Received: 28 March 2022 | Revised: 20 May 2022 | Accepted: 24 May 2022

DOI: 10.1002/sce.21742

ISSUES

Science Education WILEY

Getting to a good place with science instruction: Rethinking an appropriate conception of teaching science

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Abstract

This essay opens with a question about what science teaching would look like in a world where categorical seams of human diversity were not probabilistic determinants of science learning. After revisiting Hewson and Hewson's description of an "appropriate conception of science teaching," I detail the ways in which the field of science education has advanced in the decades since that article's publication. Drawing upon Cohen's notion of teaching as an "impossible profession," I highlight how conceptions of science teaching compete with other popular models of teaching and learning science. Fenstermacher and Richardson's distinction between *successful teaching*, and *good teaching* is then presented to demonstrate that even science teaching that is considered successful and good remains embedded in a constrained system where well-regarded classroom practices may still lead to accumulated negative consequences. The essay ends with a discussion of complexity and recursiveness in science teaching, an argument for science teaching that includes embedded understandings of that teaching and learning on the part of the students themselves, and suggestions for a revised conception of science teaching.

KEYWORDS
complexity, conception of teaching science, science instruction, science teaching, teaching

1 | INTRODUCTION

In this framing essay, I take up the instruction theme for this special issue by examining the barriers to good science teaching that exist both within and beyond the relationship between instructor and learner, a topic also taken up by the other two articles in this section. Jones and Burrell's (2022) article, "Present in Class Yet Absent in Science: The Individual and Societal Impact of Inequitable Science Instruction and Charge to Improve Science Instruction" examines the various ways in which specific groups of students are "left out" by science education. Jones and Taylor's (2022) article "Within the Walls of the Classroom: How Science Teachers' Instruction Can Develop Students' Sociopolitical Consciousness" presents both an argument and strategies for developing students sociopolitical consciousness within science instruction.

The field of science education is filled with people who wish to do a good job in teaching science, and yet the evidence points to a system in which many students are not actually learning science all that well, and whatever measurable achievement exists appears unequally distributed. The current system of science education—as it operates both locally and globally—was conceived, implemented, and sustained for a number of different purposes (Rudolph, 2020), and the current outcomes are a product of the operation of that system. Though the range of outcomes certainly includes standardized measures of scientific knowledge, other educational attainment goals such as science course-taking in secondary school and subsequent performance in higher education science courses, major selection, and trajectory into science, technology, engineering, and mathematics (STEM) careers are also highly valued (McGee, 2021; Rodriguez & McGuire, 2019; Sadler & Tai, 2001; Witherspoon et al., 2019). As in education broadly, science learning appears to be quite sensitive to context, and specific desired science outcomes in 1 year may be erased by experiences in subsequent years as the learner moves through different grade levels, teachers, settings, or their own developmental trajectory (e.g., Carlone et al., 2014; Dawson, 2020; Wade-Jaimes et al., 2021). Other goals, such as individuals' capacity to understand science or use scientific knowledge to address social issues of importance—sometimes characterized as scientific literacy—are also valued by science educators as well as the wider public (Meehan et al., 2018; Oreskes, 2021; Trefil, 2008).

When examined through a categorical lens, troubling inequitable patterns appear in achievement of measured science outcomes across broad categories of race, class, gender, disability, and language. For example, in the United States, scores from the National Assessment of Educational Progress (NAEP) regularly show that Black and Hispanic students are outperformed by White and Asian students even when controlling for parents' education and family income levels. As shown in Table 1, with data drawn from the last reported NAEP 12th grade science assessment in 2019 (National Center for Education Statistics, 2022), White students who were from less well-off households (i.e., eligible for free lunch) and whose parents did not finish high school had a *higher* average score on the assessment than Black students who were better off (i.e., *not* eligible for free lunch) and whose parents graduated college.[1]

The same report shows that students in higher-income households, as well as those identifying as White or Asian were also far more likely to express an intent to pursue a career in science than students not included in those categories. Black students who expressed that they would be quite likely or extremely likely to pursue a career in science scored lower than White or Asian students who reported that they would not be likely at all to do so.[2] The 12th grade NAEP 2019 science proficiency outcomes for a wide range of demographic categories are shown in Figure 1.[3]

Clearly, these demographic categories have strong predictive power, and of course may be in part attributable to biases in these measures themselves.[4] But with the exception of cases where developmental disabilities directly impact certain students' facility for learning, it is difficult to claim that such scores reflect actual categorical differences in innate ability or potential that are not attributable to societal factors. Though the question is rarely posed in this way, why should a student who comes from a less affluent household, has a disability, or is learning English be denied the opportunity to learn science in a way that permits them to achieve at levels comparable to their peers? In a world with equitable and effective science instruction—and unbiased assessments—it would seem reasonable that every student could indeed be a robust science learner.

