



The Baby and the Bath Water: Improving Metaphors and Analogies in High School Biology Texts

Citation

Shors, Luke. 2017. The Baby and the Bath Water: Improving Metaphors and Analogies in High School Biology Texts. Doctoral dissertation, Harvard Graduate School of Education.

Permanent link

<http://nrs.harvard.edu/urn-3:HUL.InstRepos:33051608>

Terms of Use

This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at <http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA>

Share Your Story

The Harvard community has made this article openly available. Please share how this access benefits you. [Submit a story](#).

[Accessibility](#)

The Baby and the Bath Water: Improving Metaphors and Analogies in High School
Biology Texts

Luke Shors

Dissertation Committee:

Dr. Catherine Elgin

Dr. Tina Grotzer

Dr. Jerome Kroll

A Thesis Presented to the Faculty of the Graduate School of Education of Harvard
University in Partial Fulfillment of the Requirements for the Degree of Doctor of
Education

2017

©2017
Luke Shors
All Rights Reserved

For Madhuri,
My partner through so many adventures

Table of Contents

ABSTRACT	IV
BACKGROUND TO THE RESEARCH SUBJECT	1
METAPHORS IN SCIENCE	2
SIMILES, METAPHORS AND ANALOGIES	5
PEDAGOGICAL METAPHORS AND ANALOGIES	7
TAKING A DEVELOPMENTAL PERSPECTIVE	16
THESIS ROADMAP	18
METHODS	19
SAMPLE	19
PROCEDURES	22
PHILOSOPHICAL ANALYSIS	24
REINFORCING METAPHORS	28
INFORMATION METAPHORS	28
DNA AS LANGUAGE	29
DNA AS BLUEPRINT	35
DNA AS A MACHINE OR SOFTWARE	38
SUMMARY OF INFORMATION METAPHORS	40
MACHINE METAPHORS	41
MACHINE METAPHOR EXAMPLES IN THE TEXTS	43
MACHINE-INFORMATION-BUSINESS METAPHORS	47
BUSINESS METAPHORS	51
COMPETITION AND WAR METAPHORS	55
COMPETITION METAPHORS IN THE TEXTS	55
EXAMPLES OF COMPETITION AND WAR METAPHORS IN MICROBIOLOGY	57
CASE STUDY: REINFORCING METAPHORS AND NATURAL SELECTION	62
OTHER FINDINGS	70
COMPARISON WITH FINDINGS OF PAST TEXTBOOK ANALYSES	70
METAPHORS AND ANALOGIES ILLUSTRATING PHYSICAL STRUCTURE AND FUNCTION	71
PRESENTATION FORMAT OF METAPHORS AND ANALOGIES	72
LEVEL OF ENRICHMENT OF METAPHORS AND ANALOGIES	72
IS THE ANALOGUE EXPLAINED?	72
IS A COGNITIVE STRATEGY PRESENT TO ALERT THE STUDENT TO THE PRESENCE OF THE METAPHOR?	73
ARE LIMITATIONS IN THE ANALOGY DESCRIBED?	74
ANALOGIES AND METAPHORS IN PROBLEM SETS	75
MIXED OR LAYERED METAPHORS	77
OTHER IMPORTANT METAPHORS: GEOLOGICAL TIME	78

OTHER IMPORTANT METAPHORS: THE TREE OF LIFE	80
ANALOGIES WITH ANTIQUATED SOURCE ANALOGUES.....	82
ANALOGIES WITH SUBTLE ERRORS IN MAPPING.....	83
<u>DISCUSSION</u>	<u>86</u>
NEW DIRECTIONS FOR PEDAGOGICAL METAPHORS	86
REVIEWING METAPHORS FOR OBSOLESCENCE, CULTURAL ASSUMPTIONS AND INACCURACIES.....	86
TARGET ACQUISITION VERSUS TARGET EXPLORATION	88
BETTER METAPHORS AS FOR PROCESS	90
METAPHORS FOR UNDERSTANDING CAUSALITY.....	91
METAPHORS FOR SYSTEMS BIOLOGY	92
<u>CONCLUSION.....</u>	<u>97</u>
<u>VITA.....</u>	<u>109</u>

Abstract

This dissertation is concerned with understanding how metaphors and analogies function in biology education and whether some of the philosophical critiques of the language used in the field of biology — and in particular its accompanying metaphors and analogies, have a basis in the educational materials used to teach the subject. This inquiry was carried out through examining the pedagogical features and content of metaphors and analogies from three high school biology textbooks. After identifying over two hundred and twenty-five verbal and pictorial metaphors and analogies, these figures of speech were coded based on prior research that establishes effective characteristics for their use. In tandem with this quantitative analysis, a philosophical analysis considers how well the content of these metaphors and analogies aligns with current scientific understanding and what misunderstandings may be engendered through the use of these metaphors and analogies. The major findings of the analysis include: 1) Textbook authors are much more likely to utilize metaphors and analogies as well as signal their presence to students compared with past analyses; 2) A number of metaphors and analogies either contain errors in analogical mapping or use source analogues that are too antiquated to support today's students; 3) The content of many metaphors and analogies is frequently outdated in reference to current scientific understanding; and 4) Many metaphors and analogies tend to reinforce tacit elements of past scientific paradigms – these are termed ‘reinforcing metaphors’ in the dissertation and include *nature as machine*, *nature as blueprint or information*, *nature as business* and *nature as war*.

The present work submits several implications for students learning biology as well as the manner in which students come to understand the natural world. The work suggests ways to reduce ineffective metaphors and analogies as well as reliance on reinforcing metaphors. It offers new approaches for the use of metaphors and analogies in biology education as well as specific directions that better reflect a more balanced and modern conception of important topics in biology including viruses, eukaryotic and prokaryotic cells, genetics, natural selection and ecology.

Background to the Research Subject

Like natural selection itself, the origin of this research was without a predefined end state. It was instead propelled by a belief that language matters in biology education and it would be valuable to examine the language used to introduce the subject of biology to students in a more systematic manner. I can trace that belief to a single genetics lecture in college when the professor spoke of DNA polymerase making a ‘mistake’ in base pair matching. My college-self opined “on what basis can we call it a ‘mistake’ when mutation is central to the origin and diversity of life?”

In a “more in heaven and earth than dreamt of in your philosophy” Horatio-style moment, I have subsequently learned that a vast literature touches on many facets of my simple college question. In science education this literature is most robust in examining how metaphor and analogy are used to teach scientific concepts to students as well as how we learn through metaphor and analogy in general. Outside of the science education literature, the critiques of language in science (including its accompanying analogies and metaphors) are co-extensive with the history of science itself. If these two bodies of scholarship are depicted in a Venn diagram, the literature that represents their overlap is surprisingly scarce. That is, 1) Scholars, who have voiced questions and dissent about some of the language used within the main of science, have, by-and-large, focused on scientific writings and not on pedagogical materials and 2) Scholars who have focused on how students learn through metaphor and analogy have mostly focused on the mechanics of such learning and the proper construction of these pedagogical techniques and not on the broader social and ethical implications of some of these metaphors and analogies. My primary purpose then, is to 1) Determine whether the many philosophical critiques of the

language (particularly metaphor and analogy) used in the field of biology have an evidentiary basis within biology educational materials; and 2) Re-examine the effectiveness of these metaphors and analogies in biology education recognizing that many prior studies on this topic are more than twenty years old and pedagogical materials may have changed substantially during this time. Although these are distinct questions, they can be connected in instances where a pedagogical metaphor or analogy may be well conceived but the scientific target being taught is outdated or biased. The following sections of the Introduction further describe the research topics, the potential value of the work as well as the methods and data I use in my analysis.

Metaphors in Science

When I began seriously researching the topic of metaphors in biology education I was surprised how much was written about the usefulness of metaphors and analogies in helping students of science grasp new concepts and furthering creative reflection. Articles revealed that analogical thinking had brought about major reconceptualization in physics, biology and chemistry and colorful examples abounded (Nersessian 2008). The German chemist Kekule reportedly identified the molecule benzene after a dream he had where a serpent was biting his own tail (Pinker 1999). Edwin Schrodinger famously influenced Watson and Crick through his metaphorical postulation that chromosomes must be “law-code and executive power...architect’s plan and builder’s craft – in one” (Schrödinger 1969). Emil Fisher hypothesized the tight coupling of enzyme and substrate interactions through an analogy to a lock and a key (Paton 1992). In arguing against the prevailing presumption in his day that gravity was a material force, Kepler provided the analogue of light:

“Who I ask, will say that light is something material? Nevertheless, it carries out its operations with respect to place, suffers alteration, is reflected and refracted, and assumes quantities so as to be dense or rare, and to be capable of being taken as a surface where it falls upon something illuminable” (Gentner 2002).

Beyond wonderful examples of how using metaphors and analogies could spur major paradigm shifts in science, learning to reason analogically was powerful across domains – perhaps even the core to what real creativity was all about (Franke, Poetz, and Schreier, 2013). And great metaphors have an arresting vividness to them. For instance, one of the great explicators of physics, Richard Feynman, compared a magnified drop of water to the brimming energy of a “crowd at a football game as seen from a great distance” (Feynman, Leighton, and Sands, 2011). Stephan Hawking made accessible the mathematics underlying the curvature of space-time to an orange: smooth from a distance, bumpy and wrinkled on close inspection (Hawking and Jackson, 1993). Richard Dawkins spoke of the selection of genes across generations as a series of sieves: unhelpful genes may make it by chance through a few sieves, but not a thousand in succession (Dawkins 1996). In all these instances, phenomena that for many were too abstract or vast to understand were made palpable and approachable. Suddenly anyone who had ever looked at an orange had at least a sense of the mathematics describing the curvature and distortions of space-time.

If examples such as these illustrate the potential utility and even beauty of metaphors in science and how metaphors can render these concepts accessible to the public, another argument to support metaphors in science education is their inevitability. In discourse analyses of interviews, lectures, essays, presidential debates and news programs scholars find metaphors regularly cropping up – somewhere around six metaphors a minute for spoken discourse and every ten to twenty-five words for written

discourse (Bowdle and Gentner, 2005). Reading Lakoff and Johnson (1984), moreover, we realize that a metaphorical conceptualization of the world runs *deep*. It is not an unnecessary adornment of language but an essential component of thinking (Gibbs, 1991). Why should language use in science be any different than in any other domain of human activity? And beyond these cognitive aspects of metaphor use, provision of metaphors makes science texts ‘friendly’ and hence has an affective appeal in addition to a strict intellectual one (Singer, 1984; Bean, 1991).

Yet for all these reasons to infuse scientific curricula with metaphors and analogies, philosophers have long suggested metaphors can mislead and deserve to be examined critically (Camp, 2006). The innovation that was glimpsed through yesterday’s metaphor or analogy may be an impediment for the advancement of today’s theory. Perhaps it is for this reason that Thomas Kuhn considered metaphor in discussing paradigm shifts, “Theory change, in particular, is accompanied by a change in some of the relevant metaphors and in the corresponding parts of the network of similarities through which terms attach to nature.” (Kuhn, 2000 pg. 203). The physicist Robert Oppenheimer captured the double-edged nature of metaphor and analogy in science well:

We cannot, coming into something new, deal with it except on the basis of the familiar and the old-fashioned . . . We cannot learn to be surprised or astonished at something unless we have a view of how it ought to be; and that view is almost certainly an analogy. We cannot learn that we have made a mistake unless we can make a mistake; and our mistake is almost always in the form of an analogy to some other piece of experience. (Oppenheimer, 1956. Pg. 129-130)

In science education we have a choice which metaphor or analogy to use. We don’t need to compare magnified H₂O to a football game seen from a distance; we could, for instance, compare it to sand or water sitting on a speaker and being jostled by the bass. Even for the ingrained metaphors Lakoff and Johnson famously investigated in

Metaphors We Live By (1984), with reflection, we still have an opportunity to choose whether we compare an argument to a war or a dance or to alternate between these comparisons to illustrate different aspects of arguments once we become aware of the metaphor. This sustained awareness of ingrained metaphors, while difficult in oral discourse, should be possible for pedagogical materials that are subject to multiple reviews.

In science, we also have the choice to alternatively illustrate different facets of nature through changing our language. And some times we can avoid the use of some metaphors altogether or at least limit their centrality. Employing metaphors to describe the structure of a cell at high-magnification is only necessary if we lack a powerful microscope. With such a microscope anyone can come to his or her own conclusions as to what a particular structure in a cell looks like and we don't need to rely on the poetic sensibilities of a well-known scientific luminary. Of course, even in these instances metaphors may still be used to guide the novice towards the structure of interest or a component's function that cannot be revealed on a static microscope slide.

Similes, Metaphors and Analogies

At this point, it is worth stepping back and critically examining what we mean by 'metaphor'. We tend to think of similes, metaphors, and analogies as comparisons with some conventional distinctions among the terms. In the traditional logic, recognizing a metaphor is a two-step dance: we search for a literal interpretation of the statement and, when the search fails, we seek a non-literal account (Searle, 1979).

To take an example from Hills (2012) when we encounter the sentence "a road grader is like a bulldozer" we understand this as being literally true: they are both big trucks that move dirt. But when we encounter a novel phrase, "Margaret Thatcher is like

a bulldozer” we recognize that phrase is not literally true in that she cannot possibly scoop large piles of dirt or is composed of metal. We then consider more abstract properties of bulldozers: they may be forceful or even blunt; they can push through obstacles that may be firmly rooted, etc. It is in this reflection that we understand the sentence as metaphor.

In Ortony’s (1979) account, metaphors and similes are both non-literal comparisons, with the former being indirect and the latter being a direct comparison. The problem with this logic, as pointed out by Glucksberg and Keysar (1990) is that statements of likeness should be reciprocal but metaphors rarely have the same meaning when reversed. To take one of their examples, the statement “my surgeon is a butcher” has a markedly different meaning than “my butcher is a surgeon” with the former denigrating the surgeon and later praising the butcher. Examining the asymmetric nature of simile and metaphor leads Glucksberg and Kesar to conclude that simile and metaphor are not comparisons but set inclusion statements where the metaphorical source is a prototypical example of a set of concepts that may be more challenging or time consuming to list as part of a literal statement. There are many examples in the literature that support the notion of metaphors functioning as class inclusion statements. To take one of Glucksberg’s (2008) examples, when I say, “my lawyer is a shark” I am not really commenting on his or her dorsal fins or extensive cartilage. I am instead using “shark” as a prototypical example of an aggressive and merciless being and it is to this abstracted category based on a subset of features ascribed to an actual sharks that I am placing my lawyer.

Metaphor comparisons are thought to yield stronger statements of class inclusion than comparisons using simile, as the presence of the words ‘as’ or ‘like’ hedges or qualifies the comparison (Glucksberg and Kesar, 1990; Glucksberg, 2008). In the science education literature the terms ‘metaphor’ and ‘analogy’ tend to be used interchangeably perhaps due to the central influence of Lakoff and Johnson (1984) in the field. However, a few scholars regard analogies as having a more defined and explicit pedagogical purpose (Duit 1991; Glynn, 2007).

Nessarian (2008) notes that scientific models bear a relationship to analogies where analogies typically possess fewer mappings between a source and a target phenomenon. This suggests that in a rough way, there is a continuum in how these terms relate to scientific concepts and theory. In this continuum, similes and metaphors may have a more tentative or even implicit relation to scientific concepts they point to, whereas analogies and models have more explicit relationships with more detailed mappings between source and analogue.

In general I agree with Nessarian’s (2008) distinction. When encountering a phrase such as “the cell is like a factory” I view this as primarily metaphorical. At the point that various cell components are compared with conveyors belts, power stations, shipping departments and the like, the metaphor becomes an explicit analogy. In the text, I frequently use both terms together (metaphor and analogy) when I’m talking about the role both have in biology education. When I’m mostly talking about figurative language in the text, I use the term ‘metaphor’.

Pedagogical Metaphors and Analogies

In the field of metaphor and analogy in science education, it is hard to find a more influential scholar than Dedre Gentner. Her structure mapping theory describes how learning can take place from a known source or ‘analogue’ to an unknown target and establishes the overall learning process (Gentner 1983; Gentner and Wolff, 2000). This model consists of five stages: 1) retrieval of the analogue concept; 2) mapping and aligning the analogue and target structures; 3) evaluating the fit; 4) abstracting the features common to both into a new schema and; 5) re-representing the initial characterization of the analogue and target to better the analogical match (Gentner and Colhoun, 2010).

Gentner and Markman (1997) conceptualize the distinction between metaphors and analogies (on the one hand) versus literal similarities between two things (on the other) as a phase space consisting of shared attributes and shared relations. Where there is limited congruence in either attributes or relations the analogy is nonsensical (e.g. a cell is like a protractor). Instances, where both shared attributes and relations are significant are more literally similar (e.g. a eukaryotic cell is like a prokaryotic cell). Where shared attributes exist but shared relations are limited we have analogies or metaphors of limited teaching value (e.g. cells are like balls as both are round). Fruitful pedagogical metaphors and analogies exist, according to Gentner and Markman (1997), where shared relations are high but shared superficial attributes may be limited. For instance, in Darwin’s Tree of Life metaphor, the branching pattern of a material tree is analogous but superficially unrelated to speciation over time where the ‘length of branch’ equals ‘duration of time’.

