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CROSSING THE THRESHOLD TO DEEPER DEVELOPMENTAL BIOLOGY

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I sometimes encounter a peculiar mix in my undergraduate course in developmental biology. A student is able, flawlessly, to recite the molecular and cellular details of a complex developmental process, but is then unable to describe the experimental evidence that supports those details. When confronted with a novel situation not discussed in the lectures or the text, such a student also struggles to propose appropriate experiments to test her own hypotheses. Why are my students sometimes able to learn how organisms develop, but then fall short when asked to think critically, like developmental biologists?

I believe this difficulty stems from confusion concerning the relationship between types of evidence and the claims based on them, and I suspect this difficulty plagues the students of many disciplines spanning both the sciences and humanities. In the context of developmental biology, a student may state that a particular gene "causes," "is responsible for," or "is involved in the development of " a particular anatomical structure. While specialists may sometimes use this type of imprecise language in order to be deliberately vague, students often resort to it because they lack more precise descriptions, which are based on specific types of evidence.

In my own course, I target this confusion by using a catchy, clever mnemonic originally devised by Dany Adams and then slightly modified and promulgated by Scott Gilbert in his textbook on developmental biology (Adams, 2003; Gilbert, 2006, 2010). The mnemonic describes a step-wise methodology, with each step, if successful, resulting in a different type of evidence that supports a different type of claim. The three steps are:

1. *Find it*
2. *Lose it*
3. *Move it*

The first step is meant to represent the process of obtaining descriptive, correlative evidence, such as the expression of a particular gene or the presence of a cell type associated with the development of a particular anatomical structure. Such evidence is merely a weak indicator of causation. The second step represents a test for necessity, wherein the putatively causal factor—expression of a gene in a particular tissue, for example—is removed and the consequences observed. The claim that such-and-such a gene (or cell type, or act of cell-cell communication, etc.) *is required* for the development of a particular anatomical outcome rests on this type of evidence. The third step represents a test for sufficiency wherein the putatively causal factor is placed in a novel context—say a gene expressed in a tissue in which it is not normally expressed—and shown to result in a particular outcome. The steps need not be (and often are not) pursued in this order, but any reasonable claim of developmental causality rests upon successfully obtaining at least two of these three of types of evidence.

A frequent and persistent refrain of "Find It, Lose It, Move It" in a developmental biology class can go a long way (Adams, 2003). While many have explored concepts that are central to learning developmental biology (for example, Gilbert, Hardin, & Wood, 2008), to me this concept, more than any other, represents a "threshold concept" in the sense that it is troublesome, transformative, integrative and, to some extent, irreversible (Meyer & Land, 2006). It is perhaps an odd example among more conventional threshold concepts in that it is a set of related ideas, rather than a single idea, and methodological rather than content-based. Nevertheless, Find It-Lose It-Move It is often troublesome for students at first, but in the end transformative and integrative in that it allows students to engage more deeply with the textbook descriptions of development to which they are exposed, many of which are incomplete at best and wrong at worst, by keeping a critical eye out for the evidence on which they are based. And arguably, learning the concept is irreversible in the sense that a student who crosses this threshold will no longer entertain a claim about development without wondering about its foundations.

Given the importance of crossing this threshold, it behooves an instructor of developmental biology to devote adequate time to Find It-Lose It-Move It and to persistently refer to the mnemonic throughout the course. In my personal experience, however, it is the initial presentation and working through of the concept that seals the deal. While excellent pedagogical suggestions for presenting the concept have been made (Adams, 2003), here I share an additional suggestion that seems to help. Typically, I quickly present the mnemonic somewhat prosaically, but then tell the students a story for which I solicit their input.

A space alien arrives on Earth. She is bright and inquisitive, but completely naïve to the ways of our planet. One of the first things she observes is an automobile moving back and forth on a street. She notices that the wheels on the car move at the same time the car moves, and stop when the car stops. What does this suggest to the alien?

This "Find It" evidence *suggests* that wheels might cause cars to move. What should the alien do to test this hypothesis?

The alien removes the wheels on a car and observes that the car ceases to move. This "Lose It" evidence suggests that wheels are indeed necessary for cars to move. But the alien doesn't stop here. What's her next step?

The alien places the wheels on a different, similarly sized object. Any suggestions?

The alien attaches the wheels to a garbage dumpster (or whatever the students might suggest) on flat ground and does not observe movement. This "Move It" evidence suggests that wheels are not sufficient to cause cars to move. Considering all the evidence, the alien determines that wheels are necessary but not sufficient to cause cars to move.

This story is pedagogically effective, and I suspect this is for two reasons. One is that it uses a simple and familiar system—wheels and cars instead of gene expression patterns and tissue types. The second is that the story empowers students with a sense of dramatic irony; they are an audience-in-the-know watching the struggles of an ignorant alien. (A fun alternative here might be to have students actually act out the story in front of the class, though I have yet to try this.) To reinforce the concept further I typically follow the alien story by challenging my students with a similar example, one that is mechanical and non-biological in nature (a particular cog in a complicated machine, for example), but change the scenario so that they are now the ignorant aliens. Once we work through this example, I remove the familiarity support and challenge my students with a real example from developmental biology, one that involves a gene's pattern of expression, the effects of mutating the gene, and the effects of expressing the gene where it is not normally expressed (not necessarily in that order). This whole process typically takes at least a half an hour, but is an investment that easily pays for itself as we progress through the course.

Of course, as students become more comfortable with the Find It-Lose It-Move It concept they begin to see that it is over simplified. In particular, students soon come to realize that the sub-concepts of necessity and sufficiency are relative to particular developmental and environmental contexts. A particular gene may be "required" for a particular developmental process at one temperature, but not at another. Expressing a gene involved in eye development in every cell in the body may produce extra eyes in some tissue types, but not in all tissue types (and thus is only "sufficient" to produce an eye given a set of particular conditions). My feeling is that students often learn such rules and mnemonics only to later, appropriately, unlearn them to some extent. It is in this sense that this threshold concept may not be completely irreversible; sophisticated students will move back and forth across this methodological threshold as needed.

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