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Anatomy of a Scientific Explanation

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> "If I'm going to explain this theory, the question is, are you going to understand it? Will you understand the theory?" --Richard Feynman, 1979 Douglas Robb Memorial Lectures

In this way, Richard Feynman, recipient of the 1965 Nobel Prize in Physics and renowned teacher, author, and bongo player, introduced scientific explanation as an interesting problem with understanding as its testable outcome. Making quantum mechanics understandable to an audience of non-specialists is no easy task. Feynman had his audience in stitches, on this occasion, after noting that advanced graduate students in physics often "do not understand it either, and that's because the professor doesn't understand it."

Leaving aside faculty comprehension, university professors more often face the challenge of producing a unit of understanding in their students. College teachers explain in order that their students comprehend key concepts, important theories, tricky problems, and experimental methods. But we know that understanding doesn't always appear. What gets in the way? Feynman put it like this: "my task, really…is to convince you not to turn away because it appears incomprehensible." Why do so many well-intentioned scientific explanations cause students to turn away, or just not end up 'getting it'?

Observations of excellent scientific explanations provide a useful functional anatomy—a study of their structure in relation to how they work. The best explainers of science tend to align the structure of their explanations with how learning works. By using this *anatomy* to build explanations on small scales (the single concept, the five-minute problem) and large scales (the hour-long lecture, the semester-long course), we can also produce more understanding, and less turning away, for our students.

Anatomy of a Scientific Explanation

The three metaphorical structures and functions below are all essential parts of the *anatomy* of an effective scientific explanation, each with its own associated teaching strategies. As teachers, our job is to adapt these strategies to our unique styles, goals, and priorities. This anatomical metaphor may seem overly simplified, but its strength is in its immediacy—as Diamond (2005) tells her Human Anatomy class at UC Berkeley, "You will always have your anatomy with you, wherever you are." Try it out as a way to organize the functional pieces of your explanations and as a memory aid to insure that your explanations are complete and fully 'alive' for your students.

1. **The head and neck are for direction.**
   Effective scientific explanations begin by revealing exactly what students should understand by the end. Although suspense might seem interesting, explanations that try to surprise students at the end are more disorienting than helpful. Use the first part of your explanations to capture students' attention, in other words, to 'turn their heads.' In his TED.com talk, "The Astonishing Promise of DNA Unfolding," Paul Rothmans (2008) lets us know right away that "life involves computation," a non-intuitive concept at the heart of his explanation. He also gives us a reason to look, a motive for why we should want this unit of understanding: comprehending how the genetic program is like a computer program will change what we understand life to be. Similarly, Diamond (2005) lets her biology students know in the very first lecture, "You're going to look at each other differently from now on, introspect, learn who you are beneath the surface."

   As the explainer, your head is already pointed in the right direction. Without guidance, students might be looking somewhere else, or not realize why they should look at all, and miss both the brilliance of your explanation and the understanding that might result. State the goal, provide a motive, and keep it in students' sights at all times.

2. **The limbs are for locomotion and interaction.**
The details of an explanation require movement from one step to the next, which is what legs are for, and manipulation of the ideas and concepts along the way, a perfect use of hands and arms. But limbs need assistance in the form of structured explanations to keep from aimless wandering and unproductive flailing. Both wandering and flailing are well-documented characteristics of novice learners (Bransford et al., 2000). For example, whereas you (an expert) have coordinated your intellectual *limbs* to move easily through the process of solving a problem or making logical connections, novice students don't know all the small, implicit moves that are involved, and need to work much harder than you to arrive at understanding. This difference leads to a common situation: science teachers often leave out steps that are obvious to them because those steps are imbedded in the cognitive equivalent of muscle memory. Examples of putting in all the steps to help coordinate limbs include rewriting an algebraic manipulation of an equation line-by-line rather than jumping to the end result, and pausing to articulate a magnitude estimate for the answer to a problem before carrying out the calculation.

Scientific understanding is not like a thermodynamic state function, such as entropy, whose value depends only on the current state of the system, *not* on the particular path taken to get there. On the contrary, it matters very much how you and your students arrive at a new understanding. The result of a wandering, flailing approach is rarely the same as your expert understanding. By showing students how you move through and interact with the material you're teaching, you're more likely to engender deep and lasting understanding. Your own path, including the implicit parts that are difficult to articulate, is a good model for students to follow. It is not the only possible route to understanding, but it is a reasonable one to show them.

Effective science explainers demonstrate a few other strategies for guiding students through the details of an explanation while appealing to a wide range of student backgrounds and learning styles:

- *Use metaphors, analogies, and familiar examples*. These might seem superfluous, but they are essential to building new understanding on to a base of familiar concepts. Just as it is far easier to coordinate one's limbs to hit a pitched baseball after starting with T-ball as a child, your explanations will produce more understanding if they are built on a strong scaffolding of prior learning.
- *Use visuals*.The Picturing to Learn approach (http://www.picturingtolearn.org/about.html) reminds us that actively reproducing alternative representations of an explanation is an important way to deepen understanding. Where Feynman only drew on the board—a good first step—you can get your students drawing, too.

- *Address likely missteps and problematic terminology*.Sometimes it helps to know what kind of wandering and flailing to avoid, particularly where students hold common misconceptions or inaccurate intuitions about the subject (Halpern and Hankel, 2003). Similarly, science uses specialized jargon and common terms with new meanings that are likely to block understanding if not translated or highlighted.

3. **The torso is for digestion and integration.**

Effective explanations of science end in the gut. Students need an opportunity to process their new understanding, extract meaning from it, and appreciate it as an integrated part of their own anatomy. At the very least, this means re-articulating the new understanding in a way that wasn't possible before the explanation. For example, Kwabena Boahen (2007) explains (in a TED.com talk) the difference in energy efficiency between the serial, rigid structure of a typical computer and the parallel, fluid structure of the brain. By the end, he integrates our vivid understanding of this difference by sharing a quote from Brian Eno: "The problem with computers is that there's not enough Africa in them". We would not have seen the significance of the quote at the beginning of the explanation. You may not always have a witty quote with which to end your explanations, but bringing the understanding home to your students at a gut level through careful re-articulation will nonetheless help.

Beyond Anatomy, Beyond Explanation

The above *anatomy* is intended as a pneumonic, as a source of inspiration, and as a resource of specific strategies employed by great explainers of science. In teaching, in contrast to formal public lectures, we can ask students to articulate their understanding to us and to each other, and we can respond, turning one-way explanation into interactive exchange. In doing so, we surpass both anatomy and explanation. When students become active participants in the construction of their own knowledge of science, we can accomplish Feynman's goal—understanding—in a far deeper way than explanation alone allows.

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