TABLE 1 Average scale scores for NAEP grade 12 science, by National School Lunch Program eligibility, parental education level, and race/ethnicity (National Center for Education Statistics, 2022)

Race/ethnicity using 2011 guidelines, school-reported	National School Lunch Program eligibility, 2 categories									
	Eligible (low SES)					Not eligible (high SES)				
	Did not finish high school	Graduated high school	Some education after high school	Graduated college	Unknown	Did not finish high school	Graduated high school	Some education after high school	Graduated college	Unknown
White	138	141	151	156	121	137	148	159	170	131
Black	118	112	127	128	100	[a]	115	132	137	[a]
Hispanic	132	129	137	135	118	134	136	145	157	126
Asian	148	146	153	159	[a]	[a]	166	155	180	[a]
American Indian/ Alaska Native	[a]	[a]	139	136	[a]	[a]	[a]	[a]	165	[a]
Native Hawaiian/ Other Pacific Islander	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
Two or more races	[a]	132	141	146	[a]	[a]	[a]	158	170	[a]

Note: Black includes African American, and Hispanic includes Latino. Race categories exclude Hispanic origin. Some apparent differences between estimates may not be statistically significant. The category of "Information not available" for National School Lunch Program eligibility is not shown here.

[a]Reporting standards not met.

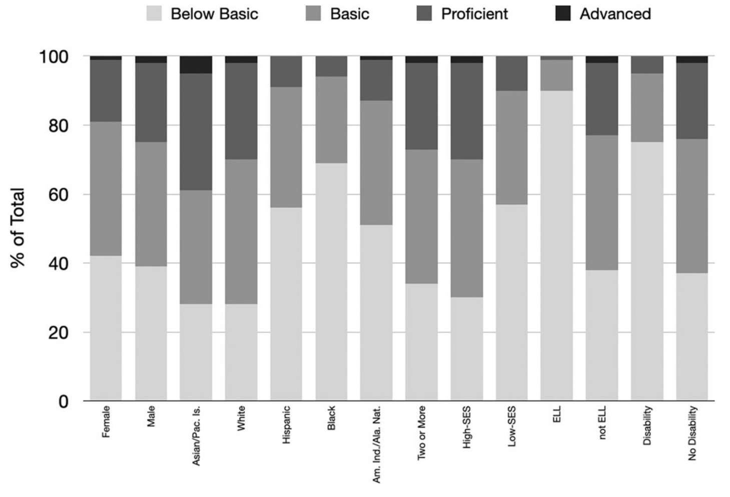

FIGURE 1 12TH-GRADE NAEP science profiency scores disaggregated by demographic categories.

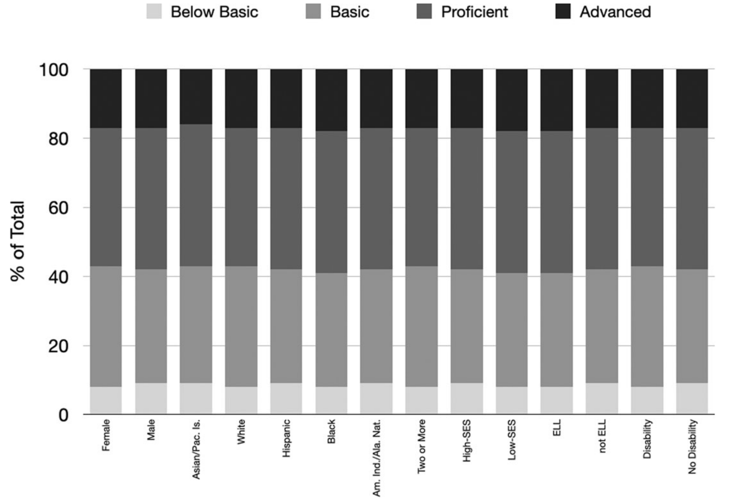

FIGURE 2 An aspirational vision of science education in which demographic categories do not correlate with outcomes.

A wholly fictitious, yet aspirational, depiction of such student achievement (that still makes allowance for variation in performance) is shown in Figure 2, with differences between categorical groups reduced to statistical noise. What would it take to achieve these results? Of course, standardized test scores are only one type of educational outcome. Given that the NAEP categories themselves are incomplete in depicting human diversity, we might ask the broader question: what would science teaching and learning look like in a world where social locations of race, ethnicity, sex, gender, class, ability/disability, language, religion, neurotypicality, citizenship, or any other cut along a categorical seam of human diversity are not probabilistic determinants of science learning, as they are today?

For those of us in science education who wish to work toward such a goal, one long-term project is that of dismantling the barriers that result in inequitable outcomes in science learning. Another is constructing and supporting transformative models of teaching and learning science that build toward this goal. While the answer to the question above may not begin or end with science teaching, certainly attention to the act of instruction must be an integral part of building a world where race, class, and so forth do not have such predictive power.

