Teacher knowing:
Reflections on a student-teacher dialogue
and implications for professional development

A Working Paper from the
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Abstract. In current debates about science education reform, teachers' knowledge of science is a central issue. The article uses a vignette from a sixth-grade class to reflect upon the nature of knowledge-in-use (by teachers or anyone else). The article recommends a reconstruction of policies to support teachers' (or anyone's) learning which take seriously the process of knowing-in-use especially in novel situations, such as inquiry learning.

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The quality and nature of science teachers' knowledge is of great importance in the literatures on science education, education reform, and teacher professional development. The way we conceptualize teachers' knowledge will have implications for the way we recognize and diagnose problems in science teaching and learning, and therefore for the way we design and implement remedies for these problems.

Current discussions of science teachers' knowledge have brought with them different insights into a complex problem. Three common approaches consider teachers' knowledge with regard to subject matter knowledge, pedagogical content knowledge, and their understanding of the "Nature of Science" (NOS). While these constructs have some areas of overlap, the viewpoints are instructively different. Each of them seeks in some ways to describe qualities of teacher understanding, at different levels of abstraction from the concrete give-and-take of classroom action.

In some contrast to these approaches, in this paper I would like to consider a different angle on a teacher's knowledge of science, which seems to me particularly interesting and important for a teacher whose classroom includes any element of inquiry at all. In particular, I would like to reflect upon a teacher at the boundaries of his or her subject matter knowledge, a situation in which most teachers will often find themselves whose students engage in investigations with actual phenomena, whether in guided inquiry, open inquiry, or project work. This kind of practical work, long advocated for science education, is now receiving new emphasis with the Next Generation Science Standards, which include both content and practice expectations (NAS 2013, Reiser 2013). As an illustrative case, we will examine a sample of classroom dialogue, and consider the teacher's knowledge as she contributes to her students' sense-making. This examination gives rise to further reflections that may be relevant to programs of teacher preparation and in-service training.

More specifically, I will argue that

1. Anyone's knowledge (including a teacher's) is a patchwork of areas of coherent (propositional and procedural) understanding, bounded by other areas of indistinct or erroneous understanding, and of ignorance, often situationally conditioned;

2. Much of what anyone knows is made explicit (i.e. accessible to examination) under particular conditions; the moment of elicitation is likely to require the ad hoc (re)creation of an instantiation or version of knowledge.

3. Teachers' (re)creation of knowledge is exposed to examination most often in dialogue with students; and the ad hoc nature of (re)creation can be problematic for both teacher and learner.

4. These aspects of teachers' knowing should be taken into account when policy is designed to improve science teachers' "knowledge," and in particular we must make a simple but important stipulation about what we must bear in mind when we decide what "improve" should mean.

The case in point is taken from an observation of a strong, imaginative, and experienced teacher. It is an example of a very common, everyday occurrence, of the sort that can be seen whenever classroom work includes student questions as one source of classroom content and curriculum. It is the very commonness of the event that makes it important to reflect upon, because small things in large numbers can have an important cumulative effect. The effects that may result from the kind of knowing that I here analyze are at least two-fold: primary effects are upon the teacher's knowledge of her subject matter, and secondary effects may be posited for the students' experience of science as encountered in the classroom.

Theoretical and methodological considerations

In the past 25 years, there has been a swift and exciting increase in studies of teachers' practice and competence, including their knowledge. In many ways, ideas driving research on teacher knowledge have echoed ideas about children's learning. Thus, we have seen studies of teachers' understanding of specific facts in science, their understanding of the nature of science, their understanding of scientific reasoning and practice, their understandings of various kinds of representations, their use of technology, and their misconceptions in many of these general areas. Some or all of these subjects have been considered from behavioral, cognitive, sociocultural, critical, and various other theoretical stances (including many of their sub-variants, offspring, and ideological masqueradoes).