If Gentner and Colhoun’s (2010) work has a problem when applied to education it is that they tend to focus on how this process aids learning and largely ignore how it may

impede understanding or entrench a particular scientific perspective. The very same steps that allow us to be informed through a metaphor or analogy also allow us to be duped. Gentner and Colhoun recognize this potential in so far as they focus on ‘good analogies’ that “both reveals common structure between two situations and suggests further inferences” (pg. 44). Their stance here is in the main with other scholars that want us to craft good metaphors and analogies and provide educators with guidelines for developing useful metaphors in science education (Glynn, 1989; Orgill and Bodner, 2006). Although this appears to be a sensible approach, strangely the empirical investigations of pedagogical materials reveal that very few actually follow the script. For instance, among the eight biochemistry textbooks analyzed by Orgill and Bodner, (2006) limitations in the analogy are only described 4.1% of the time– despite scholars advocating for the inclusion of an analogy’s limitations since Glynn’s (1991) TWA model. Priming students to recognize the metaphor as a metaphor through a cognitive strategy or providing an explanation of the analogue are similarly scarce features of textbook metaphors in past analyses even if they are recommended features for metaphor construction (Orgill and Bodner, Curtis and Reiguluth, 1984). We can speculate about the discrepancy between pedagogical metaphors use *as recommended* and pedagogical metaphor use *as practiced*.

With some of these concerns about scholars being too lenient in their support for pedagogical metaphors and analogies in mind, I began my own research with several beliefs in mind about metaphors and analogies in biology education:

1. Metaphors may be inevitable in science and science education but in many cases we can be intentional about which metaphors we use. Moreover, in other instances, we can swap out metaphors for other representations such

as models, illustrations or ‘direct’ visualization through a tool such as a microscope.

2. That metaphors and analogies are useful in learning science is probably true but it is trivially so. Extolling metaphors and analogies as useful in learning science is akin to praising the use of diagrams. We must instead try to evaluate the potential usefulness of metaphors in science on a case-by-case basis even if we cannot directly observe the student’s apprehension of the metaphor.
3. There is a disconnect between the theoretical literature suggesting how we should be using metaphors in science education and the empirical investigations of actual metaphors and analogies in science textbooks. This disconnect between guidelines and metaphoric instances is most obvious in Glynn’s (1991) recommendation to include a discussion of any limitations in the base analogy and prior textbook analyses that have found very few limitations in base analogies explicitly discussed. The disconnect between how scholars believe we should be constructing metaphors and analogies and the way textbook authors have done so may be emblematic of something that is problematic in the guidelines themselves or some other undocumented factor.
4. An exclusively quantitative analysis of metaphors and analogies in science materials based on established criteria for ‘good metaphors’ may be insufficient at this stage as further analyses with the same coding

framework used by Orgill and Bodner (2006) is likely to replicate earlier results.

As earlier noted, my research agenda is further distinct from most scholars in this field as my interest in metaphors in science education extends beyond the student learning the target topic. When Bean (1990) introduced the *factory as cell* metaphor as an analogical study guide for learning about cell components, the outcome of interest was how students who were exposed to the study guide performed on a quiz matching cell components with their function. The outcome of the quiz, then, was the sole criterion by which to judge whether to use the analogy. And because the students who were exposed to the analogy did better as measured by the quiz, the conclusion was that the analogy was effective and should be included.

The introduction of this metaphor may have had other effects though beyond what was measured in the matching test. Critically for the present project, studies demonstrate that learners may also ‘over map’ analogies, bringing features from the ‘source’ (factory) as they understand it to the ‘target’ (cell) that were not intended by the author of the analogy (Blanchette and Dunbar, 2002). In recall tests, learners usually cannot distinguish between material that was actually present in the analogy and other independently derived inferences based on the student’s understanding of the source concept that he or she has mapped to the target. Occasionally over-mapping may be a good thing, as learners may map additional features from the source and derive novel insights not intended by the creator of the analogy. However, this natural tendency can also result in misconceptions and reconceptualization of the target.

In the analogy '*cell as a factory*', learners could suppose any number of features in the target based on mappings from their knowledge of the source. The question is what sorts of over-mappings are occurring and how significant are those over-mappings for their immediate as well as long-term understanding of the concept.

In tandem with these investigations of pedagogical metaphors, scholars have examined the use of metaphors in popular accounts of science and scientific journals—looking at metaphors that may be particularly pernicious in understanding scientific theory and for the ethical application of scientific concepts. These controversial metaphors include *nature as machine* metaphors dating from Descartes (Pigliucci and Boudry, 2011; Shiva 1998), *nature as information* and gendered language in scientific metaphors (ranging from the depiction of atoms as independent and aloof, to laudatory depiction in medical texts of 'remarkable' sperm production) (Martin, 1991; Roszak 1999a). Other authors offer critiques of military metaphors present in ecology and the war mentalities they engender (Larson 2005) as well as criticisms of reductionist metaphors and their vivisectionist implications (Kauffman 2007; Shiva, 1998).

These critiques may strike the uninitiated as surprising precisely because one does not expect to find, for instance, potential gender bias in atomic theory. On reflection metaphorical language may be as pervasive in these domains as in any other, even if the language maps to a very specific network of meanings: electrons can be 'charged' or 'excited', quarks come in 'families' that exhibit 'color', 'flavor' and 'charm'! All these terms, of course, take on new specific meanings within the specific field of investigation and physicists may scoff at the idea that the everyday meanings of these terms matter. Yet, as Larson (2011) argues, redefining these terms within scientific fields does not

expunge the terms' original meaning. In Larson's reasoning these terms become polysemic as they take on specific meaning in scientific discourse — that is, they hold multiple meanings that co-exist for the users of those terms. To give an example, 'invasive' tumors or 'invasive' species have specific meanings within immunology and ecology respectively, but those definitions do not fully eliminate the terms' origins and general usage as relating to armies occupying enemy territory— especially perhaps for the student encountering the terms in a scientific context for the first time. Larson (2011) dubs examples such as these 'feedback metaphors' as their polysemy tends to reinforce a particular perspective on the phenomena in a cyclic pattern. In the case of 'invasive species' for instance, the linguistic conflation with armies may predispose ecologists to focus more on instances where species that are new to a particular geography are detrimental to the ecological community whereas another more neutral metaphorical framing may nudge scientists towards identifying cases where the introduction of species has a mild or even beneficial effect. Additionally, the polysemy of the term may bias a particular remedy: in this case we expunge the pathogen or species in the same aggressive approach that a nation may expunge an enemy. The problem is when the implicit metaphor has limitations in the mapping from analogue (war) to the target (ecology) the metaphoric framing may suggest remedies that are deficient.

Larson (2011) cites the historian Nancy Stepan's investigation into a 19th century scientific perspective equating of women and the "lower races" to bolster his case that feedback metaphors can have real implications. In Stepan's conclusion, the implied analogy of women and lower races created a bias where data was collected to confirm the belief that women had more in common with apes than men and blinded researchers to

data that was contrary to the tacit conclusion suggested by the analogy. Stepan summed this finding by noting that, “the metaphor...permits us to see similarities that the metaphor itself constitutes” (Stepan pg. 271 as cited in Larson, 2011). The converse of this metaphorical accretion of a biased scientific perspective may also be true. That is, our default metaphors may act to obscure discrepancies between our tacit theories and evidence that would suggest their limitations.

Other recent work outside the domain of biology has empirically demonstrated that the metaphorical framing of a problem influences the decision space of solutions. Thibodeau and Boroditsky (2011) find that the inclusion of a single metaphor namely, crime as a ‘virus’ that *infects* or *plagues* cities or a ‘beast’ that *preys* on and *attacks* cities, shapes respondent groups’ assessment of how cities should respond to crime. The authors summarize their findings:

“Interestingly, we find that the influence of the metaphorical framing effect is covert: people do not recognize metaphors as influential in their decisions; instead they point to more “substantive” (often numerical) information as the motivation for their problem solving decision. Metaphors in language appear to instantiate frame-consistent knowledge structures and invite structurally consistent inferences.” (Pg. 1)

This analysis, like Stepan’s and Larson’s, suggest that metaphorical framing is often subtle and usually not perceived by the subjects using or being exposed to the metaphor. The metaphors nonetheless have real implications for how the issue is understood. Another way to understand these findings is through the literature on psychological priming (Meyer & Schvaneveldt, 1971). In priming, prior exposures or cues influence the rate of retrieval of subsequent information in subjects. In associative priming, for instance, presenting a subject with the word ‘virus’ should accelerate the retrieval of associated words such as ‘spread’ and ‘infect’ as these are words that are

often used in association with ‘virus’ (Matsukawa, Snodgrass, Doniger, 2005). Similarly, describing a Zebra Mussel as an ‘invasive species’ should prime students to more readily recollect other associations with the root word ‘invade’ – such as ‘occupy’ or ‘military control’.

For the present project, these arguments suggest there may be social and ethical implications of some of the metaphors we educate with that extend beyond their role in developing mastery of particular scientific concepts. It should be noted that I am not so concerned with ‘one-off’ metaphors: it is the repeated use of families of metaphors — nature as machine, nature as war, nature as business, and nature as information — that because of the repetition threaten to bias the understanding of the phenomena. Put another way, a single bombing metaphor to illustrate invasive species may be appropriate in highlighting an aspect of the phenomena a text intends to convey to students, yet a series of war metaphors may conceal aspects of invasive species and their behavior in new environments that are at odds with a war scenario.

As previously mentioned, scholars have written about the broader social implications of reinforcing metaphors in science, but what has not been sufficiently investigated is whether pedagogical materials contain these reinforcing metaphors and, if so, how they are presented and used in teaching. The present work then, in addition to considering the effectiveness of metaphors in understanding target biological concepts, connects some of these social and ethical critiques of scientific metaphors to an educational context.

Taking a developmental perspective

In carrying out this analysis, I attempt to keep in mind that students do not arrive at a high-school biology class free of scientific misconceptions or metaphorical understandings of scientific phenomena that may have led to pernicious over-mappings. Student misconceptions have been documented in biology subjects such as ecology (Grotzer and Basca, 2003). Meanwhile, although there is some disagreement in the literature as to when the capacity to reason analogically develops, spontaneous analogical thinking arises well before high school (Goswami, 1993). Thus, students' capacity to both learn through analogies and be misled by their misapplication is developed prior to high-school.

Similarly, students start learning about the natural world at a very young age and, according to research from early-childhood, at least one-quarter of all explanations for the natural world that they receive from their parents or caregivers are teleological in nature (Kelemen, Callanan, Casler, and Pérez-Granados, 2005). "Why do elephants have such big ears?" asks the child. "Well, so they can cool themselves. See they are like fans" replies the parent. Given this pervasive human tendency to offer teleological explanations (many of which are relayed through analogy), although analogies and metaphors encountered in school may be flawed, we can ask whether they offer an improved representation over what most students were starting with or whether they compound an already existing problem. As Perkins and Grotzer (2005) discuss, teleological or function-centered explanations are part of a broader tendency by learners to offer explanations consisting of 1) simple mechanisms of action; 2) unidirectional causality; 3)

deterministic systems that neglect stochastic effects; and 4) a focus on single agents neglecting webs of interactions, tipping points and self-organizing systems. Students struggle to understand systems that deviate from these more obvious accounts of phenomena for the simple reason that many of these scientific models contain elements that are removed from everyday experience and we educate using simple narratives of phenomena from a very young age. Thus, weak or limited analogies may be part of a more pervasive tendency to seek simple narratives and illustrations from what we have at hand to understand a complex world.

I do not imply here that the solution to problematic aspects of metaphor in education is to expunge them from scientific texts. Indeed, that was route advocated by 18th century philosophers such as Hobbs and Locke who would strike metaphors from philosophic discourse as being inherently deceitful (Camp 2006). As Geary (2011) wryly noted, 18th century philosophers liberally used metaphors in their writing even as they were calling for their elimination. I instead use the analogy of not ‘throwing out the baby with the bathwater’ in my thesis title to suggest there may be helpful as well as problematic aspects of metaphor use in pedagogical scientific materials. Since much of the literature on scientific metaphors focuses on establishing how these metaphors and analogies can be helpful in student learning, I wish to delve into some of the problematic aspects of metaphors and analogies in biology pedagogic materials offering suggestions that update guidelines for metaphor construction and review contained in earlier accounts (Glynn, 1991; Orgill, 2013).

Thesis Roadmap

In the following section I describe the methods used in the analysis including the sample and my procedures for coding the metaphors and analogies in the materials I reviewed.

I then shift to examining salient thematic categories of reinforcing metaphors that emerged from the philosophical analysis of the texts – namely metaphorical examples presenting *nature as information*, *nature as machine*, *nature as business* and *nature as war or competition*. I provide instances from the texts that document these types of metaphors and describe how they may be problematic for the learner as well as some of the social and ethical implications of these metaphors. I discuss a potential repercussion of these sorts of reinforcing metaphors through a case study on natural selection.

Following those sections I look at other pedagogical aspects of the metaphors and analogies I coded. This analysis then sets up the overall discussion along with some suggestions for new metaphors and analogies we might introduce to better reflect current paradigms in the field of biology.

Methods

I considered several methodologies based on my stated research interests. I opted for a textual review over other approaches such as classroom observation as textual reviews are potentially more representative of the metaphors and analogies used in biology education given the textbooks' wide circulation. In the following sections I describe the sample used in the textual review along with the procedures for coding and analyzing the quantitative and data along with my accompanying philosophical analysis.

Sample

With all of the new technology in teaching, it is tempting to dismiss textbooks as curricula's version of dinosaurs - soon to be pedagogically extinct. Yet as recently as the 2007 Trends in International Mathematics and Science Study, textbook-based teaching and learning informed approximately 40% of classroom time among participating countries (Devetak and Vogrinc, 2013). Moreover, authors have continued to suggest that textbooks define a subject, serve as an arbitrator in cases of dispute and enable the choice of topics and the pedagogical approaches to teaching them (Devetak and Vogrinc, 2013). Finally, although 'textbooks' used to mostly be about 'text', as printing capability has increased and textbook authors and publishers have responded to critics, textbooks have become more like the multimedia approaches that would displace them replete with tables, photos, cartoons, and all manner of illustrations including links to online content.

This is not to overplay science textbooks' merits or proclaim their immortality. A series of evaluations as part of the American Academy of Arts and Sciences Project 2061 concluded that not one middle-school science textbook ranked 'satisfactory' (Kesidou and Roseman, 2002). There are, nonetheless, very practical reasons for continuing to

choose textbooks over other biology curricula for analysis despite their alleged flaws - most notably they contain a well-delineated information corpus that prior scholarship has developed established methodologies for assessing. Additionally, whether or not textbooks persist, biology teaching will continue to use metaphors and analogies, and hence they are suitable sources for discovering the types of metaphors that may also be present in other pedagogical materials. It therefore pays to investigate how these metaphors function – what they contribute and where and how they may mislead.

There have been several textual analyses of metaphor and analogy in science textbooks including work by Curtis and Reigeluth (1984), Duit (1991), and Thiele, Venville and Treagust (1995). These reviews tended to find significant pedagogical problems with metaphor and analogy use including that they were: 1) Frequently not explained at all (Duit, 1991); 2) Of a superficial nature and lacking a functional relationship between ‘source’ and ‘target’ (Curtis and Reigeluth, 1984); and 3) Rarely identified as metaphors and analogies (Curtis and Reigeluth, 1984; Thiele and Treagust, 1995). A review by Orgill and Bodner (2006) found that of 158 analogies and metaphors coded in eight college-level biochemistry textbooks, in only seven cases were the limitations discussed.

My sample is three biology textbooks widely used for juniors and seniors in high school. This academic level was selected as metaphors and analogies are still commonplace in the texts, yet students have been exposed to enough prior biology that it is possible to critically examine their use. Textbooks were selected that have been vetted by many subject matter experts for each edition and hence, the metaphors and analogies have been presumably read and considered many times. For instance, there were more

than 50 listed reviewers for the 10th edition of Miller and Levine *Biology* (2010). Thus, unlike materials that may be developed by a single teacher for her class or other online content, we can expect that millions of students have encountered biology through some of the metaphors present in these textbooks and textbook authors have refined the metaphors and analogies over editions. The three selected texts were chosen based on Amazon.com sales rankings and have been widely used in high-school biology education over the last decade:

- Miller and Levine (2010). *Biology*: 2010 on-level student edition. Prentice Hall.
- *Biology: The Dynamics of Life* (2006). Glencoe Science
- *Modern Biology* (2006). Houghton Mifflin School.

The textbooks are quite similar in their presentation of material¹. All three textbooks begin with a section called ‘The Chemistry of Life’. In general, after ‘The Chemistry of Life’ the texts start with 1) eukaryotic cells, 2) ecology, 3) genetics, 4) evolution, 5) viruses, bacteria, protists and fungi, 6) Plants, 7) Animal structure (this can be divided into separate units on invertebrates and vertebrates) and 8) the human body. Table 1 below shows the total number of pages by textbook and topic that were reviewed for the project. Although there is some distinction in the number of pages per text this is not a substantial threat to my research as my primary objective is not to make claims about one text versus another but to explicate the types of metaphors that are present in the texts and how they function.

¹ **Campbell Biology 10th edition** was initially selected as a fourth book. Ultimately it was not included in the review as it is orientated towards a higher grade-level than the other three texts and has a substantially different organization of material.