2 | POSITIONALITY STATEMENT

I currently work as a full professor in a public state university in New Jersey in the United States, primarily in the area of teacher education. Previously, I worked as a high school physics and chemistry teacher for 10 years, most recently in Trenton, NJ. I also served as a volunteer with the U.S. Peace Corps teaching physics and mathematics, first in Kenya, then in Papua New Guinea. I am fluent in English and Kiswahili, and occasionally passable in Spanish and Tok Pisin.

I have studied science pedagogy carefully for many years: first as a student who loved science but not always science class, and later as a novice teacher grappling with the bounds of my profession. In graduate school, the nature of science teaching and learning took on new aspects for me when I worked with undergraduate chemistry students as a teaching assistant, and again when I was tasked with supervising student teachers in the field and teaching methods courses for preservice science teachers. When I became a researcher using qualitative case study methods to investigate the challenges of learning to teach science in equitable ways, the central role of teachers' conceptions of teaching science became clear to me, and is a lens through which I make sense of the critical issues within the field of science teacher education. My work within the science education community, such as serving as a peer reviewer for journals, section editor for Science Education, and working on various advisory boards, has also informed the views on science instruction I express here.

Critically, so does my identity as a White heterosexual cisgender male who has been socialized into the dominant culture of the middle-class in the United States.[5] Perhaps most importantly, I am simply permitted to even do this study, unlike my maternal grandmother who was excluded from teaching high school mathematics because she was a woman.[6] As Malcolm Butler reminded us his inspirator talk for the Science Education Campaign—Research, Equity & Teaching (SECRET), in science instruction the identity of the teacher matters a great deal:

> My background is in physics, I love teaching Newton's laws of motion….One of my mentors said, “You know Malcolm, that's great you want to do that, that's awesome. But what you have to understand is that when you walk in the classroom as a Black man, race has become a part of the conversation. Now, you get to choose how you're going to deal with it, whether you're going to deal with it. But one thing you can't ignore is that it's become a part of the conversation. Because, you're teaching at a predominantly White institution—the majority of your students are White females in this case if I'm teaching elementary—and we know the numbers bear that out. But when you walked in the door, race became a part of the conversation. Now, you can still go and teach Newton's Laws of motion if you want, but the reality is, you're the one that's teaching it! And it may be race neutral. $F = ma$ may be race neutral, but your teaching it has brought in the lens of race.[7]

In my own work, I am often positioned in the role of assessing science teaching strategies or providing feedback on science instruction. My identity and culture are central to this task because they shape how I interpret and understand the world, which for the purposes of this essay includes the phenomenon of instances of science instruction I observe. When I envision the universe of approaches to science teaching, my identity and culture influence my sense of the possible. To Butler's point above, the range of approaches and strategies for teaching Newton's second law I might envision are different from his because of who I am. Recognizing this, and being able to act upon it as a science teacher educator, can be much more difficult than is commonly understood (Windschitl &

Stroupe, 2017), and doing so requires establishing what we are even talking about when we discuss science teaching.

3 | WHAT IS SCIENCE TEACHING?

Nearly 35 years ago, an article by Hewson and Hewson (1988) appeared in Science Education that reported on a NARST conference panel dedicated to defining an “appropriate conception of teaching science.” A definition had become increasingly necessary once the science education community had recognized the conceptual change theory of learning as generative, and during which time a robust program of research to identify learners’ conceptions was launched (Duit & Treagust, 2012; Pintrich et al., 1993; Posner et al., 1982; Scott et al., 1992; Strike & Posner, 1992). This study rode the crest of the shift in the field of teacher research away from “process-product” studies—in which the aim had been to identify educational inputs that led to desired outcomes (Seidel & Shavelson, 2007; Shulman, 1986)—and toward an emerging acceptance of cognitive learning process models that attended to teacher thinking and decision-making.[8] Such a view permitted prior student conceptions about scientific phenomena to be compared with established scientific understandings as a useful guide to instruction, but at the time there was no agreed-upon notion of how to actually draw conceptual boundaries around what counted as science teaching and what did not, which was vital for making suggestions about how to teach for conceptual change.

For example, if a physics teacher passed around a box of a crystals, and asked what students knew about them, was that to be considered “science teaching”? What if a college professor lectured a group of first graders about Darwin's theory of evolution? How about a student watching a video on chemical plants which produce new plastics from coal? A teacher writing a tutorial on using a triple-beam balance? Two students working together to solve chemistry problems? A student following a recipe at home for making blueberry muffins?[9] If there was going to be an effort to assess teachers’ conceptions of teaching, then conceptions of teaching science had to be compared with a recognizable standard of what the field of science education said science teaching actually *was*.