In addition, students of teacher knowledge have been informed by studies of ways of knowing that take place outside of schooling. There has been some examination of teachers' situated knowing, using ideas of situated learning and knowing as studied in many work places (e.g. Scribner 1997; Chaiklin and Lave 1996), and in other arenas of expertise such as the grocery store (Lave et al. 1984)

Nevertheless, teacher's knowledge as used in the classroom continues to be seen as a structured body of propositions and practices — knowing "that" and knowing "how." This body of knowledge can be investigated for its propositional accuracy (as compared with the knowledge of scientists), or for its completeness, or for the extent to which it is structured effectively (so that the teacher can make reliable deductions, or can present material in a valid and effective sequence, introducing no misconceptions (Gabel 1994). In this view, the implicit ideal is that the teacher (considered as a repository of knowledge) should be on a par with an authoritative reference, in contrast, for example, with Dewey's understanding of the dynamic relationship of the knower in transactional relationship with the things known (Dewey and Bentley 1991). While researchers who think about teacher knowledge in this way may support a sophisticated and constructivist view of learning, the characterization of teachers' knowledge-in-use is still reminiscent of a database. This approach naturally lends itself to implications for teacher professional development: more advanced courses, for example, or more rigorous undergraduate training in a discipline. Such approaches also give rise to methods for the evaluation of teachers' knowledge that are natural complements to this view of knowledge, and rely to an important degree on tests of accuracy, completeness, and appropriate structuring of the teacher's knowledge base (Keller 2005 and see the National Council on Teacher Quality nctq.org).

Yet it is widely accepted that a teacher may have an impressive command of propositional knowledge of her subject matter, and yet her pedagogy may be quite unsatisfactory, from the point of view of modern understandings of teaching and learning. If the teacher's knowledge is conceived of as an ordered repository, or searchable database, in a sense a "virtual textbook" available for just-in-time production, then plainly the goal is to display the relevant material and, by dint of careful exposition and engaging style, induce the students to create reproductions of the information, or recreate the "knowledge base."

Educators have long suggested that it is not satisfactory merely to present science as the repository of established fact and theory. In the first place, as Dewey noted a century ago (Dewey 1910), science grows too fast, and sometimes contradicts itself in the course of its progress, which presents a whole series of problems for one who would wish to maintain an adequate representation of scientific knowledge in the curriculum — or in the teacher. Moreover, scientific knowledge often "looks" different, depending on the contexts it is used, or the purposes to which it is put: so "knowing geology" is one thing to a geologist, but another to an ecologist: the research questions, and the phenomena under investigation, exert a selection or filtration effect, to promote or demote the importance of specific processes or principles. [1]

In the second place, therefore, to approach (school) science as "knowing the right stuff" privileges the *results* of science over the way knowledge is created, though this is arguably the most important "content" for an informed citizenry to understand. There are many possible responses to this challenge. Lederman and others have characterized the "missing ingredient" as an understanding of the nature of science (NOS) (Lederman 1999, Lederman and Zeidler 1987). They suggest that if teachers understand NOS, as it is actually practiced, they will make better pedagogical use of their content knowledge. Ideally, this would correct the overemphasis on the results of science, and enable teachers to convey science in a way that does not obsolesce, as a way of knowing which produces explanatory theories, testable against evidence using accepted methods, and often tentative and subject to revision. It does not, however, address disciplinary differences among the sciences, and tends to create an artificial distinction between knowledge and the process of creating knowledge.

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[1] I am indebted to Chip Bruce for the illustration. A chemistry teacher once exclaimed to me, "I go crazy when I see biology teachers do biochemistry. They don't do the *chemistry* of it!"

Perhaps the most fully developed theoretical approach is that of "pedagogical content knowledge," which in its strong form posits a definable (bounded, but not autonomous) body of knowledge as distinct from a teacher's knowledge of scientific content, on the one hand, and pedagogical content or craft knowledge, on the other (Berry et al. 2015, Shulman 1987, Gess-Newsome and Lederman 1999). A variant of this approach as articulated by scholars like Deborah Ball and her colleagues, speaks of teachers' knowing in ways particularly suited to, and shaped by, the uses to which they need to put that knowledge (e.g. Ball et al. 2000).

One drawback of all three of the interesting bodies of research I have quickly sketched, however, is that there is a persistent tendency to reify teachers' knowledge. Regardless of the aspect of knowledge that is emphasized, and the elements of classroom context that are incorporated in the definition, the language of these scholars speaks of knowledge as the body of facts, theories, and processes which a teacher knows, which is shaped or characterized in unique ways by its being what a teacher knows. Once reified, even rhetorically, teachers' knowledge then becomes a thing to measure, reshape, and otherwise manipulate or manage, as an object of policy. This inevitable tendency towards reification, however, overshadows other aspects of the psychology of knowledge as it is used, which I believe are worth bearing in mind as we think about how to improve teachers' knowledge and learning, which in turn have significant implications for their teaching practice.