Table 1: Coded Material

Unit	Textbooks			
	Miller and Levine	Glencoe: The Dynamics of Life	Modern Biology	Total Pages Per Topic
	Sub-topics and pages			
Cell structure and function	Pg. 187-304 (117)	Pg. 138-220 (82)	Pg. 66-150 (84)	283
Viruses, Bacteria, Protists and Fungi	Pg. 572-618 (46)	Pg. 472-550 (78)	Pg. 458-526 (68)	192
Genetics	Pg. 305-446 (141)	Pg. 250-360 (110)	Pg. 170-254 (84)	335
Evolution	Pg. 447-570 (123)	Pg. 366-466 (100)	Pg. 276-336 (60)	283
Ecology	Pg. 62-186 (124)	Pg. 32-110 (78)	Pg. 356-434 (78)	280
Total Pages	551	448	374	2678

Procedures

There have been multiple approaches developed and put forward for the identification, classification and evaluation of metaphor and analogy in textbooks. Curtis and Reigeluth's (1984) early work classified analogies according to six categories such as: the relationship type (e.g. *structural, functional or structural-functional*), the presentation format (e.g. *pictorial, verbal*), the analogy's position (e.g. *advanced organizer, embedded activator, post-synthesizer*), the simplicity and concreteness of the metaphor, and the presence or absence of an explanation for the metaphorical source or analogue. More recent approaches have mostly preserved these early categories but added additional categories such as, whether limitations of the analogy were discussed;

whether a cognitive strategy accompanied the analogy (priming students to the presence of the analogy and the author's purpose for its use); and the global position of the analogy in the textbook (i.e. early in the textbook, in the middle of the textbook, etc.) (Thiele and Treagust, 1994; Orgill and Bodner, 2006).

The present analysis uses the approach described by Orgill (2013) which consolidates these prior frameworks. Using this approach has two advantages:

1. Orgill (2013) is the latest coding approach following a string of scholars in this domain (Curtis and Reigeluth, 1984; Thiele and Treagust, 1994; Orgill and Bodner, 2006). Orgill's (2013) coding scheme includes categories that help us assess whether the metaphor is helpful for student learning and look at the broader context surrounding the metaphor.
2. Using Orgill (2013) allows for comparison with prior analyses on topics covered by the coding structure (e.g. is the metaphor superficial? structural? is it used as an advanced organizer? a post synthesizer? etc.). This includes earlier analyses of science textbooks because, as mentioned, Orgill's (2013) framework retains prior criteria for assessing metaphors.

The quantitative coding scheme is summarized in the Table 2 below:

Data Field	Description in Orgill (2013)	Proposed Departures
Textbook name	Name of text	None
Pg.	Pg. number in text where metaphor / analogy occurs	None
Metaphor instance	Quotation	None
Relationship of source to target	(‘Structure’, ‘function’, ‘structure-function’)	None
Presentation Format	(‘Verbal, pictorial’)	Same codes, however if includes picture capture

		scan of image.
Level of abstraction	(‘Concrete’ ² , ‘abstract’)	None
Position of metaphor in relation to biology concept	(‘Advanced organizer’, ‘embedded activator’, ‘post-synthesizer’)	None
Level of enrichment (e.g. is the metaphor of a brief or extended nature)	(‘Simple’, ‘enriched’, ‘extended’)	None
Analog explanation	(‘Analog explained’, ‘analog not explained’)	Addition of corresponding notes field.
Indication of cognitive strategy?	(‘Analogy presented as analogy’, ‘analogy not presented as analogy’)	Addition of corresponding notes field.
Limitations discussed	(‘Limitations indicated’, ‘limitations not indicated’)	Addition of corresponding notes field.

Philosophical analysis

An implication of Blanchette & Dunbar’s (2002) “overmapping”, as well as the work by Larson (2011) on feedback metaphors, and Thibodeau & Boroditsky’s (2011) investigation of metaphorical framing, is that metaphors and analogies can mislead people in a number of subtle but important ways. Given that there is no established methodology for assessing the potential of particular metaphors and analogies in science education to engender these sorts of misunderstandings, I employ a form of philosophical analysis known as reflective equilibrium in conjunction with the quantitative analysis.

Reflective equilibrium is a method of epistemological inquiry that departs from the often insurmountable obstacles in traditional philosophical inquiry and is instead “rooted in the local soil” of the subject matter itself and the agreed upon rules within those disciplines (Elgin, 1999 pg 36).

As Elgin explains:

² ‘Concrete’ metaphors are those a student may see, touch or hear in the course of daily living (Orgill and Bodner, 2006).

In building a system of thought, we begin with a provisional scaffolding made up of the relevant beliefs we already hold, the aims of the project we are embarked on, the liberties and constraints we consider the system subject to, the values and priorities we seek to uphold. We suspend judgment on matters in dispute (Elgin, 1999 pg. 106).

In applying this approach, there are a number of scholarly disciplines that could inform the present project — all of which I have briefly reviewed in the Introduction. These disciplines include science education, biology (as understood by practitioners in the field), philosophy of science, cognitive science and linguistics. All of these disciplines and their practitioners have some stake in the subject of metaphors and analogies in biology education and hence I consider their specific vantage points in the analysis. I also begin with a number of general suppositions building off some of the beliefs I described earlier on pedagogical metaphors. These include:

- Pedagogical metaphors and analogies, although usually considered helpful by scholars, are not always helpful and not always equally effective in helping students learn particular topics.
- Better metaphors and analogies in science education will both possess the characteristics of effective metaphors and analogies as identified and described by educational scholars as well as represent the current paradigms of science and the particular content under investigation. That is, it is possible to have an analogy that fulfills all of Glynn's (1991) criteria for effective metaphors that teaches scientific notions that may have been discredited, abandoned or contested by a significant portion of the scientific community.
- Although a good teacher may be able to make any metaphor or analogy effective for most students through classroom discussion, in general teachers are benefited

by metaphors and analogies that contain content in line with current paradigms.

Thus, although a limitation of my analysis is that I do not observe the classroom discussion of the metaphors and analogies I'm reviewing, I assume that classroom discussion is aided by metaphors and analogies that are both pedagogically effective on their own as well as aligned with the content being taught.

- While misconceptions when first encountering complex scientific topics may often be inevitable, ideally misconceptions should be reduced as much as possible.

Beyond these sorts of general beliefs surrounding pedagogical metaphors and analogies in biology education, there are certain values that are broadly (albeit not universally) shared by many in a school community. For instance:

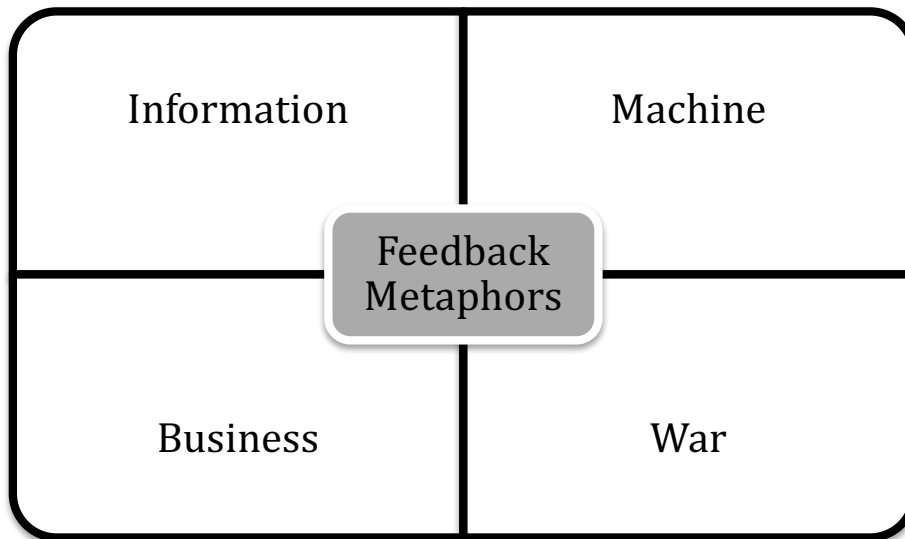
- Educators care about students learning particular scientific topics but also care about how that knowledge impacts students' future activities in the world as adults.
- It is important to be as transparent as possible when educating students in distinguishing between scientific facts and interpretations of those facts that may be culturally bound. This allows students to come to their own understanding of particular topics.

This is by no means an exhaustive list of the constraints and liberties of our system but illustrates some of the many reasonable perspectives one could bring to such an investigation. To reduce the likelihood that my philosophical analysis hinges on only a few aberrant examples, I provide many examples in the course of analysis so that others may reasonably disagree with my interpretation.

In summary, the current analysis relies on both a quantitative approach as well as a philosophical approach. The quantitative approach was defined in advance of the analysis and is based on Orgil (2013). The philosophical approach was also determined to be important in advance of the investigation in light of my research questions that could not be answered through the quantitative approach alone.

Reinforcing Metaphors

The reinforcing metaphors that I discussed in the introduction are often related to each other: instruction or information metaphors can be nested in machine metaphors and vice-a-versa. Similarly machine metaphors can be incorporated in business or competition metaphors. I describe each of these metaphor types and examples from the text separately before illustrating examples from the textbooks where these various reinforcing metaphor families are related or nested within one another.



Information Metaphors

Information metaphors are instances where nature is explained in reference to human information systems. The three information metaphor clusters found in the text are *DNA as language*, *DNA as blueprint* and *DNA as software or code*. I discuss each of these below.

DNA as Language

You belong to the first generation of students who can read the human genome almost as your parents might have read a book or a newspaper. Miller and Levine, Pg. XXII

One of the most extensive analogies in all three texts describes *DNA as language* where mappings exist between letters, words, phrases, books and libraries. The use of this metaphor by textbook authors is unsurprising given that the metaphor is built into the nomenclature of genetics itself where terms such as ‘translation’ and ‘transcription’ have specific meanings within the field. The textbook authors have taken some of these metaphors present within genetics terminology and extended them in interesting ways to attempt to foster learning.

This analogy perhaps has its foundation in postulating that chromosomes were a “code-script” in a highly influential essay by Edwin Schrödinger in 1955. Starting at the most basic mapping, “The four different nucleotides, like the 26 letters of the alphabet, could be strung together in many different sequences” (ML, 342). Three successive nucleotides then, form one amino acid “word” (MB, 207). Not all three textbooks map this analogy in the same exact way: for instance, in Glencoe, the alphabet is not nucleotide bases but amino acids “You could say that the language of proteins uses an alphabet of amino acids” (G, 291).

Richard Dawkins (2005) highlights the challenges of making this analogy fit perfectly with genetics. This demonstrates the challenge of crafting a perfect analogy:

In one respect the analogy with words is misleading. Words are shorter than genes, and some writers have likened each gene to a sentence. But sentences aren’t a good analogy, for a different reason. Different books are not put together by permuting a fixed repertoire of sentences. Most sentences are unique. Genes, like words but unlike sentences, are used over and over again in different contexts. (Dawkins, 2004. Pg. 155)

Like a human language, we need more than letters, “Any message, whether in written language or the genetic code, needs punctuation marks. In English, punctuation tells us where to pause, when to sound excited, and where to start and stop a sentence. The genetic code has punctuation marks too” (ML, 367). Here Miller and Levine use this further analogy to introduce concepts such as start and stop codons. Although this is an engaging extension of the core analogy, there is an important limitation that is not discussed. In this case the problem with the analogy is that in languages like English, separate markers, such as the period and question mark, punctuate sentences (or capitalization to signal the start of a sentence). In the cell, it is sequences of letters that constitute the punctuation scheme. The start codon is less a separate punctuation mark and more a “once upon a time” – that is a string of characters that routinely signals the start of a protein story. Meanwhile, the stop codon is a “and they all lived happily ever after” or more simply, “the end”!

Of course, for language to foster communication, words and sentences need to be heard or read. In the case of DNA’s journey to proteins, tRNA “reads the mRNA’s message accurately and to get the translation just right.” Meanwhile, mutations change letters or the reading frame itself: “THE DOG BIT THE CAT. THE DOG BIT THE CAR” (G, 298). This analogy illustrates how even a single point mutation (“R” substituted for “T”) can substantially change the meaning of the sentence or, in this case, the amino acid and corresponding protein. Frame shift mutations brought about through the deletion or addition of a base render whole sequences unintelligible, “THE DOB IIT HEC AT”³ (G, 298).

³ Here there appears to be a simple error in the analogy in that both a ‘B’ was substituted for a ‘G’ as well as the addition of an extra ‘I’.

Agency is sometimes implied within the DNA as Language metaphor, “Like a writer’s first draft, RNA molecules sometimes require a bit of editing before they are ready to read” (ML 365). DNA polymerase is also described as “proofreading” DNA (ML, 351; MB, 202). Notions of accuracy and mistakes in translation are described in all three texts (i.e. “Yet mistakes do sometimes occur” G, 300; “Cancer: a mistake in the cell cycle”, G, 212). These examples are illustrations of metaphors denoting agency, intention and teleology found in many places in the text and, although natural extensions of the metaphor, may limit students’ appreciation for the role of ‘mistakes’ (mutations) in evolution over geological time as well as epigenetic processes that promote ‘mistakes’ in response to environmental feedback.

Visual Instances

DNA as Language analogies are not limited to verbal instances but also are presented in visual form. In the figure below, for instance, the bestseller “How to be a Cell” is depicted as a series of chapters covering the critical functions of cellular life.

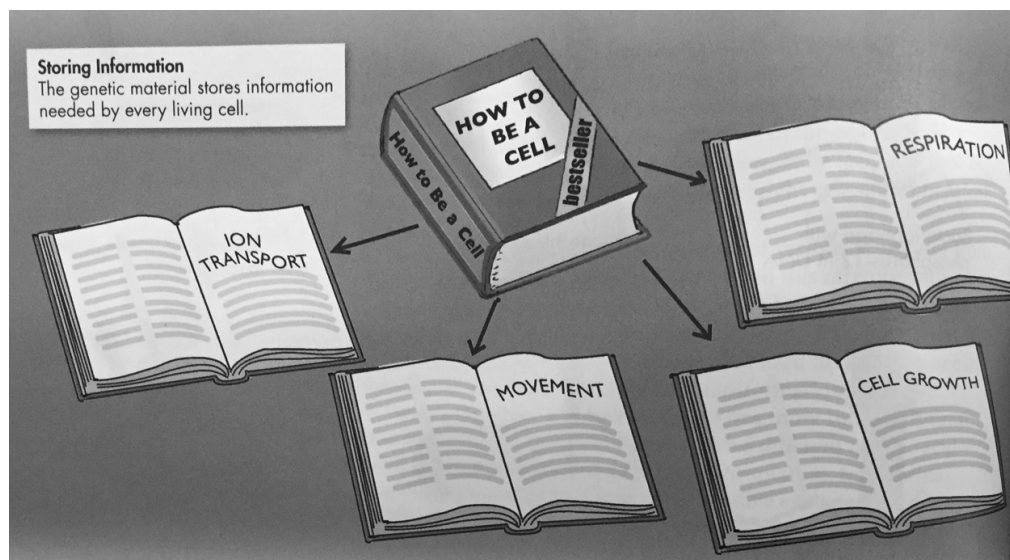


Figure 1: DNA as Instructional Guide. Miller and Levine Pg. 342.

This figure is a playful extension of the analogy *DNA as language*. If at first, short sequences of DNA are compared to letters or words, genes and the genome itself are compared with books and libraries.

The authors of Glencoe and Miller and Levine want to convey the enormity of the genome and its aggregate information content. For instance, “Can you imagine all of the information that could be contained in 1000 textbooks? Remarkably, that much information - and more - is carried by the genes of a single organism” (G, 281). One can take exception with the math


underlying this statement and this is probably a case where the metaphor is illustrative and not exact. Notably, in a language such as English with 26 letters and a slew of distinct punctuation marks although the numbers of “letters” may be approximately the same, the number of permutations of those letters is not and this gets to what we mean by ‘information’. And, of course, organisms themselves vastly differ in unintuitive ways in total genome size

Use Numbers

Storing the Human Genome It has been estimated that the human genome consists of three billion nitrogenous base pairs. How much room would all of the genetic information in one cell take up if it were printed in a 400-page novel?

Procedure

- 1 Copy the right column of the data table marked “Letters and Numbers.”
- 2 Select a random page from a novel.
- 3 Follow the directions in the table. Record your calculations in your data table.



Data Table	
Directions	Letters and Numbers
A. Count the number of characters (letters, punctuation marks, and spaces) across one entire line of your selected page.	
B. Count the number of lines on the page.	
C. Calculate the number of characters on the page. (Multiply A × B.)	
D. Let one nitrogenous base equal one character. Knowing that DNA is made of nitrogenous base pairs, divide C by 2.	
E. Record the number of pages in your novel.	
F. Calculate the number of base pairs in your novel. (Multiply E × D.)	
G. Calculate the number of books the size of your novel needed to hold the human genome. (Divide 3 billion by F.)	

Figure 2: DNA as a book repository

where some eukaryotic genomes are as small as 2.25 million base pairs whereas some plants have genomes close to 150 billion base pairs – roughly 50 times the size of a human genome.⁴

To be fair, this seems a case of an illustrative metaphor rather than something that is presented as factual and some of these assumptions are exposed later in the chapter in the form of an exercise for students (See Figure below). Although this is a good exercise for communicating the total number of base pairs in the human genome, it would have been interesting to have students think through Step D in more detail – that is, what is the total information content of the genome when letters of the alphabet become bases.

There are other instances where the mapping between DNA and language contains subtle errors. For instance, Miller and Levine illustrate the idea of a genome as a library in the following illustration (See below).

⁴ As it turns out, in some plant genomes, authors are paid by the page. More seriously, even in humans only 3% of DNA contains protein producing sections (Jablonka, Lamb, and Zeligowski, 2014). This further complicates the book metaphor.