Hence, an “appropriate conception of science teaching” emerged from the work of the NARST panel—influenced by earlier work by Hirst (1971) and Fenstermacher (1986)—and was organized into five interrelated categories:

> **Tasks and activities:** In general, science teachers should be convinced that science teaching, as one particular form of teaching, should of necessity consist of tasks and activities which are (1) intended to help particular students learn particular content (which may be knowledge, skills, or attitudes), (2) indicative of the particular content to be learned, and (3) expressed so that it is possible for the particular students to learn it.

> **Knowledge of content**: Science teachers should know the content, i.e., they should know the phenomena, the methods, and the concepts, principles, theories which constitute the science they are teaching. They should be able to select topics from the content which do justice to the science they are teaching, and are suitable to their students.

> **Student's prior conceptions**: Science teachers should know what conceptions their students hold about the topics to be taught, and the extent to which these conceptions are scientifically acceptable or not. They should know the reasons which their students use to support these conceptions. They should know which topics their students are likely to find difficult, and why they find them difficult.

> **Understanding of learning**: To support this knowledge of students' conceptions, science teachers should be aware of the role played by students' existing knowledge in understanding new material. They should know that students learn new content by using their existing knowledge in a process of active construction of meaning which can usefully be described as conceptual change involving the capture, exchange, and/or restructuring of existing and new knowledge.
>
> **Knowledge of instructional strategies**: Science teachers should know about, and be convinced of the need to use, instructional strategies which take into account students' existing conceptions, especially when they conflict with those being taught. More specifically, these include strategies which diagnose students' conceptions, allow students to clarify their ideas, present desired knowledge, establish a direct contrast between different views, and allow opportunities for explanation of and application to a range of examples. They should know that materials designed to give effect to these strategies enhance their teaching effectiveness. (p. 610)

Hewson and Hewson also noted that there was an additional meta-category of understanding how all of the above worked together, which they referred to subsequently as simply a "conception of teaching science."

A program of research to investigate teachers' conceptions of teaching science was then carried out over the coming decades (e.g., Hewson et al., 1995; Koballa et al., 2005; Park et al., 2010; Subramaniam, 2013), which began to include more specific attention to the nature of science as a component of the "knowledge of content" category, as well as learner characteristics as part of the "students' prior conceptions" category. Ultimately, researchers began to move away from snapshot depictions of teachers' conceptions of teaching science, and turn their focus to how such conceptions change over time (e.g., Bell & Gilbert, 1996; Johnson, 2011; Larkin, 2013; Larkin et al., 2022; Luft & Hewson, 2014; Mensah, 2019; Shen & Confrey, 2007).

In examining the "appropriate conception of teaching science" framework from the vantage point of the present, there are six features of its construction that appear worth revisiting. First is that the underlying theory of conceptual change has itself been modified in the intervening decades to incorporate the role played by affect and emotion in cognition (Pintrich et al., 1993; Strike & Posner, 1992; Vosniadou, 2008). Second is that this framework privileges individual learners and their cognitive processes in the classroom to the exclusion of sociocultural theories of learning, which are now generally considered to have substantial explanatory power (e.g., Carlone et al., 2014; Lave & Wenger, 1991; Wickman & Östman, 2002). Third, is that the selection of "particular content" to be taught and learned by students is itself embedded in a larger set of social, curricular, and political relationships that are not unproblematic, especially within the content domain of science (e.g., Balgopal, 2020; Lowell et al., 2021; Meehan et al., 2018; Oreskes, 2021), because selecting particular science content to teach is deeply connected to the purposes for having students learn that subject matter in the first place. Fourth, to Butler's point above, this view of science teaching does not take the identity of the science teacher into consideration, and how that identity might influence the teaching and learning that takes place by that teacher (e.g., Chen & Moore Mensah, 2022; Hathcock et al., 2020; Sheth, 2018; Zotos et al., 2020). The identity of the teacher as a person matters as much as that of the students. Fifth, and importantly for the purposes of this essay, this earlier conception of teaching science also offers little guidance in ensuring equitable outcomes for students. However the final, and perhaps foremost, shortcoming of the NARST panel's conception of teaching science is the way in which this perfectly rationale depiction of teaching and learning is positively upended by the realities of the classroom. It may as well be a massless string or a frictionless pulley for all the verisimilitude it holds. The social conditions and settings for teaching science must be part of a conception of teaching because they inform all of the other components, as do the larger sociocultural and sociopolitical contexts in which the learning takes place.

4 | SCIENCE TEACHING AS AN IMPOSSIBLE PROFESSION

Many scholars have highlighted the systemic nature of inequitable outcomes of schooling (e.g., Anyon, 1981; Baker, 2018; Ladson-Billings & Tate, 1995) and in science education in particular (Guzman-Orth et al., 2021; Lee & Buxton, 2010; Lynch, 2000). Yet the connections between broad, systemic inequities and the daily work of science teaching may remain challenging to grasp, particularly for science teachers who are doing their best to engage in what they believe is good science teaching. I share the following example to illustrate this point.