Furthermore, such thinking may unwittingly reinforce a false notion of "teacher preparation," which conceptualizes teacher's knowledge as being obtained before they get to the classroom, followed ideally at periodic intervals with updates and debugging during the teacher's subsequent career. It does not take into account, therefore, the nature of knowledge work: making use of one's knowledge inherently introduces opportunities for change (positive or negative), as the knowledge is drawn out ad hoc, at need, and in situ. Therefore, the opportunity for learning is continuous.

In this piece, we would like to shift the focus from teachers' knowledge, to teachers' knowing as a creative act, which it so often is in classroom situations. In particular, a crucial aspect of knowing is what happens when knowledge is translated from whatever its internal representation is, into action or words. It is important to recognize at the same time that teachers as knowers have much in common with any person as knower. The recognition of this point may make our reflections of more general interest, and moreover can lend a certain amount of import to the recognition of a general principle at work in the specialized case of the teacher. To set the stage for these reflections, I will refer to an incident of a science teacher employing her knowledge in a typical classroom setting. I wish to emphasize that this example comes from a skilled, knowledgeable teacher, one of the most effective teachers I have seen. This story is in no way critical of her, and I hope that while reflecting upon this article, the reader will pause to reflect similar situations from her own experience.

Background to the case

The material I will adduce for this study is drawn from notes made by a skilled observer in a 6th grade science classroom.[2] The teacher, whose name and school are disguised, had (at the time of this story) seven years' experience in teaching; her classes in this district bridged elementary and middle school, because the district employed looping, and so she taught 5th and 6th grades. Her undergraduate degree was in elementary education, and she also had a master's degree in special education; in fact, because of her training, she had a classroom with a high proportion of special needs students. Her pedagogy was remarkable for its flexibility, for the many ways she approached each question, for her adept and thoughtful use of a "multiple intelligences" model in planning her lessons. Furthermore, she took the challenge of mainstreaming seriously. When asked how she dealt with all the diversity in her classroom, she answered very differently from most teachers in our study, who spoke of aiming to the middle, and helping the more advanced and less able students as best they could. This teacher, in contrast, said that she pitched the material for her strongest students, and then worked with the others so that they could reach it.

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[2] As part of a study funded by the National Science Foundation: NSF/REC-9804929, Brian Drayton and Joni Falk Principal Investigators

The district at this point had made a sustained commitment to making its science program inquiry-oriented from K-12. As part of this effort, the district had developed kits, three for each grade, which circulated from one teacher to another on a fixed schedule. In the best of cases, the teacher has the kit for a few days or a week, to review the materials and prepare. In the worst case, the person ahead of you on the list may run a little late, and so you get it just in time to get started. In the event described here, the teacher had received the kit a little late; it included some activities that she had not done before.

The lesson

In this sixth grade class, the students are moving slowly among three activity stations. Each station has an activity relating to some property of matter. The class is taking a whole week to move through these three stations, and the children are on no fixed schedule, so that they are free to remain longer at one station than another. At each station they have to find out what the challenge will be, conjecture what will happen, perform the activity, describe carefully what does in fact happen, and then discuss— all these both orally and in writing. They are free to talk with the other students who are at the same station with them. At one station, they explore the volume of liquids, and the question, "Is there space in liquids?"

Preparation

Before doing the activity, the students are expected to make a hypothesis, complete an experiment, and answer questions on an activity sheet. Framing a hypothesis is often a tough job, but the teacher makes it seem quite matter of fact: "Just write what you think and your group doesn't have to agree on any one thing. Write down what you think is an hypothesis and then let me know what you think."

The activity observed

The experiment involves measuring equal amounts of water and alcohol in separate vessels and first predicting, then observing what the combined volume will be when they're mixed. The students predict: "It will be 75 plus 75; 150." When the teacher pours them together, the students observe that "It's decreasing. It got less." They combined equal parts water and alcohol, yet they don't add up completely: $1 + 1 \neq 2$! (See the Appendix for an explanation.)

Group 1 makes sense of the phenomenon

Now the students begin to make sense of the phenomenon, with the teacher participating.

Teacher: "What happened and what should have happened?"

Students: “There should have been a little more, but there’s a lot less.”

“When the alcohol came, it pushed the air out of (the water.)"

"There’s air in the liquid."

Teacher: "What do you think is happening? What do you think is happening to the space in the liquids?" Do we all agree that there's space in liquid?" Can someone explain it?"

Student 1: "Bubbles, air bubbles."

Student 2: "Fish live in water and need to get air out of it."

Teacher: "Possibly, such good connections!"

One student dictates while the others write: " We know there are air bubbles in water even though we can't see them." One student cautions, "Hold on. We’re just writing what we observed, not why we think it is."