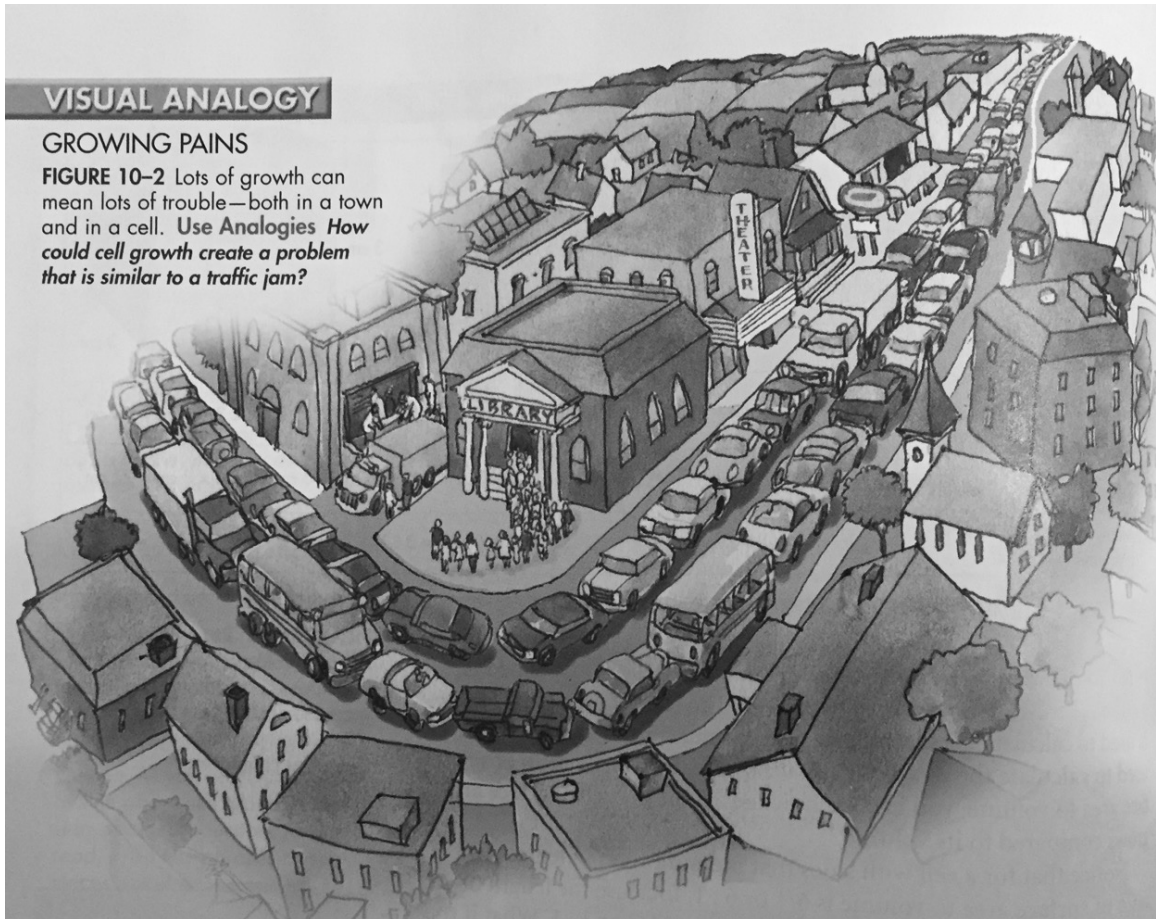


Figure 3: DNA as City Library. Miller and Levine, Pg. 276.

Here the authors are interested in conveying what happens to the library in a “growing town” (ML, 274). The library’s resources are taxed and it can’t meet the demands of the “people” who want to “borrow popular books”. At some point, “the DNA would no longer be able to serve the needs of a growing cell – it might be time to build a new library” (ML, 274). Although this is a fun and enlivening metaphor it is also slightly misleading for two reasons: 1) In this case, it is not that towns build new libraries within the same town. Instead, towns set up new towns, complete with new libraries. That is, excepting the satellite libraries of plasmids, towns (cells) only have one library (genome) and 2) it may be misleading because the cars running in opposite directions seem to clearly represent the DNA and correctly depict the chemical orientation of two single

nucleic acid strands. Transcription is more like someone trying to collect parking money from the cars and can't reasonably get to them all - the 'library' represented in the image is more likely DNA polymerase or helicase. For readers who would object that these problems are too subtle for the average student to notice, that is probably true. However, an analysis like this may show that these metaphors are primarily just for fun and serve a limited explanatory role. This is contrary to the role that scholars of metaphor believe metaphors and analogies should serve in helping students understand target biological phenomena and learn to reason analogically (Gentner, 2002; Gentner and Markam, 2010).

Finally, of course, if before we were merely reading the DNA newspaper, biotechnology opens up our ability to "edit" (ML, 23) the genome or "cut n 'paste" (G, 341)!

DNA as Blueprint

The *DNA as blueprint* metaphor was in currency before textbook authors adopted it as a teaching tool and again finds its one its earliest formulations in Schrodinger (1969):

The chromosome structures... are law-code and executive power -or, to use another simile; they are architect's plan and builder's craft-in one. (pg. 8).

A simple search on *PubMed* reveals more than 2,000 instances of the term 'blueprint' associated with biological systems with easily plucked titles such as "A Genetic Blueprint for Growth and Development of the Heart" (Olson 2002) and "Gene Therapy: Correcting Errors in Life's Blueprint" {Merz, 1984}. The genome as a blueprint or, in NIH's human genome project completion report, "all the pages of a

manual needed to make the human body” (NIH, 2010), reflect the belief that the relationship between DNA and the organism will prove to a simple matter of genotype-phenotype correspondence.

Yet, many people both within and outside of biology now understand that DNA is not a blueprint in so far as it does not, in most cases, simply depict a phenotype in the way an architect’s drawing will one day depict a building. The feedback mechanisms between gene expression and environment are complex, and neat genotype-phenotype correspondences are the exception that proves the rule (Pigliucci 2010). Especially, for emergent traits such as intelligence, we can speculate that researchers’ desire to find the ‘blueprint’ is what has led to a series of irreproducible results. An editorial in the journal *Behavior Genetics* reviewing attempts to pinpoint a genetic-basis for intelligence concluded, “it now seems likely that many of the published findings of the last decade are wrong or misleading and have not contributed to real advances in knowledge” (Hewitt 2012). However, in these cases where many in the scientific community begin to challenge the tacit assumptions in the metaphor it is unclear how quickly textbook authors revise these metaphors in light of changing scientific norms.

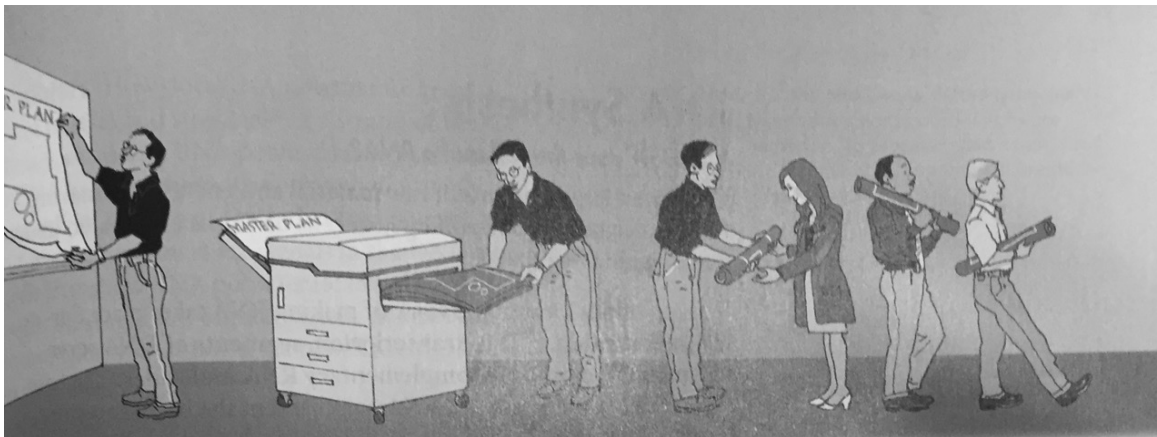


Figure 4: RNA as Protein Blueprint. Miller and Levine Pg. 363.

The textbooks use the blueprint metaphor while extending it and altering it in surprising ways. The figure above shows the “Master Plan” (DNA) being converted into “Blueprints” (RNA). This image is interesting in that the textbook authors have taken the standard scientific metaphor of *DNA as blueprint* and converted it to *RNA as blueprint*. The message is that DNA is not directly used to make proteins just as the master plan is not brought to the worksite. The “Master Plan” does seem to imply a goal or telos that could be problematic for students trying to understand developmental biology and natural selection. Additionally, the analogy seems to imply that DNA and RNA both must be present in organisms, which is not correct (i.e. retroviruses).

In other instances, ‘blueprints’ are mapped to DNA and this is another case where the Miller and Levine text does not map the metaphor in the same ways as Glencoe. For instance, “For proteins to be made, ribosomes must leave the nucleus and enter the cytoplasm, and the blueprints contained in DNA must be translated into RNA and sent to the cytoplasm” (G, 181). This description maps *blueprints as DNA* rather than *blueprints as RNA*. Moreover, it is odd to describe blueprints as being ‘contained’ in DNA – this is much like Miller and Levine’s description of “water is locked in ice” (ML, 33) as it seems to imply that ice is something other than frozen water and the DNA is the container for the information as opposed to information itself. In this case and in others, DNA is almost depicted as carrying literal blueprints.⁵

Finally, as with many other examples, the metaphorical mappings of a complex multi-layered metaphor like *DNA as blueprint* can become muddled, “You have learned that the nucleus contains blueprints for the cell's proteins...But there is a limit to how

⁵ See Appendix A for other examples

quickly the blueprints for these proteins can be copied in the nucleus and made into proteins in the cytoplasm.” (G, 202) What is confusing here is that while DNA is ‘copied’ in the process of mitosis, DNA is not ‘copied’ in the process of protein synthesis – DNA is instead transcribed into RNA. ‘Copied’ then appears to be the wrong metaphorical analogue to describe this process. This is not the only instance in the text where Glencoe talks about “the copy of blueprints” to mean RNA.

DNA as a Machine or Software

Although *DNA as language* is the more substantial analogy present in the chapters on genetics, DNA is also compared to machines or software. To take two examples:

“Protein production is similar to car production. DNA provides workers with the instructions for making the proteins, and workers build the proteins.” (G,289)

Here is an example where the analogue is left unexplained. The authors assume that students know enough about car production for the analogy to be useful and the students are going to be able to align the source metaphor and target subject. The metaphor may have value in making the text ‘friendlier’ but seems to have little pedagogical value. The comparison between DNA and machines is not limited to these instances:

“Both our “hardware” (body structures) and our “software” (genetic instructions and biochemical processes that program biochemical functions) are incredibly similar to those of all other living things.” (ML, XXI)

“You may have seen computer code, such as 00010101110000110. Through a binary language with only two options - zeros and ones - many types of software are created. From computer games to World Wide Web browsers, complex software is built by stringing together the zeros and ones of computer code into long chains. Likewise, complex proteins are built from the long chains of DNA carrying the genetic code” (G, 292).

“The sequences of bases in DNA are like the letters of a coded message, as we’ve just seen. But what would happen if a few of those letters changed accidentally,

altering the message? Could the cell still understand its meaning? Think about what might happen if someone changed at random a few lines of code in a computer program that you rely on.” (ML, 372)

“Suppose you have an electronic game you want to change. Knowing that the game depends on a coded program in a computer microchip, how would you set about rewriting the program? First you need a way to get the existing program out of the microchip. Then you’d have to read the program, make the changes you want, and put the modified code back into the microchip. What does this scenario have to do with genetic engineering? Just about everything” (ML, 420).

All three of these metaphors may be useful to students who are familiar with computers. Yet, as usual the metaphors contain important limitations not discussed (and perhaps not recognized) by the authors. One of these limitations is that in computers, software does not alter the hardware.⁶ By way of illustration, when upgrading the operating system on your computer you do not fundamentally change the processor you are using. Software can impact the way hardware operates – for instance, the provisioning of hard drive or RAM space can be set or modified through the software, but it does not create the hardware or alter its material properties. Similarly, although hardware can affect the performance of software, it does not typically alter its expression.

This is fundamentally different from how DNA operates. The “software” of DNA creates the “hardware” of the organism as the organism grows and affects and is affected by its environment along with other heritable epigenetic processes. Thus, there is both an interaction between “hardware” and “software” in biology as well as plasticity in development and expression that is missing in its source analogue. Another potential issue in the analogies is while changing “a few random lines of code” would undoubtedly

⁶ A lesser point is that the proper analogue to binary in the cell is not DNA but RNA. Today’s programmers do not code in binary – they code in a variety of computer languages that get compiled directly or indirectly into binary.

crash most software programs, living systems are frequently robust to accidental or deliberate alterations to gene sequence (Ciliberti, Martin, and Wagner 2007).

Summary of Information Metaphors

A problem with all three of these metaphors as they are presented in the text is that they don't indicate any possibility of gene-environment interactions and imply a one-way flow of information from genes to organisms. Genes are rarely "for" something in complex organisms – it is a more intricate interaction between development and environment. Although it is true that the genetic material in dog embryos does not lead to cats even in the most feline of environments, there is a remarkable degree of "phenotypic accommodation" that can occur and some of those developmental processes impact not only the organism's state but also the organism's lineage through other heritable epigenetic processes (Jablonka, Lamb, and Zeligowski, 2014). The evolutionary biologist Mary-Jane West-Eberhard (2003), for instance, recounts a goat that; when being born with only hind legs, hopped like a kangaroo and stood upright. A postmortem showed synchronized alterations in the two-legged goat from other four-limbed goats in phenotypic features such as pelvic structure, spinal shape, muscles, and hind bone density despite having a run-of-the-mill goat genome. West-Eberhard advances the far-reaching idea that natural selection operates not just on the blueprint-like genes that give rise to a phenotype, but to the phenotypic accommodation potential in the genes that the organism manifests.

Additionally, proponents of intelligent design as well as supporters of eugenics have invoked the deterministic connotation that is present in the blueprints metaphor as evidence for their respective causes (Behe, 1996). Courts, for instance, have asked whether there is a genetic blueprint for violence (Beecher-Monas, Garcia-Rill, 2006).

‘Software’ has a less deterministic connotation but still suffers in the texts from the lack of feedback mechanisms in the software/hardware analogue. This is not to say *DNA as software* metaphors can’t be helpful to students learning genetics. Detailed analogical mappings between DNA and software have been put forward by Daniel Dennett (2013) and others to explain how genes, like computer subroutines, are regularly reused in different ways to yield quite different results. But in this version (which still contains limitations), software is less a *blueprint* and more a *toolbox* that can be called on in different contexts to yield different results. The software/hardware analogy is also an example of the interplay of information and machine metaphors – the subject of the next section.

Of the three major information metaphors in the text, the one that seems the least problematic is *DNA as language* or a modified version of *DNA as software*. I consider in the discussion how these metaphors could be altered to better reflect our current understanding of epigenetics and developmental biology as well as extended in engaging ways that students would be able to understand.

Machine Metaphors

The introduction of machine metaphors into scientific thought has been described as the central triumph of the Scientific Revolution of the 17th century (Dijksterhuis, 1986). This may seem like an improbable claim. Yet Dijksterhuis finds that where before nature was inscrutable and mysterious, mechanistic thinking posited a regularity that could be uncovered and predicted and, most importantly, invited the application of mathematics. It was this mechanistic thinking and a corresponding family of machine metaphors used in the works of 17th century scientists that unites the disparate and even

sometimes opposing theories of Descartes, Galileo, Newton and Boyle. As stated by Kepler:

“My aim is to show that the celestial machine is to be likened not to a divine organism but rather to clockwork...Moreover I show how this physical conception is to be presented through calculation and geometry” (Cited by Sheldrake, 2012).

The machines these individuals used as analogues for hypothesizing about natural phenomena for the most part were the six simple machines of antiquity – the lever, wheel and axle, pulley, inclined plane, wedge and screw along with machines of the day such as the pump, clock and loom. Importantly, these machines had to be enabled by a human actor. This point is made clear in the biology treatises of the time:

Muscles are the organs and machines by which the motive faculty of the soul sets the joints and limbs of animals in motion. In itself a muscle is an inert and dead machine, which is put into action solely by the access of the motive faculty. (Borelli, 1680 as cited in Toulmin 2011).

There is an ethical implication to Borelli’s metaphors as well: if bodies and body components are ‘dead machines’ then there is no moral vexation posed in dissecting animal bodies. This ethical and affective dimension of machine metaphors is important and may still resonate today as dissection remains a contentious topic in schools and has been cited as a reason for low-participation of girls and women in STEM subjects (Holsterman, Ainley, Grube, Roick, and Bögeholz, 2012).

Machines have changed greatly in the intervening three-hundred and forty years, and hence machine source analogues have summoned different inferences by scientists and students about target biological phenomena throughout this time. Toulmin (2011) argues that machine metaphors are so integral to the scientific project that they aren’t really metaphors at all but indispensable to the scientific lexicon. And indeed, ever since Leonardo da Vinci studied bird anatomy in an attempt to build a flying machine, people

have mimicked nature in an effort to solve engineering problems— leading to a free exchange of language and concepts between engineering and biology (Vincent Bogatyreva, Bogatyrev, Bowyer, and Pahl, 2006).

Putting aside for a moment the question of whether we can talk about the natural sciences without invoking language we also developed to speak about machines, we can ask whether the pedagogical texts we are investigating use appropriate machine examples as source analogues for supporting investigation of biology concepts and how these analogues may or may not *function* as metaphors for students. In taking this approach, we recognize that the instances of things termed ‘machine’ run the gamut from screws to clocks, engines to phones, lasers to computers and that these “machines” offer a tremendous diversity of potential analogues to both understand and mislead about biological phenomena.