The NBC television program "The Good Place" (Schur, 2020) follows the story of four people navigating a fictional afterlife, where a moral and ethical point system has determined whether they go to "the good place" or "the bad place." A major story arc in the final season [spoiler alert] comes from the revelation that the system is structurally broken because negative consequences overwhelm even the most altruistic acts in the modern world. The show portrays the structural impossibility of anyone accumulating enough points for entry into "the good place" because the daily life of a person on Earth has become so entangled with systems of oppression, exploitation, and environmental harm, that every action ultimate results in a deduction of points (until of course the protagonists tackle the problem with a measure of pluck, ingenuity, and moral philosophy).

I find it useful to consider contemporary science teaching as operating within a similarly constrained system, where well-regarded classroom practices often still lead to accumulated negative consequences. Of course, science itself is no stranger to such debates about morality and consequence (e.g., Carson, 1962; Eichstaedt, 1994; Mann, 2018). My argument is that even if most science teachers can be characterized as well-intentioned, enthusiastic, and knowledgeable individuals who understand the demands and responsibilities of being a science teacher, the work of science instruction is embedded in the realities of contemporary schooling in ways that regularly result in outcomes for many students that run counter to stated aims of science instruction.

Imagine, for example, an experienced biology teacher in the United States who is well regarded by students, teaches with relevance and rigor in accordance with state standards, and whose students go on to good grades in their university biology classes and perhaps even get to use what they learned in high school biology class in their lives in some way. That teacher's work is embedded in a system where school districts are not entitled to equitable funding under a decision by the nation's highest court (San Antonio Independent School District v. Rodriguez, 1973), where marginalized students experience discrimination on a daily basis (e.g. Gopalan & Nelson, 2019; Janssen et al., 2022), and which largely values science education for its economic benefit (Rudolph, 2019). All this happens before any judgement of the quality of science teaching in that classroom can be made, and is the context for the interpersonal teaching and learning described by the 1988 NARST panel's "Appropriate Conception of Science Teaching." Is the "good place" of science teaching represented by Figure 2 out of reach?

In his now classic essay, "Teaching Practice: *Plus ça change*..." Cohen (1988) famously noted that teaching is an "impossible profession":

> Teaching is a practice of human improvement. It promises intellectual growth, humane awareness, economic opportunities, civic consciousness, and many other virtues. Like other practices in this new family of human endeavors, teaching is an impossible profession. I do not mean that teaching cannot be done. I mean that each of these practices is a medium in which we now struggle with unavoidable but insoluble problems of human nature and destiny. (p. 38)

To the list of such insoluble problems—though perhaps Cohen considered it already in the mix—we must now add the problem of teaching equitably within an inequitable system of education. Yet, this also points to a possible resolution because equity is a value, and in the decades since the first attempts to portray an appropriate conception of science teaching, a number of scholars have reckoned with notions of value judgements in teaching quality in ways that prove helpful.

In another landmark essay, Fenstermacher and Richardson (2005) distinguished between *successful teaching*, which they defined as "students learning what the teacher is teaching," and *good teaching*, which they defined as "teaching that accords with high standards for subject matter content and methods of practice," (p. 189.) Within a structurally sound and morally defensible system, aiming for science teaching that is both good and successful—as well as identifying the barriers that impede such teaching—makes a great deal of sense. And yet, teaching that might be considered successful, in that students learn the science, and also good, in that they accord with high standards for content and pedagogy, may still fall short of being equitable. Examples include:

- Schools where a significant fraction of the student population takes Advanced Placement classes, but course-taking (or exam-passing) patterns do not reflect the demographic makeup of the student body (Roegman et al., 2019; Schoener & McKenzie 2016).
- Classrooms where students' ability to use scientific knowledge to act on issues of equity and justice outside of the classroom (e.g., Morales-Doyle, 2017)—and develop their sociopolitical consciousness (Jones & Taylor, 2022) is constrained.
- Science lessons that minimize or sidestep the ethical or environmental implications of the science learning itself, and where students might ask: "Where do these fetal pigs come from? (And where do they go when we are done dissecting them?) or "What happens to the lead chloride after it is poured down the drain?" (Tolbert et al., 2018; Wallace & Loudon, 2000).

As noted above, limiting the definition and scope of teaching to interactions between teacher and learner leads to an incomplete understanding of science education precisely because teaching and learning science is always situated in multiple levels of social context. Like our massless strings or frictionless pulleys, reducing instruction to simple interactions may be a necessary first approximation for understanding, but is ultimately insufficient in comprehending its totality if the analysis stops there.