While they talk, the teacher goes to look something up for them. As she goes, she tells them, “I want you to write down what you're thinking. I don't want you to lose your thought process." Students continue discussing among themselves.

Student 1 : "There has to be air in solids. Air is in everything and air takes up space."

Student 2: "We don't know that. It's not in space."

They start debating whether or not air is in solids.

Student 3: It's not in table salt, it's not in paper."

Student 4: "Yes it is. Paper comes from trees and there is air in trees."

Teacher comes back with the reference. "I want you to read page #X, about atoms. Skim and scan. This will help you to answer the rest of the questions.

But before you start, what did we say matter was? You need to remember that."

The students take turn reading sections to each other and breaking out with comments or discussion as they go along. One student makes an attempt to synthesize his ideas and the reading. "Everything has particles because atoms are in it."

They agree on and write the following statement on their answer sheets: "There is space in particles because everything is made up of atoms." Then they refine it to these 3 points: 1. Everything has atoms. 2. These atoms take up space. and 3. Atoms have space in the particles.   But the cautionary student maintains: "But you can't say that there's air in the spaces."

Group 2 makes sense of the phenomenon

Meanwhile, in another group, the teacher is encouraging the students to use what they know to make sense of this phenomenon, and we see some additional details about the teacher's model of the science here:

Teacher: “You were talking about air. Does air take up space?”

Student1: “No, I thought air took up the space of alcohol.”

Teacher: “Did you read about atoms?   Things that make it up are made of atoms. Atoms are made up mostly of what though?”

Student2: “Air.”

Teacher: “Air takes up its own space but atoms have space in them. Water was filling in the space in alcohol. But if we added water to water, it wouldn’t happen, would it?”

Student3: “So, there’s more space in liquids because it has atoms and some parts of atoms have air in them?”

Teacher: “Exactly.”

Student3: “Oh, you’re confusing me!”

Eventually the students write:

Some liquids have space.

Some liquids have space due to particles that have atoms that are made up of space.

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Commentary

This episode is valuable to reflect on, in part because it is so ordinary, in at least two ways. In the first place, it is a kind of interaction that happens weekly or daily, in an inquiry-oriented class — by which I mean a class in which the teacher takes students' thinking seriously, and encourages them to debate and develop a common understanding of a phenomenon. The teacher's role in such a conversation includes reminding, noting when something needs to be made explicit, encouraging representations, asking leading questions, probing formulations.

The episode is ordinary in another sense, which is that it is very common for a teacher, even a knowledgeable one, to be pushed to a nearby frontier of his or her knowledge by the combination of a new phenomenon and a set of students who are used to asking questions and debating answers.

We are seeing a glimpse of a good teacher at work. She encourages students to build up an explanation for the surprising phenomenon ($1 + 1 \neq 2$), and validates both their reference to (possibly) analogous or homologous situations, and their reference to learned sources (e.g. texts). In the dialogues with both groups, the teacher participates for a while in the discussion, and then leaves the students to reach a formulation that they find satisfactory.

In Group 1's discussion, the kids' explanation — air is being driven off — seems a reasonable first approximation. It was productive, too, in that it stimulated the kids to relate it to other situations in which they had actually seen air in bubbles driven off from a container of water. The activity to that point surprised them, got their attention, and brought them to consider some interesting ideas — e.g. "water" may be a composite substance; mixing liquids of different densities may not be an additive process, revealing unseen qualities about one, the other, or both substances; the idea of "liquid" includes materials of quite different properties. The teacher's "move" up to this point has been largely to encourage and affirm the students' use of potentially relevant knowledge to explore their understanding (e.g. line 13 "Such good connections!") The teacher wants to move them further, however, and so does not validate their answer as acceptable ("Possibly.")

While the students continue to work out their rationale based on the "air bubbles" hypothesis, the teacher invokes an additional voice, that of the curriculum materials (line 27ff). This is consonant with her respectful and strategic pedagogy, in that she is not making a direct assertion, but calling their attention to materials that they have already read before. The students consult the text; the teacher merely reminds them to think in terms of materials being made of atoms, but does not, for example, hint at molecules, much less molecules' being of different sizes (or having charge). Thus, she directs them to a level of organization that is too low (too small) for the phenomenon in question. At the level of atoms, the only "space" around is that within the atoms themselves. The teacher has thus pointed the students down a cul de sac; being attentive and willing, the students work along the lines indicated.