Machine metaphor examples in the texts

Glencoe uses an explicit machine metaphor in the introduction to Cells (See Figure below). “All organisms are made of cells, and each cell is like a complex, self-contained machine that can perform life functions” G, 244. The corresponding picture is terser and simply says, “Cells are microscopic machines”. The image looks like a magnified view of a watch or at least shows a series of gears (See picture below). The image is potentially powerful in that for students who are new to cell biology, this is the first scaffold they are presented with for understanding all of the subsequent information about cells.

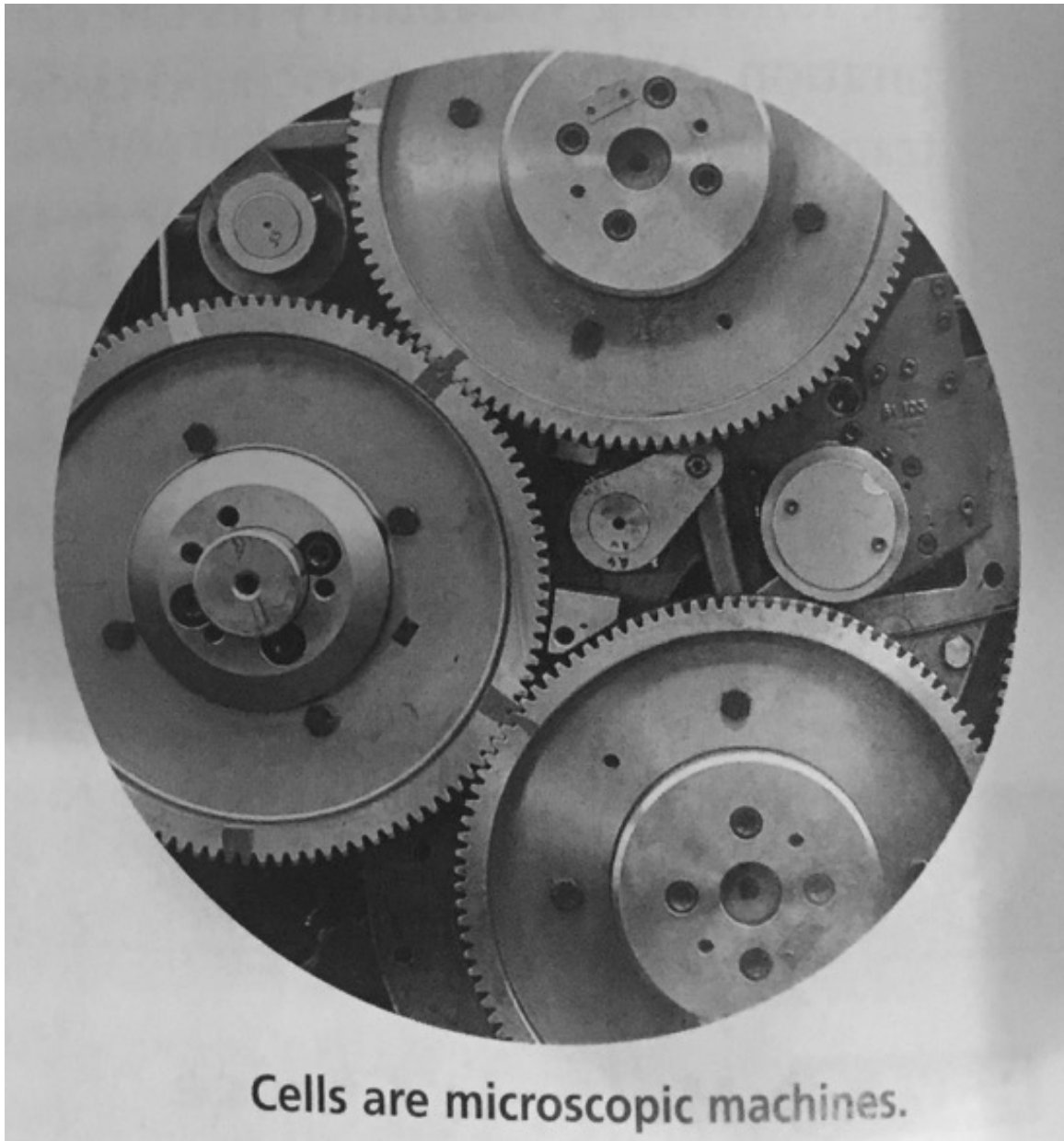


Figure 5:G244

Glencoe’s example here is perhaps the most blunt mapping of cells as machines. However, there are many other examples in the texts. The authors of these texts also talk about “machinery” as in:

“Viruses must infect living cells in order to grow and reproduce, taking advantage of the nutrients and cellular machinery of their hosts.” (ML, 579)

Machine metaphors are also used to explain to students biological speciation over generations in the presence of selection pressure.

The illustration in Figure 7 is one such attempt to show speciation and biological adaptation through metaphor. It does an excellent job demonstrating the ideas of specialization and biological niches and it is colorful and memorable. The accompanying text describes how the discovery of these different finches while on the Galapagos Islands was to become an important moment in Darwin's development of the

Theory of Natural Selection. Students can see that something as seemingly

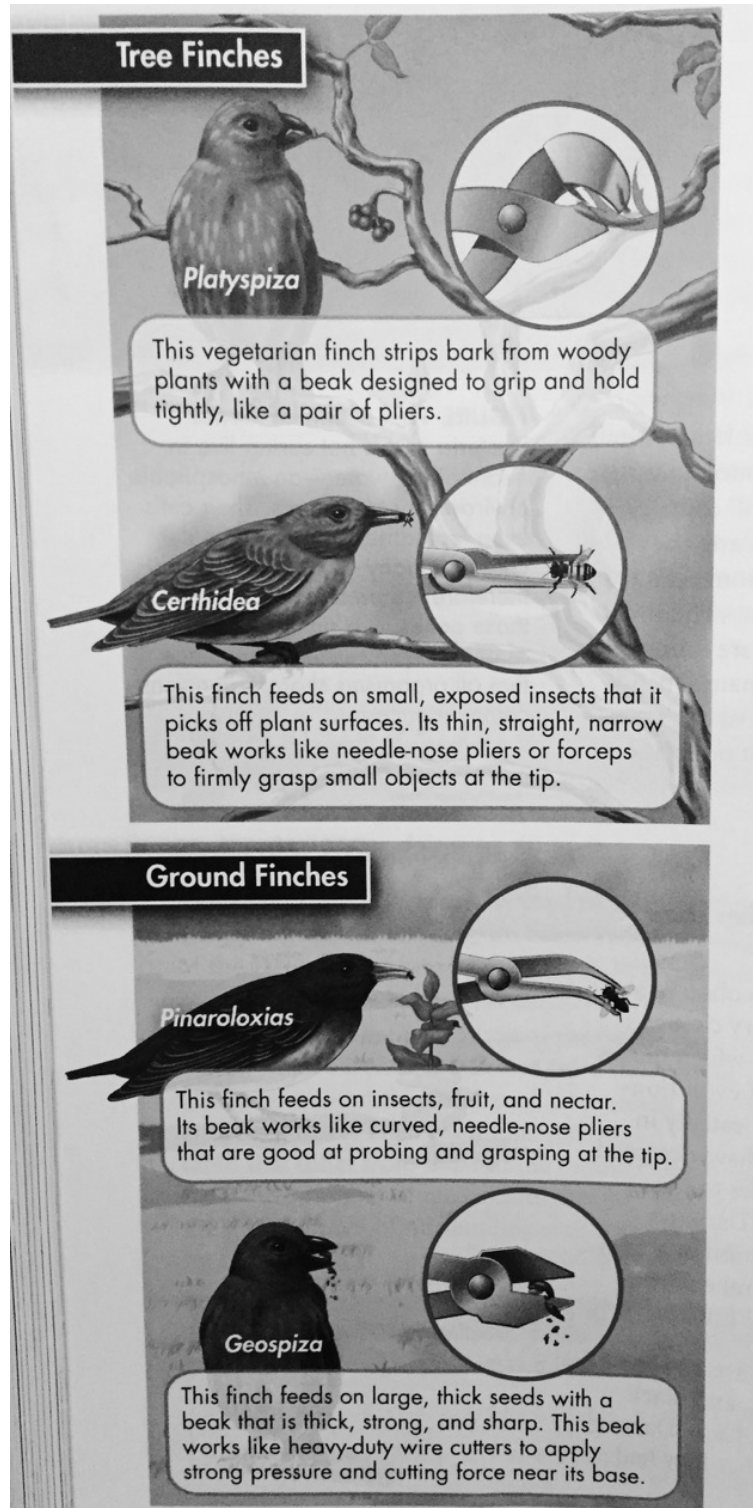


Figure 6: Specialization in Finches. ML, 472

straightforward as a beak exhibits distinctions within the finch family and how through speciation each new bird species can be adapted to particular biological niches.

Looking closely, the analogy explicitly uses the language of design (i.e. "...with a beak designed to grip and hold tightly, like a pair of pliers"). This is not the only place where the word 'design' is likely shorthand for explaining how biological adaptation over generations may have resulted in a feature.⁷ Yet, students may erroneously over map aspects of designed objects onto nature. For instance, pliers are designed for strongly grasping an object like a nut or bolt and are rarely used for hammering a nail or combing hair. In biology, however, features of organisms may have many uses in the life of that organism. Birds don't only use beaks for obtaining food. They also use beaks for grooming, fighting, courtship, feeding their young, singing, heat exchange and breathing (Tattersall, Andrade and Augusto, 2009). Selection pressure occurs on the structural feature in relation to the totality of those uses and their composite fitness in a given environment. We probably could make the beak stronger by filling the bird's nares (nostrils) with bone but then the bird would need to find another way to breathe.

If we want to compare a beak with a human made artifact we could pick something like a Swiss-army knife. Anyone who has used a Swiss-army knife knows that each of the tools differs slightly from its stand-alone counterparts. The scissors have a small spring, the tweezers are tiny, the bottle opener works differently than its broader, stand-alone, ringed cousin, etc. The explanation for this design, of course, is that in addition to the scissors needing to be able to cut, they also need to fold back into a slim

⁷ For example, "A gecko foot is covered by as many as half a million tiny hair-like projections...This design allows the gecko's foot to come in contact with an extremely large area of the wall at the molecular level" (ML, 39).

package and not disturb its co-inhabitants. These multiple constraints are similar to the multiple constraints a beak needs to fulfill for a typical bird.

The belief that a single feature must map to a single purpose tripped up many early naturalists who, for instance, thought that because an animal's skin, fur or feathers could be useful camouflage that meant that all patterns and colorings must be about camouflage. This led to rather outrageous claims such as that flamingos were well suited to blending-in during sunsets as naturalists struggled to reconcile facts with theory (Gould, 1987). As Darwin himself realized, some features of organisms are not functional for what we assume is their evident purpose: a peacock's tail feathers do not aid in flight but peahens find them very becoming (Diamond, 1993)!

The French word *bricolage* or roughly translated, *tinkering*, has been offered as a better metaphor for how natural selection generates complexity (Jacob, 1977). Natural selection is not an orchestra playing instruments designed solely for music, it is the percussion band on the street corner that uses spoons and bowls for its drums only later to use the same spoon and bowl to eat dinner.

Machine-Information-Business metaphors

In addition to the hardware/software computer metaphors already discussed, one of the most intriguing machine metaphors present in the text is Miller and Levine's elaborate analogy describing a cell and a factory. This is an analogy that demonstrates how families of reinforcing metaphors can come together in the text. A factory is composed of people and machines, it is deeply linked to the economy and it operates based on instructions and information. Thus, this single example illustrates the reinforcing metaphors *nature as machine*, *nature as information* and *nature as business*.

Table 3 presents thirteen specific mappings between cells and factories in the text.

Bean, Searles, Singer & Cowen (1990) demonstrated the positive effect of the factory metaphor with a corresponding picture on student recall of cell components and functions as measured by matching tests. In this study, one hundred and eleven high-school students were recruited to learn about cell structure and components. Students

Table 3: Cell as Factory Analogy Examples	Pg.
Organelles are “specialized machines” in factory.	197
The nucleus is the “central office” of the factory.	197
Proteins and RNA move in and out of the “central office” like blueprints or instructions.	197
The nucleolus is where the “assembly” of ribosomes begins in the factory.	197
Vacuoles and Vesicles are where things are stored in the factory.	198
Even the neatest, cleanest factory needs a cleanup crew, and that’s where lysosomes come in. Lysosomes remove the ‘junk’ from the factory.	198
The Cytoskeleton is like the ‘steel’ or ‘cement’ beams that support the factory.	199
Ribosomes make proteins, which is one of the “most important jobs in the cellular factory.”	200
Each ribosome, in its own way, is like a small machine in a factory, turning out proteins on orders that come from its DNA ‘boss’.	200
The Golgi apparatus is somewhat like a customization shop, where the finishing touches are put on proteins before they are ready to leave the ‘factory’. From the Golgi apparatus, proteins are ‘shipped’ to their final destination inside or outside the cell.	201
Chloroplasts are “solar power plants”.	202
Mitochondria are “power plants”.	202
Cell walls are like a “roof” or “wall” and serves as a barrier and keeps “its products safe and secure” until they are ready to be “shipped out”.	202

were randomized to three groups consisting of 1) a teacher presenting the ‘cell as a factory’ with an analogical study guide, 2) a teacher presenting the guide plus a corresponding pictorial analogy, or 3) the guide without a picture or teacher explanation. The authors concluded that the ‘cell as factory’ guide plus pictorial depiction was the most effective approach for teaching about cell structure and function based on a 14 item-matching test. This research may very well explain the presence of this metaphor in the text with an accompany picture. Despite the metaphor’s advantages as a mnemonic for learning cell components, there are important qualities of cells that may be occluded or

distorted in the mapping from factories. To name a few: cells may move passively or actively in response to environmental stimuli; factories usually are fixed in location. Cells can replicate through mitosis or meiosis; traditional factories have no capacity for replication or self-assembly. “Junk” from cells readily degrades; junk from factories can persist in the environment for thousands of years. Cells are tiny and cannot be directly observed without the aid of microscope; factories are usually large and this vast difference in size means that cells are impacted by and respond to different physical forces (e.g. Brownian motion). In eukaryotes, cells are pluripotent - that is, based on environmental signaling the same cells can form structures as diverse as muscle fibers, organs and nerves. Factories lack this developmental adaptive capacity. Moreover, factories are constructed for a specific purpose; cells were not designed and so there is no ultimate agenda or telos that explains their structure.

Perhaps the most profound difference between a factory and a cell is the way it came to be. A cell evolved through billions of years of natural selection pressures. Humans build factories in a few years (even if knowledge of factory design is accumulated over time). As William Paley reasoned in 1802, if we find an object that has a complex design, doesn't this in itself indicate the actions of a designer? Yet, to have a structure and function is not equivalent to, and does not require, having a designer (Topham, 1999).

Many very intelligent people throughout history have mistakenly inferred a designer from what presented as unexplained complexity in biological systems. Moreover, young children are overwhelmingly offered teleological explanations of biological phenomena and, in fact, most of us have a propensity to offer teleological

explanations when pressed for time (Kelemen and Rosset, 2009; Kelemen, Callanan, Casler, and Pérez-Granados, 2005). This is one of the most important habits students have to overcome if they are really to understand natural selection and think like biologists.

Although it is obviously unreasonable to list all the limitations, the question is whether the limitations require some discussion or whether we are okay with students potentially making numerous overmappings. I summarize some of the potential over mappings that may occur in the *nature as machine* metaphor in the table below based on the types of machines presented in the textbooks. I take up in the discussion how significant these differences may be and what we might do differently in constructing metaphors to explicate these subjects.

Characteristic	Machines	Nature
Complexity arises from...	Engineering and design by people	Natural selection over geological time
Composition is typically...	Made of inorganic materials	Organic materials
State is generally...	Fixed and unchanging	Developmental and changing
Relationship from initial state to subsequent state is...	Often predictable	Regulated by complex feedback networks
Production occurs through...	Manufacturing	Reproduction and Self-Assembly
Damage results in...	Malfunction	Self-healing and plasticity in developmental response*
Dissection or disassembly typically results in...	Interest by students	Interest along with disgust and/or empathy by students

* Ciliberti, Martin, and Wagner (2007) describe how machines tend to be ‘brittle’ to damage whereas organisms are typically robust. Take the case of children who have an entire hemisphere of their brain removed to treat seizures usually with no long-term impacts on cognitive function (Pulsifer et al, 2004). It would be rare to find a computer that one could remove half the transistors without observable effect!