5 | DEALING WITH THE COMPLEXITY OF TEACHING

Current literature regularly invokes the *problem of complexity* as one of the greatest challenges in teaching and learning to teach (e.g., Davis & Sumara, 1997; Hammerness et al., 2005; Klehr, 2012). McDonald (1992) portrays teaching as a "wild triangle of relations—among teacher, students, and subject—whose dimensions continually shift." Such complexity is situated in varied and dynamic teaching contexts, as novice science teachers quickly discover. In characterizing the process of learning to teach science for inquiry, Crawford (2007) has referred to this complexity as the "rough and tumble of practice."[10]

In a discussion of cognition, complexity and teacher education Davis and Sumara (1997) highlight three features of complex systems: their tendency toward self-organization, their ability to be adaptive in response to its environment, and their irreducibility into component parts for analysis. However, I have also found it helpful to think about the modern system of education in the mathematical sense of complexity because of its recursive, nonlinear, and dynamic nature (Hofstadter, 1979; Mandelbrot, 1983; Taleb, 2007). A defining feature of recursiveness in a complex system is that outputs become the new inputs. The recursiveness in science education is self-evident and easy to describe: over time, a subset of science learners become science teachers.[11]

One approach to managing the problem of complexity, as clearly described by Hammerness et al. (2005), is to identify the development and use of metacognitive strategies by the teacher—and by extension the students. Hammerness et al. (2005) note, "Effective teachers become increasingly aware of the complexities involved in teaching and learn how to think systematically about them so that they can better assess their own performances," (p. 375). Certainly metacognition as a process also bears the hallmarks of a recursive pathway, as the output of one's thinking becomes the new input.

Thinking about teaching and learning in this recursive manner also leads to another way to frame science teaching and learning to further leverage such recursiveness. Using Fenstermacher and Richardson's terminology, successful teaching is that which permits the learner to engage in their own successful teaching, and good teaching is that which permits the learner to engage in their own good teaching.

What I am suggesting is far-reaching, and more than advocacy for a new instructional strategy. I am suggesting here that understanding teaching and learning ought to be considered as fundamental a topic for schooling as literacy and mathematics currently are. This is not a new idea (e.g., Peterson, 1988), and is closely related to the notion of students engaging in intellectual work for an authentic audience (Ladson-Billings, 1995; Wiggins & McTighe, 1998). Certainly, some existing approaches to teaching science have incorporated various forms of student-led teaching as a vehicle for learning, with metacognition playing a starring role (e.g., Jackson et al., 2008; Windschitl et al., 2018). For example, having students engage in peer-teaching is a time-worn pedagogical approach, and it is common for teachers to encourage their students to carry out this practice as a strategy for differentiated instruction.

Having learners understand the ways in which they are being taught facilitates not only their learning, but provides scaffolding for ways in might they may engage in their own subsequent teaching of the same content. This is not to say that science teaching ought to simply become a monastic exercise in which the driving rationale is to reproduce the reproducers of knowledge. Rather, I am arguing that students ought to have clear expectations of how a particular teaching strategy, approach, or curriculum is expected to lead to learning. It is not a difficult thought experiment to consider what might happen in classrooms where children understand the principles of teaching and learning the same way that they understand how to read and do basic mathematics. If a teacher's teaching does not exhibit expectations of learning—such as in classrooms that exemplify Haberman's (1991) pedagogy of poverty—it would be as instantly recognizable to students, families, and other school personnel as a textbook with misspelled words or out-of-order pages, rather than being even superficially accepted as teaching.

An example is in order here: when I watched environmental educator Tom Card lay out a bearskin in front of a group of elementary and secondary teachers at the New Jersey School of Conservation, he did not begin with a lecture. Rather, he asked them, “What do you know about bears?” (Larkin, 2020; p. 16). This alone represents the part of the appropriate conception of teaching science that notes that teachers should elicit students’ prior knowledge. However, Tom went on to point out the reason for this elicitation to the teachers, clearly outlining for them the reasons why getting learners to share their prior knowledge of bears was important. In doing so, he was also laying down markers for their own future teaching, whether it was about bears or anything else. As learners, understanding the reasons for elicitation likely served both as a subject of metacognition (e.g., “Where do my beliefs about bears come from?) and as a pedagogical tool that they would sharpen in their own version of a science lesson in the future.

Specific attention to the process of knowledge construction in a variety of cultural forms is already established as a key element of effective science pedagogy (Bang et al., 2013; Hudicourt-Barnes, 2003; Ladson-Billings, 2003). However, by centering knowledge about teaching and learning in the classroom, science teachers may also increase the likelihood that the teaching and learning that happens there will be consistent with students’ ways of accessing and interacting with the world. The broader challenge is recasting teaching as educational design for learning as an iterative process (Halverson & Halverson, 2020).