Now the teacher moves to Group 2 (line 40ff). The students here are working with the same phenomenon. Much more quickly, the teacher brings up atoms as a hint, and links "atoms" and "space" in her indications. This is despite the fact that she seems at first to be starting off at the molecular level of explanation, which would be more productive of accuracy. Even though she does so at first by asking about air and space (line 44), when the student responds by questioning whether air takes up space, the teacher moves on to atoms again (line 46), and quickly moves to invoke the text's authority again, which may lend greater force to her suggestion to think in terms of atoms and space (presumably interior space). It is possible that she is confusing atoms and molecules, but when the students try to work concretely with her suggestion about atoms, she follows the logic of her words. At this point, the Group 2 students follow up this line of thinking, and so they formulate their explanation in those terms. One student expresses cognitive dissonance (line 55), not unlike the Group 1 student who, in line 33, withholds assent to the "space in atoms = air spaces in the liquid" theory.

Discussion

It is important to remember that such moments of quick, improvised knowing are not confined to science teachers, but are also part of the everyday experience of scientists, as well, and probably of everyone engaged in frequent articulations of their knowledge in the face of novel situations: it is of the nature of inquiry, as Dewey argued (1938/2008). The formal processes of scientific discourse — writing up ideas and findings for publication, peer-review, etc. — tend to screen out such moments, in which quick flashes of discovery yield to second- and third-thought tests of validity. Sometimes, however, they have been recorded. One example from the scientific literature of the last century, however, may be of interest. In 1938, Irving Langmuir, a chemistry Nobelist with an interest in "pathological science," wrote a brief note in Science reflecting on a report of a noteworthy insect velocity (Langmuir 1938). He had become aware of a report by Dr. Charles Townsend, an expert on botflies, in the Journal of the New York Entomological Society, which stated "On 12,000 foot summits in New Mexico I have seen pass me at an incredible velocity what were certainly the males of Cephenomyia [C. pratti, the deer botfly]. I could barely distinguish that something had passed...As closely as I can estimate, their speed must have approximated 400 yards per second." (quoted in Langmuir 1938).

This finding was widely circulated as establishing the fastest speed of any flying animal, at approx. 818 miles/hr. Langmuir, skeptical that a fly could move (under its own power) at near the speed of sound, calculated the power requirements of such a phenomenon (370W, or a half a horse-power), and after further reflection, proposed that a deer botfly might appear as the blur Dr. Townsend saw at a more likely rate of 25 mph. There is no reason for Dr. Townsend not to have made his 'guesstimate' of botfly velocity on the spot, and it was also part of the knowing processes of science for colleagues to bring further reflection and critique to bear on this seeming moment of discovery.

The teacher's "atom" remarks, which were (formally speaking) good "moves" for a teacher to make in such a dialogue, revealed some of the limits of her own science understanding. This good teacher was in a tight spot, because she had not had the materials for long enough to really prepare. She had not conducted this particular activity before, so she had no experiential knowledge of the system and the problem herself, which might have promoted further inquiry on her own as part of the preparation. She was conscientious, so I would expect that she tried the activity ahead of time. Yet as to the sense making, either she made a judgment on her own about the explanation for the surprising results (making perhaps a snap assessment that it "made sense" to her) or she read an explanation provided with the materials, which she did not fully comprehend. In either case, however, we can say that her interpretation of events or of the provided explanation was shaped by her prior understanding, which provided her with the impression that she basically understood what was happening. She also brought to this situation her prior experience, as a competent teacher — she has come to rely on her judgment in the classroom.

Yet here we have captured, quite unexpectedly, the teacher under demand, at the unsuspected boundary of her understanding. She is feeling the strong pressure to act strategically but confidently that a good teacher feels when she sees students making headway, but not reasoning expertly yet, and in need of a little help, not to the answer, but to more comprehensive formulation. Here is a crux, inherent in inquiry-based pedagogy, in which a teacher's knowing is tested ad hoc and "in the wild," in response to a student's constructive reasoning. At this point, let us return to the four-part argument outlined in the introduction.

<u>1. Anyone's knowledge (including a teacher's) is a patchwork of areas of coherent (propositional and procedural) understanding bounded by other areas of indistinct or erroneous understanding, and of ignorance</u>.