Business Metaphors

In addition to machine and information metaphors, the factory analogy also invokes *nature as business* metaphors. This is clear in the introduction to the factory metaphor where “The cell and cytoplasm work together in ‘the business of life’” (ML, 196). This is a curious phrase in the text – as on the one hand, it has little pedagogical value as a metaphor as there are no explicit or even implied mappings between business and life. On the other hand, it is appropriate in setting up the factory metaphor as factories are fundamentally part of industry and business. As with the other reinforcing metaphors, this is not a one-off, but is a message that is reinforced elsewhere in the discussion of cells. The production of ATP, for instance, is compared with earning interest on a bank account (ML, 255). Chloroplasts, have a “trade secret” in converting solar energy (ML, 235). Meanwhile, cell membranes are like ports regulating the transfer of goods:

“When you think about how cells move materials in and out, it can be helpful to think of a cell as a nation. Before you can learn anything about a nation, it’s important to understand where it begins and where it ends. The boundaries of a nation are its borders, and nearly every country tries to regulate and control the goods that move across those borders, like the shipping containers seen here entering and leaving the port of Seattle.” (ML, 208)

Nature as business metaphors are also present in ecology: “Describing a species ‘address’ tells only part of its story. Ecologists also study a species’ ecological ‘occupation’- where and how it ‘makes its living’” (ML, 100). Thus, a species’ niche within the ecosystem is equated with its job and students are encouraged to see the parallels. Evidence of this can be found in questions posed to readers such as, “How is a

niche like a profession? In ecological terms, describe your niche” (ML, 104). Although Miller and Levine is the textbook that primarily uses the *nature as business* metaphor, language common in the scholarly literature of ecology is used in the other texts: species are ‘consumers’ at different trophic levels (G, 46). Plants meanwhile are the ‘producers’ and “...use the sun's energy to manufacture food in a process called photosynthesis” (G, 46). If individual species have occupations, the biosphere collectively is linked to the economy, “Ecosystem goods and services are the goods and services produced by ecosystems that benefit the human economy” (ML, 157). In some of these cases, these analogies help in illustrating an aspect of the target phenomena – for instance the analogy about the port of Seattle is evocative in getting students to consider how cells interact with their environment. The broader question is whether the overmapping student brings other notions of economies and business into their understanding of the subject.

This analysis is complicated by the fact that people in commerce have regularly used the language of biology to explain or justify business actions since the publication of *On the Origins of Species* (Klaes, 1995). The founder of Boston Consulting Group remarked for instance, "Darwin is a better guide to competition than economists" and such statements are common in the business literature and may justify predatory business practices (Nandy 1998).

Yet, scholars have critiqued the metaphor of economic production in biology as it becomes codified in concepts such as GDP that recognizes economic productivity derived from natural resources. The objections include a system of accounting that minimizes negative externalities on the environment and emphasizes production of services vis-à-vis future utilization of those same natural resources. In this perspective we

talk about ecosystem “goods” and “services” but don’t assign “costs” to the production of those goods and service where “costs” are both reductions in future “goods” as well as intangible benefits such as future generations’ ability to enjoy natural settings that haven’t been disrupted by human activity or the impacts on non-human animals (Sen, 1991; Raymond et al, 2013).

Economic metaphors for natural selection are present in the popular scientific literature as well and textbook authors may have borrowed from these authors:

Every decision that an animal takes, whether behavioral (when to tug on which muscle) or developmental (which bits of the body to grow bigger than others), is an economic decision, a choice about the allocation of limited resources among competing demands. So are decisions on how much of the time budget to allocate to feeding, how much to subduing rivals, how much to courting a mate and so on. So are decisions on parenting (how much of the limited budget of food, time and risk to spend on the present child and how much to hold back for future children). So are decisions on life history (how much of life should be spent as a caterpillar, growing by feeding on plants, and how much as a butterfly, sipping aviation fuel from the nectaries of flowers while pursuing a mate). It’s economics everywhere you look: unconscious calculations, ‘as if’ deliberately weighing up the costs and benefits. (Dawkins, 2015 pg. 55)

Yet again, when we introduce *nature as business or economics*, so many source features may creep into our understanding of the target phenomena and nature becomes fundamentally transactional and individualistic. Through reinforcing metaphor logic, this metaphor obscures non-transactional and social elements of nature, reinforcing the original metaphor.

Ironically, the economic decision-making Dawkins draws from for his analogy is also passé. Behavioral economists have shown the *homo economicus* of Dawkins is a chimera. By and large, humans (and presumably other animals) do not make decisions through formal payoff matrices but by a complex array of heuristics (Kahneman, 2011). The phenomenological experience of parenting, for instance, does not seem to be

grounded in constant mental calculus as implied by Dawkins but in emotional attachments!

Dawkins (2015) would likely regard these criticisms as sentimental drivel as the organism is but a fantastic “digression” of the DNA’s desire for replication and of course Dawkins himself is talking metaphorically about the genome (pg. 316). Yet, clearly this metaphor still suffers from the one-gene is for one-behavior logic that underlies the information metaphors we have discussed. Stanley (2007) shows that there is an information gap of many orders of magnitude between what genes could encode for and the positions and interactions of trillions of nerve cells in the human brain. Thus, it seems terribly unlikely that every possible animal characteristic and behavior can have a direct gene correlate that undergoes selection pressure. We also know that there are biological phenomena that make no sense under this strict economic logic: worker ants and other eusocial insects have no progeny yet have continued to exist over millions of years; suicide is as old as human history, but clearly no behavior is as detrimental to the passing on of one’s genes.

Within the scientific mainstream the existence of natural phenomena such as sterile insects is explained through kinship selection; an idea that has been around since Darwin and profoundly shifts the competitive economic calculus that is usually offered to explain natural selection (Wilson 2012). Outside of the scientific mainstream, various thinkers suggest the possibility of emergent phenomena – that is real (or at least not practically reducible) and still consistent with evolution through natural selection (Kauffman 2007). Thus even from the perspective of a materialist, something like love

and attachment, persists as *on balance* the ‘heuristic’ is useful in reproduction even if it is not always optimal.

Competition and War Metaphors

There have been a number of scholars who have tried to understand how evolution via natural selection came to be understood primarily as a ‘struggle’ and how this overarching conceptual metaphor seeded similar metaphors in various sub-domains of biology. Weingart (1995) argues that “struggle” came out of the particular cultural milieu in which Charles Malthus’ ideas supplanted previous norms of natural harmony. Keddy (2001) meanwhile suggests that a male dominated science has been more prone to uncovering examples of competition than cooperation, reflecting a gendered bias in discovery and interpretation.

Larson (2005) quotes the mostly frequently cited paper at the time on invasive species to demonstrate the bombastic rhetoric that can be common in the field:

“Eradication of an established invader is rare and control efforts vary enormously in their efficacy ... [Control] is most effective when it employs a long-term, ecosystem-wide strategy rather than a tactical approach focused on battling individual invaders” (Mack et al. 2000 as cited in Larson, 2005)

This language may be important as it prejudices our understanding of the topic prior to even looking at the actual issue and directs attention from humans’ complicity in the spread of such species through economic activity by framing the issue in confrontational terms.

Competition metaphors in the texts

There are examples of competition metaphors present in the text although they are more subdued than some of the language common in scientific papers cited by Larson

(2005) and others. Glencoe uses metaphors and analogies to illustrate the concept of the competitive exclusion principle:

Think about a goldfish in a bowl...The goldfish needs members of the same species to reproduce. To meet its needs, the goldfish may compete with organisms of the same or different species that share the same bowl. (G, 38)

The authors of Glencoe later tell us that, "Not all organisms living in the same environment are in a continuous battle for survival" (G, 44) which while disavowing the competition metaphors also seems to emphasize that many organisms are in such a 'battle'!

Miller and Levine also evoke nature as competition metaphors:

"Ever since humans began farming, they have battled insects that eat crops. Many farmers now use chemicals called pesticides to kill crop-destroying insects. When farmers first used modern pesticides such as DDT, the chemicals killed most insects. Today, farmers fight an on-going "arms race" with insects. Scientists constantly search for new chemicals to control pests that old chemicals no longer control. How do insects fight back? By evolving". (ML, 487)

Miller and Levine clearly marks "arms race" as a metaphor, but does not mark "fight", "fight back" or "battled" as metaphors. Furthermore, even if "arms race" is denoted as a metaphor in the text, there is no discussion of alternative framings or other ways to balance human needs for food with insects that seek to exist. Ever since Rachel Carson's *Silent Spring* (1962) there have been people both within and outside the scientific mainstream that have challenged whether an "arms race" mentality is an appropriate and sustainable way to regard insects that eat crops and evolve in the presence of pesticides. The challenge with developing ever more lethal pesticides as a response to evolving insects in the context of an evolutionary arms race, is that newer

generations of pesticides can present significant side-effects for other plants, animals and humans.

Metaphors also exist in ecology describing ‘webs’, ‘streams’ and ‘chains’.

Although these are not reinforcing metaphors in and of themselves and can invoke quite different ways of relating to nature, they are used to illustrate predator-prey relationships as in:

A feed chain is a series of steps in which organisms transfer energy by eating and being eaten (ML, 73).

In most ecosystems, feeding relationships are much more complicated than the relationships described in a single, simple chain (ML, 74).

There is nothing wrong with these metaphors as clearly these phenomena exist in nature and chains and webs are one way to describe these interactions. What are missing perhaps are examples of beneficial interactions that extend beyond what appear to be very rare interactions between species. To give one example, respiration is mutually beneficial between plants and animals – this would be a case where two taxonomic kingdoms benefit one another rather than compete with one another.

Examples of Competition and War metaphors in Microbiology

Much as in the case with crops, “Over time, disease-causing organisms engage in an “evolutionary arms race” with humans that create constant challenges” (ML, 23). “In fact, the very word ‘virus’ is Latin for ‘poison’” (ML, 574). The authors go on:

“Viruses must infect living cells in order to grow and reproduce, taking advantage of the nutrients and cellular machinery of their hosts. This means that all viruses are parasites. Parasites depend entirely upon other living organisms for their existence, harming these organisms in the process” (ML, 579).

Even when language is not so extreme, bacteria and eukaryotes are nonetheless engaged in battle and this may be the standard way we think about bacteria. The intent of these organisms is malicious and deceitful: “In either case, the proteins “trick” the cell to take in the virus, or in some cases just its genetic material” (ML, 275).

Meanwhile, in a more colorful way, Miller and Levine compare a virus to an outlaw (See figure below). These characterizations essentially perpetuate the dominant worldview of bacteria and viruses as universally harmful and in competition with humans and human interests. It is not that there is anything objectively incorrect in comparing viruses to outlaws. The analogy does reveal specific parts of the virus’ cycle and viruses can effectively bring down the local law enforcement.

FIGURE 4-8

A white blood cell (eukaryotic) changes shape as it attacks purple-stained bacterial cells that are much smaller (prokaryotic).

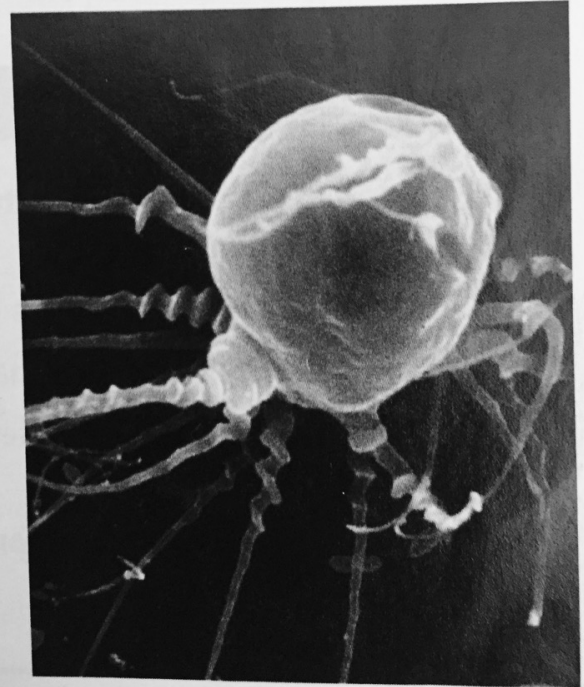


Figure 7: Bacteria as Invaders. Modern Biology. Pg 75.

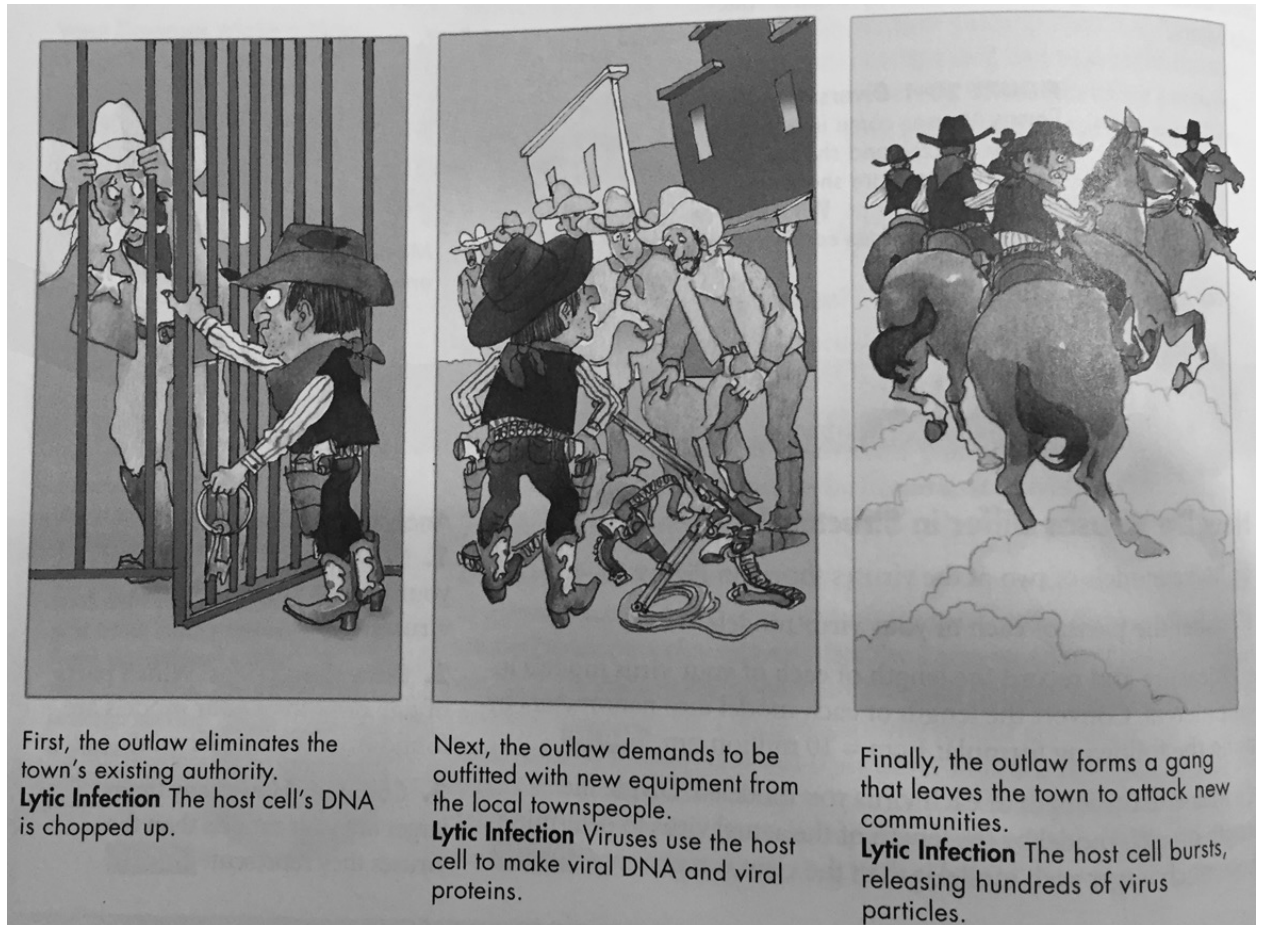


Figure 8: Viruses as Outlaws. Miller Levine. Pg 576.

Instead the analogy is akin to having high school students take a class on Islam and focus on radical jihad. Many liberal community members and parents would object that Jihad is only one aspect of Islam and not even one that all Muslims believe is part of the teachings of the Qur'an. They might argue that anyone who watches TV is all too aware of Jihad and that a school's role is to potentially correct an overemphasis of Jihad as emblematic of Islam by bringing students' attention to the hundreds of millions of peaceful Muslims in the world. While Jihad is a real and true phenomenon then, equating Islam and Jihad can result in equally real and harmful stereotypes.

Much as radical Islamists garner the lion's share of the media's focus on Islam, so too do the activities of bacteria and viruses that can cause disease to humans come to

dominant our perception of them as a domain of organisms. In the case of bacteria, medical perception is shifting as clinicians and public health officials are realizing that killing off bacteria often leaves people vulnerable to more pernicious bacteria and viruses.

This relatively newfound recognition that not all bacteria are harmful hasn't yet started to shift our thinking around viruses. But research suggests that enteric viruses may be similar to bacteria. A recent *Nature Reviews Immunology* article suggests that Murine norovirus may promote 'normal intestinal architecture' and be protective against chemically created colitis when the right conditions are present. The study's authors believe that other symbiotic viruses will be identified in the mammalian intestine (Bordon 2015). That we are only now starting to identify these symbiotic viruses may reveal how deep seated our prejudice is against these organisms as anything besides vectors for illness. Even more radically, there are prominent scientists who now believe that natural selection operates on the 'hologenome' of the organism including all the symbiotic genetic information and that microorganisms' rapid cycles of reproduction allows the symbiotic organism as a whole to more quickly adjust to new environments.

The point here is that if we are using analogies and metaphors in science texts to spur students to view the world in new ways and to challenge cherished beliefs, it would be much more interesting to compare a bacteria or virus with a new resident of a town that is trying to make friends than with an outlaw. Students arrive in biology class thinking of viruses as outlaws or opposing armies. Getting them to reflect that this characterization is not universally true allows scientists to formulate new hypotheses and the public to support fewer ill-conceived plans for the eradication of pathogens. What this

new research from the frontiers of biology also reflects is that context matters. Many bacteria (and likely viruses) are harmless or even beneficial most of the time. It is the context that makes them sometimes run amok and cause harm to their host.