Cohen (1988) observes that one of the barriers to educational reform in the direction of what he calls “adventurous teaching” is that teaching practices in schools often reflect popular practices of instruction occurring outside of schools:

> Most reformers have assumed that traditional instruction is rooted in teachers’ bad habits and that it is an obsolete, boring, stupid, and needless imposition on children. In a sense this is not surprising: Reformers have been broadcasting the idea that children are naturally adventurous learners for roughly a century. Most also have argued that they would be so in schools, if traditional teachers

> would only get out of the way. But my account suggests another view: that traditional teaching in schools echoes and reflects popular practices outside schools. The conceptions and practices that reformers wish to replace thus are not simply the needless impositions of bad old boring teachers, as Dewey and most reformers since have asserted. The instructional practices that reformers wish to eliminate contain views of knowledge, teaching, and learning to which many parents, teachers, and students have deep loyalties. (p. 17)

While Cohen goes on to note the futility of trying to change teaching practices outside of schools, he was writing just before access to knowledge became readily available at the fingertips of billions of people, transforming the nature of autonomous and personalized learning (Halverson, 2019), although maybe not so much in schools (Watters, 2021). As I write this, my 18-year-old automotively-inclined son is trying to solve a problem with an engine, and he just watched a web-tutorial on his phone that provided step-by-step instructions on how to replace a fuel filter for his car. We are living through a proliferation of models of teaching and learning, with new forms of Cohen's "deep loyalties" being forged daily in YouTube and TikTok page views. Those of us who study teaching and learning—and science teaching and science learning in particular—have much to contribute to this conversation, with the potential to shift what counts as teaching and learning science both inside and outside of schools.

6 | A REVISED CONCEPTION OF TEACHING SCIENCE

To conclude, I wish to suggest a number of additions to the appropriate conception of science teaching introduced above. The first two, as previously mentioned, appear to have already been accepted over time as part of an appropriate conception of science teaching both in the literature on science teacher conceptions as well as in science standards documents (Achieve Inc., 2013):

> **Knowledge of the nature and practices of science**: Science teachers should understand how scientific knowledge is generated, as well as the practices in which scientists are engaged and the various types of disciplinary arguments and claims that are made in different areas of inquiry (Bartos & Lederman, 2014; Miller et al., 2018; Stewart & Rudolph, 2001).

> **Understanding of sociocultural contexts**: Science teachers should understand ways in which the sociocultural context of the school, community, and larger social units impact students' lives and shape their learning. This includes the categorical and demographic descriptions of the school's student and teacher population, the geographical, spatial, and cultural layout of the students' worlds, and the lived experiences of the students both within and beyond the environment of the school. All weave together to form the prior knowledge, experiences, and motivations that students bring to the task of learning science, which ought to be accounted for in the teaching of science (Bell et al., 2013; Larkin, 2020).

To these I add the following:

> **Student access to the subject matter**: As Jones and Burrell (2022) argue, it is unfortunately all too common for students to be excluded from the types of teacher-student interactions that are necessary for science learning. An appropriate conception of teaching ought to include proactive advocacy for access to learning for all students, including the use of universal design principles for learning (Meyer et al., 2016).

Systemic barrier awareness and mitigation: Science teachers should understand the ways in which social power impacts science learning through the creation and maintenance of systemic barriers. These barriers may result from ability grouping, housing segregation, inequitable school funding, curricular erasure of indigenous knowledge and peoples in science class, and the overuse of standardized testing. All operate on a systemic level to deny, constrain, or impair students' opportunity to learn, and may require inquiry and reflection to identify in a given teaching context. Such barriers also affect students because they impact the practice of science, as in the case of scientists from marginalized groups who have been prevented from engaging in their research because of their racial and ethnic identity.[12] An appropriate conception of science teaching names and recognizes such barriers, and though incorporating productive strategies for mitigating or dismantling them may pose a challenge, good teaching does not ignore them.

Embedding understandings of science teaching and learning: Science teachers make it clear to students how learning is expected to occur as a result of their teaching, in accordance with the "understanding of learning" conception described above. An appropriate conception of science teaching views successful learning as that which makes it possible for the learners to subsequently teach what they have learned to others.

