they are. Otherwise our teaching may be transient—like building sand castles or drawing on a sidewalk with chalk—and likely to fade over time, as students revert to ideas that are more familiar and make more sense to them than the science content the teacher intended them to learn. Only when students' ideas are out in the open does it become possible to engage in discussion about the intelligibility, plausibility, or the explanatory power of those ideas.[1]

This does not mean that teachers need to elicit every student's idea about every topic they teach. It can be enough to be aware that for any given science topic, there will be a percentage of students who hold one particular idea, while others will think differently. Even if we cannot predict who exactly will believe what, knowing the possible misconceptions that our students may hold will help us teach them.[2]

There are a range of wonderful strategies for eliciting students' ideas, and plenty of resources to help teachers do that, but here I wish to focus on the question of what we are actually eliciting their ideas about. One kind of elicitation—represented by Tom's question, "What do you know about bears?"—is designed to probe students for the cognitive and cultural resources they bring to the task of learning. In this type of elicitation, there is no need for students to justify their responses; the important thing is to get that prior knowledge out in the open.

When Tom asked, "What do you know about bears?" he knew that most of the students had likely heard quite a bit about bears in their lives. Others, particularly those who had grown up in places where bears were less a part of the culture then they are in the United States, might have less prior knowledge about bears and therefore draw more directly from the bear skin right in front of them. He also knew from years of experience that as students talked, he would hear a number of misconceptions about bears from students, and the conversational tone he used helped to put the students at ease because they were not being judged on the correctness of each idea.

Elicitations take stock of students' cognitive and cultural resources, and help teachers plan for instruction. A prompt for elicitations may take the form of an open-ended question that can be answered with a range of divergent responses. Examples include:

- "What are some reasons why we might look at things under a microscope?"
- "Where have you seen something made from rock in your everyday life?"
- "What are some situations where water might change from one phase to another?"

Such questions have multiple possible answers, and students' responses inform teachers about the existing resources that students can bring to bear on a further understanding of the topic. The best-designed prompts allow for every student to give an answer and participate in the discussion. This type of elicitation has its limits, however. In the examples above, students would need to have familiarity with microscopes, rocks, ice, and steam. If Tom had asked a group of first-graders, "Tell me what you already know about woolly adelgids," he might not have unearthed too many cognitive and cultural resources.[3]

I have had conversations with teachers who are skeptical about the whole notion of eliciting student ideas, and their argument goes something like this: if I am going to teach DNA transcription and translation to my biology students, it may be a topic that is brand new to them. In fact, their understanding about DNA may be so limited that if I ask them what ideas they have about transcription and translation, they are not going to have any because they have never even thought about those things before.

I would actually agree that it makes little sense to ask students at the beginning of such a unit, "What do you know about DNA transcription and translation?" There are many times when I have seen teachers engage in this type of elicitation at the beginning of a unit or lesson, and it almost always ends up positioning students as ignorant, as if they should already know.[4] The problem in such a case is that teachers are attempting to elicit prior knowledge about scientific *concepts* instead of tapping into students' ideas about a *phenomenon*. The distinction is subtle but important. Asking students about a concept they have never encountered before can be confusing for them. However, if you show them a phenomenon that requires crafting an explanation of some sort, even if it is simple, students can immediately begin by drawing on what they know and from what they have observed about the puzzling phenomenon.

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Imari cued up the video clip and got the attention of her high school biology class. "I'm going to play you a short segment from a documentary that has a mystery for you to think about," she said to her students. She pressed play and the video showed multiple clownfish brushing up against a sea anemone. The narrator on the video described how sea anemones use their stinging tentacles to paralyze, ensnare, and consume small fish. But clownfish, he continued, seemed to use the anemone's tentacles for protection from other predators.

"How can this be?" asked the narrator, at which point Imari stopped the video. She turned on the lights and said, "I'd like for you to get into your groups and come up with as many possible ideas as you can for that question. Give each idea its own sticky note. How might it be possible for a fish to live so close to another organism that is so dangerous?"

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A second kind of elicitation is illustrated by Imari's prompt to her students about the puzzle posed in the video, which allowed students to share their ideas even if they had never seen or heard about clownfish or sea anemones before watching the video.[5] In this elicitation, students were presented with a puzzling phenomenon and tasked with describing their ideas about how the unseen processes operate. Such an elicitation takes advantage of the human capacity for generating inferences and explanations.

For example, if I walk into a room, notice a burning smell and see a blackened popcorn bag next to a microwave oven, I can put together a fairly plausible explanation of what happened before I got there. The problem with elicitation prompts that are only about concepts is that they do not provide students the opportunity to create explanations. Imagine how different this lesson would have looked if Imari began by asking, "What do you know about mutualism?"

Eliciting students' ideas about a puzzling phenomenon offers an opportunity to explore the big ideas in the science curriculum in ways that are accessible and familiar to students. This is where the teacher's knowledge of students becomes critical, because by being familiar with both the students and the content, the teacher will be able to pick the phenomena that resonate with their students.