Of course, this framing may be particularly important in medicine, and biology is the primary subject students have to study to enter the medical field. Hauser and Schwartz (2015) showed participants in a study messages with minute variations in whether they possessed the ‘*Cancer as War*’ metaphor. Just as Thibodeau and Boroditsky’s (2011) work demonstrates that framing *Crime as a Beast* (Criminals prey on...) does not obviously invite solutions like increasing intermural sports (as we do not provide extracurricular activities to beasts), so to framing *cancer as war* reduced study participants identification of preventative actions (i.e. limiting red meat consumption). The authors concluded that the framing of cancer as a ‘fight’ or ‘heroic battle’ against a ‘harsh enemy’ already directed people towards certain kinds of interventions and getting people to eat more fruits and vegetables is not consistent with seizing up the public health problem as a *war*. I would also suggest that there might be other implications of the ‘*disease as war*’ metaphors that we haven’t studied. Atul Gawande (2014) writes poignantly about the often ill-informed decisions people make when opting for last-ditch medical interventions versus palliative care. It seems consistent with Schwartz’s (2015) research that patients and providers may be slower to choose palliative approaches to end-of-life care when they are still enraptured with ‘battling’ an enemy.

In conclusion, without being an infectious disease researcher, an agronomist, or cancer specialist, we can nonetheless be confident that a framing of human / pathogen interactions as *war* or “*arms race*” may limit our understanding of those organisms and

restrict our creative full exploration of options for how to coexist in a world populated by other animals, insects, viruses and bacteria. The examples from the text show that some of these *war* and competition metaphors do exist in biology curricula. In the following section I speculate on how these reinforcing metaphors may coalesce around the central topic of natural selection.

Case Study: Reinforcing Metaphors and Natural Selection

A common assumption among educators and the general public is that as more and more discoveries are made in science there is more and more for students of science to memorize. The Nobel laureate Peter Medawar (1965) provided outrageous exam questions from the field of zoology in the 1860s to illustrate why this may not be the case:

By what special structures are bats enabled to fly through the air? and how do the galeopithecii, the pteromys, the petaurus, and petauristae support themselves in that light element? Compare the structure of the wing of the bat with that of the bird, and with that of the extinct pterodactyl: and explain the structures by which the cobra expands its neck, and the saurian dragonflies through the atmosphere. By what structures do serpents spring from the ground, and fishes and cephalopods leap on deck from the waters? and how do flying-fishes support themselves in the air? Explain the origin, the nature, the mode of construction, and the uses of the fibrous parachutes of arachnidans and larvae, and the cocoons which envelop the young; and describe the skeletal elements which support, and the muscles which move the meoptera and the metaptera of insects.

This quote, which is only part of one out of eight very unfair exam questions, strikes a modern reader as an impossible request for a series of arcane facts. Medawar's point is that before Darwin's theory of natural selection and the discovery of DNA, biology was just that: a lot of jumbled facts. With natural selection and genetics, all these various animals and the physical structures that allow their locomotion can be classified

in relation to one another as they are placed on a common phylogenetic tree. The theoretical power of natural selection and genetics aid memorization and assessing individual biological phenomena even as there is more to learn.

Unfortunately for students, no subject is as contentious in high school biology as natural selection and so the theory may not operate effectively as a framework for understanding biology. A 2011 nationally representative survey of high school biology teachers found that 60% of U.S. high school biology teachers are neither “advocates for evolutionary biology nor explicit endorsers of nonscientific alternatives” (Berkman and Plutzer, 2011a). Meanwhile 13% of respondents are advocates of creationism/intelligent design and reject natural selection -which is remarkable given the survey population. Among the “cautious 60%”, many present both natural selection and creationism as viable alternatives to one another putting the onus on students to decide “based on their own beliefs and research. Not on what a textbook or on what a teacher says” (pg. 405). The cumulative effect of this stance by teachers is students’ exposure to natural selection is usually minimal and often misleading (2011a).

One interpretation of this data is that there is an overt political agenda where creationists have taken an argument they have lost in the courts to the classroom and/or there is a high-proportion of high-school biology teachers who are either biblical literalists or sympathizers. There may be some truth to this claim, however, even among the “cautious 60%” very few believe in a “young-earth” hypothesis (that is an Earth less than 10,000 years old) that is consistent with Biblical accounts and hence there doesn’t appear a definitive rejection of all scientific facts and theory among these teachers.

The authors of the study and authors of similar investigations believe the major source of the problem is a lack of *knowledge* about natural selection and the primary remedy is in providing education about natural selection for teachers (Gillings 2012). This belief is writ large in their recommendations, “Requiring an evolution course for all pre-service biology teachers, as well as provision of resources to provide such a course, would likely lead to meaningful improvement in secondary school science instruction” (Berkman and Plutzer, 2011b).

It may be that pre-service and in-service education focused on natural selection would help teachers discuss the theory in their classrooms – certainly it couldn’t hurt. Perhaps the most important objection to overcome with teachers and students is the same objection that was present among Darwin’s contemporaries – how can ‘blind’ evolution result in tremendously complex structures such as the human eye? In modern Intelligent Design language this has been described as the problem of ‘irreducible complexity’ – that is, a structure like the eye is only effective because of the complex relations of its parts - and there is no stepwise route to that final state that confers fitness at each point along the way (Behe 1996).

Luckily, far from being an unsolvable paradox the evolutionary path of many complex biological phenomena are well documented (Dawkins, 1997). Nonetheless, the ID rhetoric and argument at first glance is seductive. Metaphor and analogies offer opportunities for demonstrating how generating complexity is possible through simple steps. Richard Dawkins uses this strategy in his metaphorically-rich books such as ‘The Blind Watchmaker’ and ‘Climbing Mount Improbable’. Dawkins demonstrates, for instance, how a simple plastic bag filled with water can act as a rudimentary magnifying

glass solving a complicated computational problem of focusing light. It is easy enough to imagine or even demonstrate, how variation in the amount of water in the bag could result in better optical characteristics that could be further refined through time.

Analogies such as these, which could be developed into class exercises or labs, can suggest to students that advantage can be conferred by simple adaptations and that these adaptations can be refined into complex feature sets over time.

Analogies that demonstrate evolutionary process would be a welcome addition to the texts. However, it strikes me as unconvincing to advance that it is mostly ignorance of the theory of natural selection that is the major impediment for teachers presenting natural selection as established theory to students. After all, this is a group of people who have chosen to become biology teachers in the first place and hence must have some interest and aptitude for the topic.

I would suggest that at least part of what might make biology teachers uncomfortable with presenting natural selection as established scientific theory is the metaphors that have historically accompanied the theory and are present and reinforced in high school biology textbooks. We know, for instance, from a different survey of the National Association of High School Biology Teachers, that 85% of all teachers agreed with the statement “A struggle for survival characterizes evolution” (Larson, 2011). Yet as Lewin (1991) explained “struggle” merely represents one possible interpretation of natural selection and is not is not foundational to the theory:

No scientist doubts that the organisms on earth today have evolved over billions of years from organisms that were very unlike them and that nearly all types of organisms have long since gone extinct. Moreover, we know this to be a natural process resulting from the differential survivorship of different forms. In this sense, we all accept Darwinism as true.

But Darwin's explanation for that evolution is another matter. He claimed that there was a universal struggle for existence because more organisms were born than could survive and reproduce, and that in the course of that struggle for existence those organisms who were more efficient, better designed, cleverer, and generally better built for the struggle would leave more offspring than the inferior kind. As a consequence of this victory in the struggle for existence, evolutionary change occurred. (pg. 9)

The texts indeed reiterate this competitive message, beginning the topic of natural selection with subject headings of "The Struggle for Existence" (ML460) and "Survival of the Fittest" (ML, 461) with a corresponding image (ML, 462).

Although speculative, it may be the case that today's biology teachers are facing a complex mandate that is hard for them to reconcile. On the one hand they are helping students develop self-awareness and responsible decision-making, to take the perspective of others and be thoughtful citizens. Schools and districts meanwhile are implementing school-climate surveys and promoting 'zero tolerance' attitudes towards bullying. Yet in biology classes, textbooks through a collection of metaphors are confirming some of the metaphors that have long framed evolution — that the world boils down to economic self-interest and is fundamentally competitive and often violent. This perspective is given authority by the authority of science itself and reinforced by machine metaphors that suggest the ultimate truth of natural phenomena is found in our cellular factories, cogs and gears and not in our social niceties. The reductionist and deterministic implications of the *DNA as blueprint* metaphor and its kin are very much part of this unstated but powerful logic. Lewin (1991) traced this implicit argument and its repercussions more than twenty-five years ago:

Genes make individuals, individuals have particular preferences and behaviors, the collection of preferences and behaviors makes a culture, and so genes make culture. That is why molecular biologists urge us to spend as much money as necessary to discover the sequence of the DNA as a human being. They

say that when we know the sequence of the molecule that makes up all our genes, we will know what it is to be human...we will know why some of us are rich and some poor, some healthy and some sick, some powerful and some weak. We will also know why some societies are rich and others are weak and poor, why one nation, one sex, one race dominates another. (pg. 14)

I would suggest it is possible that the totality of these metaphors creates a bind for biology teachers who are helping students learn to be respectful and kind to their peers while teaching a subject that is quietly and subtly intoning, “the only real truth is self-preservation and the only real actor is the genes”. These metaphoric perspectives are also at odds with many religious teachings and hence may create potential classroom politics. Teachers may, in turn, hedge, shy-away from and qualify their support for natural selection theory to lessen their discomfort in their multiple roles of biology teacher, leader in a caring school community and interlocutor with parents who may have strongly held religious convictions.

Yet, we need not stick with these metaphors to be in alignment with our current scientific paradigms. On the contrary, as I have previously argued, the bias present in many of these metaphors is out of step with modern biology. Vigorous debates within and outside the scientific community continue on whether the phenomena we call ‘culture’ and ‘society’ truly is reducible to genes and atoms and, even if it were, whether we could even know it! These authors would tell us as a practical matter, it is more fruitful to try to understand say, the crisis in Syria, through understanding Ba’ath party politics and US-Russia relations rather than population genetics applied to the Syrian people!

Similarly, it would be hard to definitely say if nature was more competitive or cooperative – in large part because those are human notions. There are however, valid

perspectives on nature that would suggest the zero-sum game mentality underlying competition metaphors is not universally correct and these perspectives are largely absent in the metaphors present in the biology textbooks reviewed here. Taking a historical view we can say that all existing species have done relatively well vis-à-vis the hadean era four billion years ago when no life existed at all! Ironically, even when some scientists speak about kinship selection and its well-established place in nature, it can still be subsumed in competition rhetoric and this demonstrates how deeply our conception of *nature as war* runs: E.O. Wilson's recent book "The Social Conquest of Earth", for instance, is about "pro-social" organisms such as people, bees and ants that will sometimes act in ways that are not in their immediate self-interest. Even here, altruism is a *conquest* vis-à-vis non-altruistic species and we substitute interspecies competition for interspecies conquest!

One could reasonably object that I am making too much out of these metaphors. After all they only constitute a small proportion of the text and aren't the only metaphors. However, as I have previously argued, they are often in prominent positions in the text serving either to introduce a topic or to summarize it. Furthermore, in some cases these metaphors aren't just aberrant one-offs: they are indicators of the overall content in the text. *DNA as a blueprint* is not merely a metaphor: that is the dominant framing of the genetics chapter as a whole. Absent in the texts is any mention of the numerous gene-environment feedbacks and the more recent Lamarckian-inspired ideas that attenuate the deterministic relationship between genes and organisms.

I would further posit that unlike a subject like chemistry, at some point it is hard not to reflect on the implications of biology texts. Students and teachers may say to themselves consciously or unconsciously, "I know I'm reading about cells and genes, but

what is this saying about me, my friends and my family?” The ultimate overmapping of machines, blueprints and competition metaphors occur if students map, “Am I also without free will? Am I also bound to be aggressive?”

Some of these questions are empirical ones albeit difficult ones to study given prior research that suggests the pull of metaphors is often unconscious (Thibodeau and Boroditsky, 2011). In the absence of such research, I would suggest the burden of proof is on textbook companies and educators to demonstrate why we need the reinforcing metaphors previously described.

I am not suggesting biology textbooks adopt pedagogical metaphors that only stress holism, interaction and cooperation where any investigation at a level less than a planetary one amounts to reductionism. I am instead suggesting that the pendulum of biology textbooks and the public understanding of biology are too far in the direction of atomism, mechanism, economic self-interest and competition and this too represents a biased account of natural phenomena. It is therefore incumbent on schools and textbook authors to attempt to correct students and teachers’ prior biases on these topics through the inclusion of language and examples that allow students to view nature from multiple vantage points. It is possible such a shift would lessen what may be reticence on the part of high school teachers to present natural selection as the extremely well validated theory that it is and to use it to scaffold the other topics in biology.

Other Findings

Comparison with findings of past textbook analyses

Prior analyses of science texts have tended to find a limited number of metaphors and analogies (See Table 4 below). In Newton's (2003) study of Elementary School Science books, 45 out of 80 books contained no analogies at all. The highest number of analogies per text was reported by Thiele et al., 1995; specifically the biology text subset in the sample.

No. of texts	Total Metaphors	Average No.	Study
80	92	1.15	(Newton 2003)
26	216	8.3	(Curtis and Reigeluth, 1984)
8	158	19.75	(Orgill and Bodner, 2006)
4	174	43.5	(Thiele et al., 1995)*

* Only including biology texts.

The present study identified significantly more metaphors and analogies than prior investigations. A total of 242 metaphors and analogies were identified from the three texts of which 199 met the criteria for being fully coded. The text Modern Biology contained the fewest metaphors and analogies that were fully coded. However even in Modern Biology there were 22 metaphors and analogies coded across four units.

In the Miller and Levine text alone 134 metaphors and analogies were coded for in just four of the eight total units. If the other four units had as many metaphors and analogies as the first four, the Miller and Levine text would contain more metaphors and analogies than the entire corpus of 26 textbooks reviewed by Curtis and Reigeluth (1984). Although some of the distinction can be accounted for by definitional differences between my approach which also examined figurative and prior works that largely

omitted metaphorical instances without an explicit analogy, this by no means accounts for the distinction. In Miller and Levine, for example, there are dozens of instances where the authors have labeled analogies with the phrase “using an analogy”. Even if all we included were these specific and very intentional instances, they would greatly exceed the instances found by all but Thiele et al., 1995. This finding suggests that at least some publishing companies and textbook authors have responded to scholars and educators who have called for more active and thoughtful inclusion of metaphors and analogies in science texts. It may additionally suggest that biology as a discipline is more prone than other high-school science subjects to being explicated through metaphors and analogies.

Metaphors and analogies illustrating physical structure and function

Prior work has examined the proportions of metaphors and analogies that map source and target through their physical structure and/or their functional relationships. Structural analogies relate to the material properties of biological phenomena as in, “The inner membranes are arranged in stacks of membranous sacs called grana, which resemble stacks of coins.” (G, 184). Meanwhile, as the name implies, functional analogies relate to some aspect of what a biological system does as in, “It is the job of the plasma membrane to allow a steady supply of these nutrients to come into the cell no matter what the external conditions are” (G, 175).

Of the 199 coded metaphors and analogies, 48 relate to physical structure only, 49 relate to function and 103 represent both the physical structure and the function. Thus, metaphors and analogies are relatively balanced in mapping physical structure and function with the majority of metaphors and analogies illustrating elements of both.

Presentation format of metaphors and analogies

Of the 199 coded analogies, 65 contain a visual component. This represents a higher proportion of visual analogies and metaphors than in prior works. That being said a large within-sample range exists in both Curtis and Reilguleth's (1984) work as well as in Orgill and Bodner's (2006) where metaphors that contain a visual component comprise anywhere from 0% of the sample to 36% of the sample. As noted in the introduction, there is no established means of coding these metaphors – the current codes (i.e. “are limitations discussed?”, “is the source analogue explained?”) require an extra interpretive step in the case of pictorial metaphors and analogies. How future analyses treat metaphors and analogies that are partially based on images or videos is a subject that will be returned to in the discussion.

Level of enrichment of metaphors and analogies

Nearly 60% of the coded metaphors are ‘simple’ – that is, consisting of one or two sentences only. These often are verbal-only and illustrate a structural relationship such as, “Cellulose is made of long chains of glucose units linked together in arrangements somewhat like a chain-linked fence” (G, 159). Meanwhile, enriched metaphors appear more carefully constructed such as many of the reinforcing metaphors previously discussed. Although enriched metaphors and analogies seem to garner the lion's share of critical attention, simple metaphors are nonetheless important to examine, as they constitute a significant proportion of all metaphors in the text.

Is the analogue explained?

In only 59 out of 199 coded metaphors and analogies is the analogue explained. An example of a metaphor with an explained analogue is Miller and Levine's comparison

of a screen window to the actions of the cell membrane, “In your home, a screen in a window can perform selective permeability in a similar way. When you open the window, the screen lets fresh air in and keeps most insects out” (ML, 175).

Usually, even unexplained source analogues do not seem to be a problem when the analogue is commonly understood. It is not practical for scholars to insist that authors of pedagogical materials explain the analogue in all cases as in Glynn (1991) or to code for explanations of the analogue in a purely quantitative manner. Instead authors should reflect on whether the analogue is commonly and consistently understood by a diverse student body.

Is a cognitive strategy present to alert the student to the presence of the metaphor?