The dialogue suggests a possible model of the atom that the teacher may have in her mind at this moment. Her remarks would be consistent with a mental model of an atom as a sort of wire-frame structure, within which there is some interior space, into which (and out of which) air could pass. The possible equation of "air" and "space" (lines 20-22) also fits with this. At this point, she is not aware of the contradiction between this idea and what she perhaps knows about the composition of air, and the relation of molecules and atoms. It is very likely that if she were to be examined on the relevant propositional knowledge, she would assert correct understandings about the relationship of atoms and molecules, of inner space and air. In this moment, however, she is required to be aware of these ideas, plus at least one other one (the idea of molecular packing), to help students to move towards at least partially adequate answers. The connections don't happen, however.

Now, a reader might be tempted to say, "Well, this teacher should have been better prepared. It's possible that if this teacher had had a science background, or a more thorough preparation with these particular materials, she would not have retained some particular misconceptions, though it is not clear whether any specific preparation would have addressed the collection of things that might be wrong with her understanding of the physics involved here." This response, I believe, overlooks some important characteristics of knowing which are quite germane to teachers' work, if that work includes interaction with students inquiring. Our case of imperfect knowing allows us to point out some of these characteristics, which relate to the second and third parts of my argument.

2. Much of what anyone knows is made explicit (i.e. accessible to examination) under particular conditions; the moment of elicitation is likely to require the ad hoc (re)creation of an instantiation or version of knowledge.

3. Teachers' (re)creation of knowledge is exposed to examination most often in dialogue with students; and the ad hoc nature of (re)creation can be problematic for both teacher and learner.

Our classroom incident allows us to identify some important aspects of the act of knowing: when one knows, why one knows, and how the knowing happens.

When one knows. In the first place, knowing is, to an important degree, an event in time. To speak very simply, sometimes we know things which at other times we do not seem to know. Perhaps we encounter this peek-a-boo of knowing most often when trying to recall isolated data, information not embedded in a web of associations which lead us, like the strands of a spider's web by any one of many paths towards the center. Yet this metaphor has one deep flaw, which is that the "center" of a web, which in the case of knowing at a particular moment is the "target" we are seeking, is often not the main target of search — something else in the web may at different times be the "center" which is both the target of a search, and the organizer of its own explanatory web. In our case, the Teacher is called upon to know something at a moment when some students are making sense of a discrepant event, which the Teacher has not herself confronted before. This is not a case in which the Teacher is creating a presentation or lecture, in which she would make use of the various mechanisms that experienced reasoners have, to test and improve the validity of assertions and arguments.

Furthermore, we see the Teacher "knowing" twice, once in each group. In the first event, she develops her ad hoc theory: suspecting that "air bubbles" are not right, she moves the students past this line of thinking gently, reaching for the text on the atomic basis of matter, and directing the students' sense-making down the atomic cul de sac. In the second group, this composite response (don't think about air, think about atoms and atoms being space, remember what you've read about this) comes rather quickly: her immediately previous experience has primed her for this move.

Why one knows. The source of the need to know, which directs mental attention and what Bartlett (1936) called the "effort at meaning," is itself in many cases a powerful shaper of what is known in a particular moment. In the case of knowing, say, the year in which Charles I of England was beheaded, the date may be sought merely in the course of constructing a chronology, or because someone else asks for it, for their own reasons. More often, and more interestingly, however, a "piece" of knowledge is needed in the course of constructing an explanation or an argument — sense making for its own sake, or for some polemical or dialectical demonstration (in the case of poor Charles, it might be part of an exposition of political trends in revolutionary England). Very often this is the challenge for a teacher who is facilitating student inquiry, and it is a challenge precisely when the "need to know" is contextualized in an area containing some unknowns: the students may stumble upon some aspect of even a commonplace system which seems strange and wonderful (and unknown) because of the way the problem presents itself to the student, and therefore for the teacher.

In such a situation, one is called upon to know something, as part of the building up of a coherent (local) body of explanation. In supporting student inquiry, the Teacher's challenge is yet a little more complex, because she is not herself creating the explanation, but, as it were, creating scaffolding or some more ethereal structure to shape and guide the students' as yet incomplete (and imperfectly developed) explanation in their own terms.

How one knows. This is, I think, the heart of the matter. In almost any theory of teacher knowledge (or student knowledge), the way we talk about what people know tends to reify their knowledge, to take an abstract thing and give it the status of a real object. This is natural and convenient for people in some branch of the knowledge improvement business, and we all of us get so used to handling the abstractions of our particular specialty that they take on for us a substance rather like that of our luncheon sandwich or our favorite pet. Naturally and conveniently, too, we can then invest this reified thing with many of the characteristics of physical objects: we can talk about its depth, its robustness; we can compare it with other people's knowledge, measure it with instruments, and find flaws to be fixed either systemically or with some spackling from the professional development tool box.