When we present students with a puzzling phenomenon, what we are really doing is giving them both an opportunity to draw upon their existing resources and put them together in a way that makes sense to them. For example, if we present students with a hot and a cold beaker of water, and put a drop of food coloring in each, the phenomenon is that the beaker with the hot water disperses the color much more rapidly than the beaker with the cold water. The elicitation question we might put to students in a case like this is: what ideas do you have about why the color spreads more rapidly in the hot water? In order to respond, students must draw upon whatever existing knowledge they have in order to construct an explanation. They may draw on their life experiences—like making juice from a mix or dropping tints into a bathtub—as analogies for their explanations. And even if the student gives a perfect textbook answer that reflects a sophisticated knowledge of kinetic theory, they can still be pointed towards other components of the phenomenon (like the downward trajectory of the food coloring drop) that still require explanation.

Phenomena can be videos, demonstrations, or even just simple descriptions of situations. Often, they describe events that unfold over time, and usually entail an unseen process in some way.[6] Students may not be able to explain the whole phenomenon, but often they are able to bring in ideas that hold the prospect of being part of an explanation. Even something completely foreign to students, like observing the slow fall of a strong magnet through a copper tube, can be the source for student ideas. A teacher who asks students for ideas to explain the behavior of the magnet—rather than asking, "Who remembers what Lenz's law is?"—will get much greater participation on the part of students, and also get everyone thinking.[7]

Prompts for elicitation can also be genuine questions that result from everyday experiences in the classroom. I was recently in one chemistry class where students reacted solid magnesium with hydrochloric acid, and then heated the resulting liquid until only a white solid remained. The class ran out of time and left the white solid in the evaporating dishes, and when they came back the next day they found that overnight the white solid had turned into a puddle of liquid. This was a good puzzling phenomenon, albeit one only tangentially related to the lesson on empirical formulas the teacher had planned for that day, and the teacher—abandoning the "do-now" he had previously planned for the first five minutes of class—made good use of the unexpected situation with a class discussion.

Science teachers who start keeping their eyes open for puzzling phenomena will begin seeing them everywhere. Recently in a grocery store in Colorado, my family and I noticed that all of the bags in the snack aisle seemed to be filled with a little extra air, making them more puffed out than they are in New Jersey. We bought a few bags for our ride through Rocky Mountain National Park, and later when we stopped the car at the alpine tundra, one small bag of popcorn on the center console resembled a balloon; there was not a single wrinkle or indentation in the bag. The signs told us that we were at 12,000 feet, about a mile higher in elevation than we had been in town. I took out my phone and began to record video of the swollen popcorn bag. It would make a great puzzling phenomenon.

Notes

1 This language comes directly from foundational work on teaching science for conceptual change (Hewson, Beeth, & Thorley, 1998; Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1992), which informs this chapter greatly.

2 The MOSART project report (P. M. Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013) makes the case that the ability to identify common student misconceptions is a valid measure of science teacher quality.

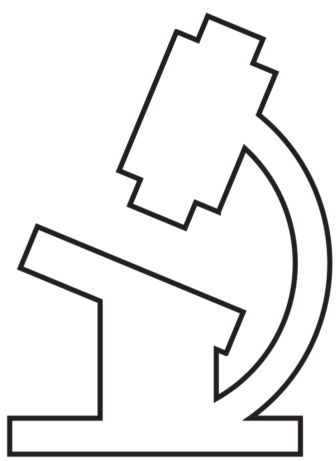
3 The wooly adelgid is an invasive species of aphid that has become a major killer of the hemlock tree population over the past decade in New Jersey and the northeastern United States. It is currently being fought with some success through the introduction of a predator beetle, Sasajiscymnus tsugae (Eschtruth, Evans, & Battles, 2013). I learned this at the New Jersey School of Conservation.

4 This can be worse if there are one or more students who do know, because it sends a message of academic exclusion to others.

5 Many students in the class immediately made a connection to the opening scene of the Pixar animated movie, Finding Nemo, in which a clownfish uses a sea anemone for protection from a predator.

6 Windschitl, Thompson, & Braaten (2008) developed a set of tools for teachers to use in the identification and development of phenomena appropriate for model-based inquiry, and note that good phenomena or "anchoring events" for classroom use have comprehensible causal underpinnings, (p. 16). See chapter 2 of Windschitl, Thompson, and Braaten (2018) for more detail on identifying big science ideas, selecting anchoring events and meaningful essential questions, and sequencing learning activities.

7 At the end of a summer working with teachers in Tanzania, I was sitting around a fire talking with a mix of Americans and locals, when one young Tanzanian man asked me what I taught in America. When I answered that I was a physics teacher, he stood up and said in a fast monotone voice: "A current induced in a circuit due to a change in a magnetic field is so directed as to oppose the change in flux and to exert a mechanical force opposing the motion!" He had just recited Lenz's Law. "I have no idea what I just said," he laughed with an undercurrent of resentment, "but it got me an A in physics." I think of him often whenever I am made aware of students who earn good grades without enjoying or even understanding the ideas of the science.