Undertaking a project of reimagining science teaching and learning on local, national, and global scales requires thinking systemically about all of its aspects, including its goals, inputs, outcomes, measures, and reckoning with the social context in which such teaching and learning is situated. Getting to a real "good place" with science teaching is indeed an impossible task with unavoidable problems, and yet it remains a worthwhile endeavor.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under NSF Grant # 2029956—Science Education Campaign for Research, Equity & Teaching. I gratefully acknowledge the assistance of Barbara Ryan Larkin and Teen Mulholland in the preparation of this manuscript.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] A crosstab table produced from the NAEP 2019 report showing student science scores by National School Lunch Program eligibility (as a proxy for household income) and school-reported race/ethnicity may be found at: https://www.nationsreportcard.gov/ndecore/shareredirect?su=NDE%26sb=SCI%26gr=12%26fr=3%26yr=2019R3%26sc=SRPUV%26ju=NT%26vr=SRACE10-false–SLUNCH3-false–PARED-false%26ct=SRACE10-SLUNCH3-PARED%26st=MN-MN%26sht=REPORT%26urls=xplore%26mi=false%26svt=true%26nd=0%26vl=SHORT%26yo=DESC%26inc=NONE%26up=true%26rrl=SAMPLE%7CSAMPLE%7C1–JURISDICTION%7CJURISDICTION%7C2–SRACE10%7CVARIABLE%7C3%26rtl=SLUNCH3%7CVARIABLE%7C1–PARED%7CVARIABLE%7C2%26sm=false

[2] A crosstab table produced from the NAEP 2019 report showing the response to the "likely to pursue a career in science" survey question by school-reported race/ethnicity may be found at: https://www.nationsreportcard.gov/ndecore/shareredirect?su=NDE%26sb=SCI%26gr=12%26fr=3%26yr=2019R3%26sc=SRPUV%26ju=NT%26vr=SDRACE-false–K824301-false%26ct=SDRACE-K824301%26st=MN-MN%26sht=REPORT%26urls=xplore%26mi=false%26svt=true%26nd=0%26vl=SHORT%26yo=DESC%26inc=NONE%26up=true%26rrl=SAMPLE%7CSAMPLE%7C1–JURISDICTION%7CJURISDICTION%7C2–SDRACE%7CVARIABLE%7C3%26rtl=K824301%7CVARIABLE%7C1%26sm=false

[3] Disability status of the student here excludes those with a 504 plan only, and the full categorical labels are "Identified as students with disabilities" and "Not identified as students with disabilities," which were truncated for the axis label on the figure. The category labels of English Language Learner (ELL) and non-English Language Learner (non-ELL) are used in the score report.

[4] Note that the framing document (National Assessment Governing Board, 2015) used for the construction of the 2019 NAEP assessment states: "The assessment should be designed and written to be accessible by the majority of students, minimizing the need for special accommodations for both students with disabilities and English language learners, (p. 5). This raises the question about the validity of the assessment for students not in that majority.

[5] In the affiliation convention advocated by Liboiron (2021), I would be marked primarily as "Larkin (United States)," though a designation of New Jerseyan, settler, or even diasporic Irish might be warranted in some circumstances.

[6] My aunt described the story recently in an email to me, reprinted here with her permission: Your Grandma (Mareitta) majored in Math and minored in English. She graduated from St. Joseph's College for Women, Brooklyn, NY (now called St. Joseph's College) in 1926. While teaching after graduation, she attended Fordham University for her Master's degree. After this, she started her doctorate, finishing most of the requirements. During this time she met your grandpa and married him. Your grandma told us that he wouldn't let her complete it. One of her first job interviews was at Bushwick (?) High School. She applied as a math teacher and was told by a male (!) principal that women were not allowed to teach math. She was hired and assigned to teach English. Your grandma was married August 1932 and pregnant with me in January 1933. She taught only 6 months during her pregnancy until the end of the school year. Pregnant women were not allowed to teach but she wore clothes that covered her expanding waist. I'm not sure when she moved to elementary school but was teaching there by the time I was four.

[7] The transcript for this conversation is currently available at: https://www.dropbox.com/s/hlr1d4lf4sen54g/Interview%20with%20Malcolm%20Butler.pdf

[8] Thousands of articles about student conceptions were ultimately published out of this widespread program of research (Anderson, 2007; Duit, 2009).

[9] These examples are drawn from the Conception of Teaching Science instrument (Hewson & Hewson, 1989; Hewson et al., 1995).

[10] Horn and Garner (2022) identify this state of contextual complexity as an often underappreciated aspect of learning to teach and a reason why notions of "best practice" are often difficult to transfer. They emphasize that learning to "bridge the often-puzzling gaps between idealized instruction practices and their lived realities," requires interpretive work and recontextualization of such practices on the part of teachers and teacher educators (p. 83).

[11] And like all complex systems, systems of education have islands of stability within chaotic patterns. I find the nonlinear dynamics concept of a "strange attractor" (Hénon 1976; Lorenz, 1963) to be a much more apt description of educational change than the more common trope of a pendulum swing.

[12] Recent examples in the literature of Black scientists being hindered in their fieldwork on the basis of racial or ethnic discrimination include soil scientists (Berhe & Ghezzehei, 2021), ornithologists (Bittel, 2020), and others throughout the sciences (Schell et al., 2020).

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How to cite this article: Larkin, D. (2022). Getting to a good place with science instruction: rethinking an appropriate conception of teaching science. *Science Education*, 1–17. https://doi.org/10.1002/sce.21742