Yet our case reminds us that in fact, knowledge, or (better) knowing, is in fact a complex, creative act — as John Dewey would argue, it is bounded by a consciousness of disequilibrium or question, on the one end, and by resolution or the achievement of a new equilibrium at the other end. (Burke 1994, Dewey 1938 [2008]). Not only is it situated in a particular moment and motivational setting, but it takes some physical shape, external to the knower. In our case, it takes the form of words, and the words are chosen by an alert Teacher who is not making a presentation for herself, or for colleagues, but for 6th graders, whose science background and sophistication she understands and accommodates in her own act of knowing. It may well be that this additional constraint, the nature of the other participants in the knowing, adds a powerful element of surprise or unfamiliarity to the content she seeks to know about: not only has she not thought about this, or needed to create an explanation for it before, but she is to a certain degree seeing it through her students' eyes, and this difference of vantage point, which affects the way a Teacher chooses words, may in fact have interfered with the Teacher's reasoning from first principles about the problem, in a way that she might have done if solving the problem for herself.

Perhaps the best way to put this is as follows: Most of the time, when we talk about people's "constructing knowledge," we have in mind situations of learning, or relearning: building internal conceptual representations of some subject. But very often, knowing takes place as a construction, an improvisation, for a particular purpose, under particular constraints (Dewey 1938/2008). Furthermore, the conditions under which the knowing is stimulated are often unique, and unlikely to recur — and therefore unpredictable, and impossible to prepare for (or against). This dialogue with this particular student required the teacher to know in a way that produced this particular response, and her mental model might not otherwise have been deployed, without this stimulus.

Bartlett long ago argued compellingly that remembering is a reconstructive and creative act, rather than the pulling out of a preserved fact from its storage drawer. The knowing that a teacher does, under time pressure, and in the service of students themselves constructing knowledge, includes this creative process of remembering, and of constructing on the spot, in the moment, to help these students with this question. Having in mind many previous experiences and robust explanatory scenarios, as well as factual knowledge, enriches the resources a teacher can draw upon in the moment of knowing, and increase the likelihood that the knowing will be reliable, replicable, and productive.

<u>4. These aspects of teacher knowing should shape efforts to improve science teachers' content knowledge, and in particular make a simple but important stipulation about what "improve" must mean.</u>

The stakes were not very high in this classroom event, nor is it likely that the teacher's (momentary) inadequate knowledge was likely to cause much lasting "harm" to the students' understandings of science. It is likely that in later months or years, perhaps even later that year with this Teacher, the students will read or see or do something which will stimulate them to work out a better understanding of what was going on. On the other hand, though this incident is not so very important per se, the Teacher's misconception on such a fundamental point as the relations of atoms and molecules (if she in fact had any confusion on that point) could in fact affect the way she works with other ideas, and it is of course greatly to be desired that students not be given misinformation. But how could this sort of imperfect knowing have been prevented?

I think it can be taken for granted after decades of educational research and philosophy that the "knowledge transmission" model of learning cannot apply in its crude form to teachers any more than it does to students. The situated nature of teachers' (or anyone's) learning— and knowing — is foundational and empirical studies strongly support it as a basis for effective professional development (Reiser 2013, Rosebery and Puttick 1998) . Yet because of the tendency to reification of "knowledge," other more sophisticated approaches to improving teachers' content knowledge are flawed by their own simplifications. Because knowing in the classroom is an improvisatory, situated act, elicited often at the boundaries of a teacher's knowledge (growing out of an encounter with phenomena), deeper reading and more formal training in the subject matter, as typified in college courses, will be helpful, but will not solve the teacher's problems at the boundaries of knowledge. No one knows everything about how all aspects of the world work. This problem may be particularly acute in middle school, since, as presently construed, the middle school curriculum confronts a teacher with a substantial slice of the known universe, in small sample chunks — and student inquiries increase the length of the borders to be defended. The need to improvise (infer, extrapolate, and otherwise create knowledge on the spot) is one that every teacher encounters.

I would argue also that, for the same reasons, "misconceptions" or "incomplete perceptions" are a permanent part of anyone's mental landscape, and therefore there is a limit to how complete their destruction can be. Certainly one can gradually and thoroughly improve someone's science knowledge, building up not just a database of facts, or pre-rehearsed explanations, but of interlocking theories, so that as an explicit goal it should not be a principal target of professional development. Indeed, too great an emphasis on, or reification of, this persistent feature of human cognition may distract a teacher from paying attention to the process and situation by which concepts are developing in the child (a genetic approach, to use the Vygotskyan term, Wertsch 1988).