3

EVERY MISCONCEPTION A SHINY PEBBLE

Glimpsing Beautiful and Productive Extensions of Prior Knowledge

Donna moved among her students as they cut out the photocopied chromosomes from the handout. Unbeknownst to the students, there were 47 chromosomes, instead of the more typical 46 for humans, and when students made matched pairs, they would find an extra chromosome, do a little research in their packets, and recognize that the karyotype was indicative of a person with Down's Syndrome. It was an activity that Donna's cooperating teacher used every year during the genetics unit, and she was glad to see her high school students engaged in the lesson. She knelt down next to one group who was having a little trouble matching the chromosome pairs, and she drew their attention to the patterns of light and dark bands. "The size is more important than the shape," she said, "and look at the alleles." She pointed to the light and dark bands along the length of each chromosome shape on the photocopied handout. Of course, it was not scientifically accurate, but was an idea I had not heard before, and I was captivated.[1]

Every misconception I encounter is like a shiny pebble on the beach. I love looking at them, rolling them around, and trying to figure out where they came from. Donna's was not difficult to figure out, nearly every biology textbook has an illustration of a length of DNA highlighted on a chromosome to represent a gene, and Donna—even as a biology major in college—likely took that representation and interpreted the dark bands of densely-packed chromatin on the chromosome as exactly such a band. Further, she likely applied her knowledge of genetics in calling it an allele instead of a gene because she knew that in a chromosome pair, the gene might be coded slightly differently on each.[2]

This sort of forensic analysis of misconceptions is second nature to master teachers because in the process of unraveling the mystery of an idea's source, paths leading toward future understanding are also revealed. In Donna's case, this could be as simple as providing images of chromosomes under higher magnification, to show that the light and dark bands are a function of the coiling of the DNA. Donna could also be pressed to investigate how scientists know where genes begin and end, and whether that information can be visually ascertained at all. To an attentive observer, Donna's use of the word "allele" as a label is a key to understanding her whole cognitive architecture around the topic of genetics.

This is why I find it incredibly frustrating whenever I hear mockery of students' misconceptions, which happens a great deal more frequently in private teacher conversations than one might hope. When a student is sincere to us about an idea that seems absurd, we are being handed a map of their brain.[3] A teacher who interprets sense-making as stupidity is committing educational malpractice.

Sitting in the back of science rooms, I often get to hear the most wonderful misconceptions. One of my favorites happened in the back of a physics room, during a lesson on sounds and waves. Students were given the task of answering a series of questions from the board, and then constructing a concept map using a list of vocabulary words. They were permitted to work together, and one pair of students began to debate the meaning of the word *mute*. One student claimed that mute was a type of sound, while another said that it meant the same as quiet. It was not hard to envision the student's idea of a television remote broadcasting one type of sound wave that canceled out others. They each ended up making their concept maps their own way, but even that brief exchange gave me insight into how each of them was thinking about the nature of sound.

Sometimes misconceptions take a while to bubble to the surface. In one classroom where students were developing models on flip-chart paper to explain the dispersion of food dye in water, an interesting argument emerged between two groups of students. One faction felt that when the beaker of water turned a uniform color, the particles of dye and the water molecules were evenly mixed, as their model demonstrated with red (dye) and blue (water) dots evenly distributed. However, the other part of the class felt that because food dye changed the color of things, it had actually changed the color of the water molecules themselves. I think about how my own high school chemistry teachers might have handled this, and it is difficult to think about any response that would not contain some level of sarcasm or derision directed at the students for believing such a thing. There is a misconception among some teachers that giving voice to a wrong idea in a classroom is harmful, as if it could spread like an airborne infection. Decades of cognitive and educational research have found these fears to be unfounded.[4]

In this case, the teacher not only permitted a student-to-student discussion to occur in class, but also made sure to facilitate it in a way that gave each group an opportunity to question one another in a manner that furthered the conversation. When pressed by peers to explain whether or not they also thought that the dye was made of atoms and molecules, the color-change group seemed to give ground and admit that they had not quite thought of that. When conversations like these—in which the comparison of science ideas happens in the open spaces of the classroom instead of remaining closed away in the private recesses of students' minds—occur regularly in every classroom, those of us working to reform science teaching will know that we have made real progress.

Notes

1 It is reasonable to ask if misusing a vocabulary word or scientific term ought to be considered evidence that someone holds a misconception about an important scientific idea. This question quickly leads to Wittgensteinian debates about the relationships between ideas and language, but it does seem reasonable to concede that a misused word need not represent a misconception (Hofstadter & Sander, 2013). However, it may be a clue that a person's understanding of a central scientific idea or concept may not be aligned with that of the broader scientific community. For example, when someone refers to a warm winter day as "global warming," they are using a phrase that more properly refers to the measured fraction-of-a-degree annual average rise in global temperature, and serves as an indicator of the way that the person has organized their knowledge about climate change more generally.
2 It was a wonderful example of "faulty extensions of productive prior knowledge," to use the phrase coined by Smith, diSessa, and Roschelle, (1993, p. 152).
3 When I was seven and infatuated with all things dinosaur-related, I was genuinely convinced that all pebbles were fossilized dinosaur poop. The idea made total sense to me.
4 See Larkin (2012) for an extended discussion of this point.