Rather, it is worth bearing mind what we know about the quality of knowing that teachers need, and how that relates to the quality of their content understanding, and more especially the kinds of experience of knowing that teachers can build up as part of their growth of expertise. Learning the content of their kits or curriculum materials is a useful approach, when the goal is to ensure that a teacher can reliably know the material their students are learning.

This will not be enough, however, if the curriculum incorporates inquiry to some extent, because there is always the likelihood that teacher and students will find themselves pioneers in strange terrain. The preparation for such an event, for a teacher, involves extensive experience in exploration — to extend our metaphor, the teacher as explorer needs to have a sure sense of what to do when lost. This involves encountering such boundary events with a firm grasp of explanatory theories and principles, which can orient the improvisatory explainer; experience also with the process of testing conjectures for logical and theoretical plausibility, and being able to identify where the boundaries of the well-known are: "You know, I am not sure, I'll have to think about that, or ask So and So."

Yet the graceful admission of temporary ignorance is not by itself the best move, if the teacher wishes in fact to grow as an inquiring learner herself; her teaching gains power if she construes this as an opening for shared inquiry. When one engages in the kind of (re)creative knowing that is often required, and puts something into words, the formulation can have one of several fates, and if our goal is a powerful, reflective practice, we are in a position to express a preference in principal among these fates.

In the first case, the knower may just forget or bypass the product of the knowing: the event may be so casual and trivial as to be discarded. However, the likelihood of this is lessened for a teacher, whose practice rests in a fundamental way upon her knowing. For this reason, she is more likely to be aware of these events, and remember them. In this case, the knowledge that was created and articulated becomes a part of the teacher's knowledge. Since our knowledge is a dynamic thing, and elements of what we know are often combined and recombined spontaneously and under many circumstances, the bits of knowledge that we create may well have farther reaching consequences than we might think, at first, as they are employed in other acts of knowing, and in a sense become part of our conceptual tool kit. In our present example, we may even have a small example of just such an event, at least as the teacher moves between Group 1 and Group 2, as we see her acting on the basis of her just-previous experience. She makes pedagogical moves that seem to rest upon the theory improvised upon first demand earlier in the classroom.

A third possible fate, however, which I would argue is the most desirable from the point of view of an inquiry-based practice, is that teachers develop the habit of noting these moments of knowing, and marking the products as provisional, and as the subject of their own inquiry. In this way, student inquiry and the surprising events that arise in the midst of investigations, feed directly into teacher inquiry, both as teachers and as knowers.

For this reason, and on the basis of this view of knowing as a (re)creative act, we must insist upon a broader view of teacher professional development, which moves beyond teachers' acquisition of ever better and more advanced science content knowledge (though this is good), and beyond an exploration of student knowledge, misconceptions, and similar factors, but bears in mind that anyone's knowledge (including teachers') is a creative organism, and most creative at the knower's frontiers. Knowledge is the product of inquiry, and teaching thrives as the teacher sees inquiry as the key to her learning, as for her students' learning (Ballenger 2009).

Hence, science teachers' professional development must involve teachers in inquiry, not just about classroom events, but about the science that arises in those events (and ideally other science as well); in reflection about problems met, and the knowing that was drawn forth by them; and in discussion and study that extends a teachers' familiarity with their subject's terrain in many settings, and from many unusual angles — the sort of learning that is dramatically enhanced by collegial exchange: talk and inquiry with colleagues. Our knowing does get better, when we work with it as it really is, a creative act that draws on previous knowing, at a particular moment of need. Good knowers often have developed habits of mind that do the needed cultivation and reflection, but they often have not worked with it as a kind of knowing and expertise in its own right. Our professional development (for ourselves and for others) can become much more efficient and valuable in the service of good science learning if we design explicitly for the improvisatory knower at the edge of their knowing.

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Appendix: What happened in the experiment?

The critical point is the polar nature of the water molecule, which is important in so many aspects of water's behavior. The molecule has a higher electron density on one side of the oxygen atom, , which therefore results in region with a slight negative charge. The two hydrogens are on the other side, yielding a region with slight positive charge. That makes it polar.

Liquid water is highly structured, with the mildly positive Hs of one molecule aligned to alleviate the mildly negative O of another. When the alcohol molecules are mixed in, they disrupt the organization of the water; the effect is that mixture of molecules pack more compactly.

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