Cues to the student indicating the presence of the metaphor and analogy are much more common in the three textbooks than in prior works where, in some cases, no cues were present in the texts at all. This finding would suggest textbook authors have responded to Glynn’s Teaching-With-Analogies model (1991) and other subsequent scholars who have suggested that alerting students to metaphors and analogies in texts aids in comprehension of the metaphor or analogy. Cueing in the Miller and Levine text is frequently in the form of putting quotations around the metaphor as in:

“DNA polymerase also “proofreads” each new strand, so that each molecule is a near perfect copy of the original” (ML, 351)

It is unknown how effective quotations are in signaling the presence of the metaphor to students, particularly as quotes are also applied to non-metaphorical language as well. All three texts use phrases such as “like”, “akin”, “is similar to”, “can be thought of being like”, etc. Although some form of cueing is present in the majority of coded metaphors this is not universally the case:

“Our genes may come from our parents, but each of us gets a fresh shuffle and a brand-new deal of those genetic cards as we start our lives” (ML, 305).

“Gel electrophoresis can be used to produce a DNA fingerprint as shown” (G, 15).

“What this means, of course, is that nearly all animals, from flies to mammals, share the same basic tools for building the different parts of the body” (ML, 382).

“First, for beak size and shape to evolve, there must be enough heritable variation in those traits to provide raw material for natural selection” (ML, 472).

In instances where there is not cognitive strategy presented it is unclear whether the textbook authors understand the sentence as being metaphorical.

Are limitations in the analogy described?

In only 4 of the 199 coded metaphors was there an indication to the students of a potential limitation. This is in keeping with prior analyses that find limitations rarely presented.

“The cytoskeleton forms a framework for the cell, like the skeleton for your body. However, unlike your bones, the cytoskeleton is a constantly changing structure. It can be dismantled in one place and reassembled somewhere else in the cell, changing the cell's shape” (G, 185).

This finding is important, as potential limitations are always present in metaphors and analogies and subsequent overmappings are possible even if very few have been empirically studied. Many examples of the limitations in some of these metaphors and analogies have been presented in past chapters. It is unknown why textbook authors do not highlight limitations. Some hypotheses include the following:

- Authors are not aware of the research that establishes the value of both highlighting where the analogy fits as well as where it falls short.

- Authors are not aware of the limitations and their importance. This seems particularly obvious in cases where authors are mapping from an area beyond their expertise (for instance, computers as analogues for biological systems or human languages as an analogue for DNA).
- Authors don't want to undermine their own analogy. Pride of authorship may be a reason textbook authors avoid discussing limitations in the analogy.
- Authors don't want to confuse students by discussing the limitations. Authors may believe that an initial understanding is bound to include misconceptions anyway.

There is likely not a one-size fits-all policy here. Instead authors need to reflect on what spurious mappings the student might make from source to target and how significant some of those mappings may be. It should also be stressed that students can learn from considering the limitations of an analogy just as they can learn from an apt analogy. I discuss what to do about this situation in the discussion.

Analogies and metaphors in problem sets

There are a number of instances where metaphors and analogies are present in the problem sets. These were excluded from the quantitative coding as the codes cannot be appropriately applied to questions posed to students. These instances are nonetheless worth investigating recognizing any analysis is limited by the lack of student response data. The questions can be straightforward given the chapter content:

Compare and contrast the functions of a cell wall to the functions of a plasma membrane (G, 187).

A change in pH can change the shape of a protein. How might a change in pH affect the function of an enzyme such as carbonic anhydrase? (*Hint*: Think about the analogy of the lock and key) (ML, 53).

In other instances, they reference an explicit analogy presented earlier in the text.

For instance, in the following examples the text previously compared ATP to banking and the lac repressor to a switch. It is unclear in these questions whether students are supposed to write a new analogy or simply re-write the analogy presented in the text:

Develop an analogy to explain ATP and energy transfer to a classmate who does not understand the concept. (ML, 244)

Write an analogy that demonstrates how the lac repressor functions. (ML, 384)

There are also instances where students are asked questions where the answer is not directly present in the text. These may be challenging questions for most students to answer in the absence of support from a teacher:

Compare the characteristics of life with the flames of a fire. How are they similar and different? (G, 31)

Use eggs and a frying pan on a stove as an analogy for reactants and an enzyme. Use the control knob on the stove burner as an analogy for how a variable can affect the action of an enzyme. (ML, 54)

How is shotgun sequencing similar to doing a jigsaw puzzle? (ML, 409)

Finally, there are questions where there are limitations in the question posed to the students are similar to the sorts of limitations discussed elsewhere. For instance, although the following analogy may be helpful for students understanding random mutation, it contains no potential analogue for selection pressure or sexual reproduction:

You tell a story to a second person who tells it to a third person, and so on. As the story is retold, changes are introduced. Overtime, the number of changes increases. How is this process an analogy for what happens to DNA over time? (ML, 474)

Mixed or layered metaphors

There are a number of instances in the texts when multiple metaphors are used in close proximity to one another in the chapters. Although the research literature on such metaphoric clustering in pedagogical texts is scant, in some cases these multiple metaphors may be confusing to students. To take an example:

Think of this message as being written in a language that uses nitrogenous bases as its alphabet. As you know, proteins contain chains of amino acids. You could say that the language of proteins uses an alphabet of amino acids. (G, 291).

In this example, two alphabets are introduced as analogues in the same paragraph. The first alphabet is the individual nitrogenous bases of DNA and the second alphabet is amino acids. Because each amino acid is composed of three bases the ‘alphabet’ is effectively mapped to two distinct biological phenomena.

While this analogy seems simply in need of editing, there are many other instances where the mixed metaphors and analogies are not so obviously problematic but still seem unnecessarily complicated. To take two examples:

Microtubules are thin, hollow cylinders made of protein. Microfilaments are smaller, solid protein fibers. Together, they act as a sort of scaffold to maintain the shape of the cell in the same way that poles maintain the shape of a tent. They also anchor and support many organelles and provide a sort of highway system through which materials move within the cell (G, 185).

The monomers in a polymer may be identical, like the links on a metal watchband; or the monomers may be different, like the beads in a multicolored necklace (ML, 46).

In the first instance, the authors of Glencoe seem to want to convey the fact that microtubules and microfilaments both provide structural support to the cell as well as facilitate transport of molecules within the cell. Yet tents, anchors and a highway system are an odd metaphoric group particularly because in this case the highway system is

entirely within the tent. Similarly, ‘links on a metal watchband’ and ‘beads on a multicolored necklace’ also seems needlessly complex given that the ‘links’ and the ‘beads’ are both monomers. In other instances, Miller and Levine compare DNA to a twisted ladder, a coiled spring and a spiral staircase in a single page (ML, 346). In at least one instance, there is the use of the metaphor ‘hot spots’ to describe locations of biodiversity and species loss on the adjacent page that is describing the literal phenomena of global warming (ML, 585). Finally, there are instances where the verbal metaphor is similarly mixed with a different pictorial metaphor. All of these instances seem potentially confusing to students.

Other Important metaphors: Geological time

Both Glencoe and Miller and Levine attempt to convey the age of the earth via clock and calendar analogies – perhaps in reference to ‘molecular clocks’ used in radiocarbon dating (See Figures below). Of these two clock models, the Miller and Levine model is considerably more detailed. Both clocks effectively convey that human history only constitutes the last moments in the day. Glencoe also uses a 1-year calendar to reinforce this message with analogues to January 1st (formation of the earth), mid-October (end of Precambrian) and December 26th (modern humans). There is a math error in the 1-year calendar analogy that is interesting:

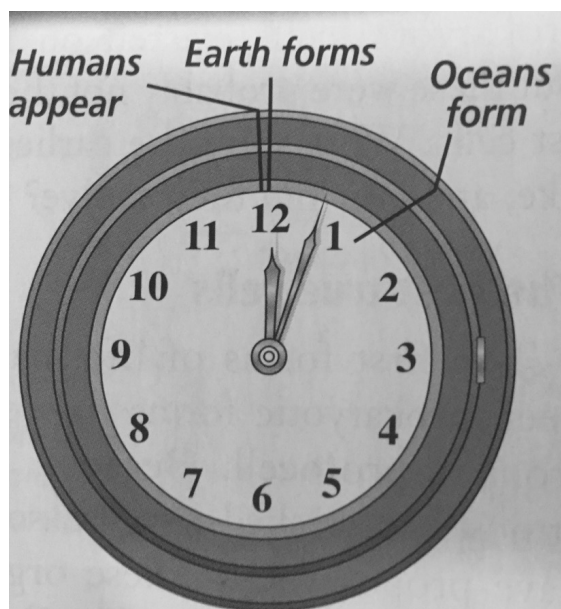


Figure 9: A 12-hour clock as analogous for geologic history. G384

“The Precambrian accounts for about 87 percent of the Earth's history - until about the middle of October in the hypothetical calendar year” (G, 376). One presumes the source of this error is in believing that because October is the 10th month, we divide 10.5/12 to obtain 87.5%. The error is mid-October would be

represented as 9.5 (nine complete months and one half month) just as mid-December would be represented as 11.5 and not 12.5! The correct equation is then $9.5/12$ or 79% and the correct date to mark the end of the Precambrian is mid-November. Although this is a trivial error, similar absence of math rigor among the analogies described in other metaphors and analogies provide some evidence that these metaphors and analogies are not give the same level of scrutiny by reviewers – after all the Glencoe book had seven authors, twenty-seven reviewers, thirteen content specialists, an advisory board, a student advisory board, field-test schools, and a majority of the high-school population of California reading it! It is possible that because metaphors and analogies like this are meant to be illustrative and not factual, that errors pass the scrutiny of so many reviewers and readers.

An additional question that would be interesting to pose to students in order to understand whether they understand the analogy is what happens at 12:01am? Of course, the answer is that the day was arbitrarily proportioned to the history of the Earth and

12:01 represents a future state of the Earth, but it seems very possible many students would be confused by such as question.

Other Important metaphors: The Tree of Life

One of the most powerful metaphors in Natural Selection is the Tree of Life (ToL). This metaphor, used by Darwin himself, presents the diversity of life represented in a schematic branching or tree form, where speciation events are shown as distinct branches and junctures or nodes represent common ancestors. The trunk of the tree is the origin of life located in deep time.

All three texts utilize ToL to explain the diversification of life. Modern Biology presents it like this, “Figure 15-10 shows a phylogenetic diagram, or "tree," which models a hypothesized phylogeny. The "trunk" represents a past species that could have been the ancestor of all these animals. Each "branch" over time represents a separate population or lineage. More closely related groups appear closer to each other on the branch” (MB, 306). The accompanying diagram (below) is necessarily a simplification and it elucidates as well as muddles the topic. The major point of confusion is the depiction through photos of the modern animal represented. The camels of seventy million years ago look quite different from the camel represented. The camel of 40-50 million years ago, for instance, was “about the size of a rabbit”! (Bernstein, 2009). Thus, the tree diagram presents these evolutionary byways as more static than in the fossil record but the basic point is conveyed.

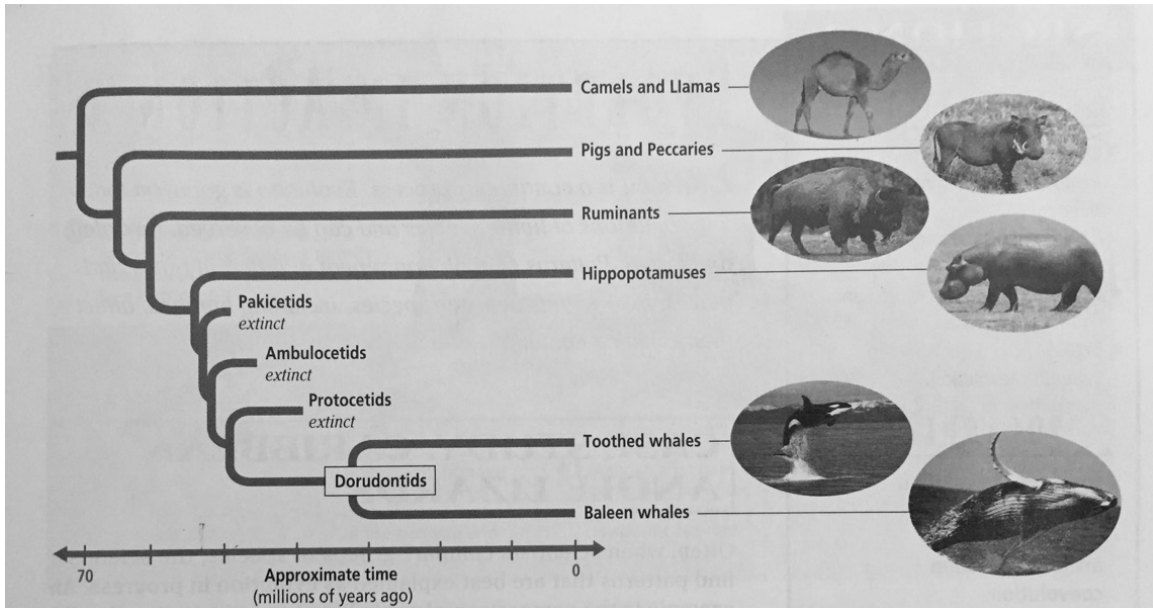


Figure 10: The Tree of Life (MB, 307)

Importantly, the ToL was not just a metaphor for Darwin and his contemporaries but a heuristic for interpreting geological and biological evidence to reconstitute the course of evolution: Missing branches could be identified and tagged for research; junctures could be explored and hypothesized. However, advances in evolutionary theory since Darwin’s time have complicated the tree. As expressed by David Mindell (2013), “...as biologists identify more entities and events to describe—including species, organisms, cells, genomes, gene families, extra-chromosomal genetic elements, endosymbioses, hybridizations, recombination types, and lateral gene transfer (LGT) events—the ToL strains under the weight of multiple uses and expectations” (pg. 479). In other words, if we were to actually draw the tree we would find that in many epochs and domains, the tree is tangled and knotty, dense with networks that merge as well as divide.

Despite these limitations the ToL persists in the scientific community. An article last year offers evidence to suggest there may be a hidden fourth domain of life. The

article is titled, “Searching for new branches on the tree of life” (Woyke and Rubin, 2014). For the learning student, all of this is potentially grist for the mill. Is ToL more like a pine tree? An oak? A ficus that can sprout new aerial roots? Does the tree of life have roots or only a trunk? The questions can help students grasp concepts such as lateral gene transfers and hybridization events. Students could even draw different sections of the tree and critique one another’s representations. Thus, this seems an instance of a powerful scientific metaphor that textbooks could use to prompt students to really investigate natural selection.

Analogies with antiquated source analogues

In some cases the chosen analogies seem quite antiquated. For instance, in Glencoe, the description of the endoplasmic reticulum (ER) contains a metaphor of the ER as an accordion. Although this metaphor is effective in conveying how folding takes place, it seems a safe bet that not all students would know what an accordion is without an image or further description. This example may connect with the literature that examines the subtle ways in which culture and social capital can bias testing (Jenks, 1998):

Its folds are like the folds of an accordion. If you spread the accordion out, it would take up tremendous space. By pleating and folding, the accordion fits into a compact unit. Similarly, a large amount of folded ER is available to do work in a small space (G,181).

Another example of an antiquated analogy is below. Although this is an instance where the source analogue is described and fits well with the target phenomena, it nonetheless seems obsolete and in need of updating:

Each protein in the chain passes energized electrons along to the next protein, similar to a bucket brigade in which a line of people pass a bucket of water from

person to person to fight a fire. At each step along the transport chain, the electrons lose energy, just as some of the water might be spilled from buckets in the fire-fighting chain (G,226).

A final example of an out-of-date analogy is the discovery of DNA as ‘cracking the code’, which Glencoe illustrates through pictures of safes (G, 292). This metaphor may very well trace to WWII and the decoding of the Axis powers’ Enigma cipher that allowed for encrypted military communication. It seems a little outdated for students who were born long after DNA was discovered and understood. Additionally, it seems to imply there was some effort by DNA to remain concealed.

Analogies with subtle errors in mapping

Finally, some of these examples contain subtle errors in the referenced structure or function. To take an example:

Under an electron microscope, chromatin looks like beads on a string...Before a cell can divide, the long strands of chromatin must be reorganized, just as you would coil a long strand of rope before storing it. (G, 204)

Although chromatin may resemble ‘beads on a string’, in the case of the analogue the strings runs through the beads, whereas in chromatin the ‘string’ winds around the exterior of the ‘beads’. This is an example of a minor inaccuracy that nonetheless may reduce the value of the metaphor as a teaching tool.

The challenge of crafting good analogies can be seen in both Miller and Levine’s and Glencoe’s attempt to communicate through analogy why cells tend to be small. Both textbooks use a cube to communicate this thought – as the cube increases in size the volume disproportionately increases vis-à-vis surface area.

If a cell were to become very large, the volume would increase much more than the surface area. Therefore, the surface area would not allow material to enter or

leave the cell quickly enough to meet the cell's needs. As a result, most cells are microscopic in size (MB, 73)

Picture a cube-shaped cell like those shown in Figure 8.9. The smallest cell has 1 mm sides, a surface area of 6 mm, and a volume of 1 mm. If the side of the cell is doubled to 2 mm, the surface area will increase fourfold to $6 \times 2 \times 2 = 24 \text{ mm}^2$ (G,202)

Of course, cells aren't cubical and presumably the textbook authors assume students will get this basic point. Presumably, the authors of the texts didn't use spheres because the math then introduces π . Of course, the other problem with this analogy is that it assumes that natural selection could not have solved this problem in other ways – for instance, by more complex geometries or more active diffusion across membranes. And single cells do vary greatly in shape ranging from *E. coli* at $2 \mu\text{m}$ to the non-spherical Chaos amoebas topping out at 5 mms – a 2,500-fold difference in scale!

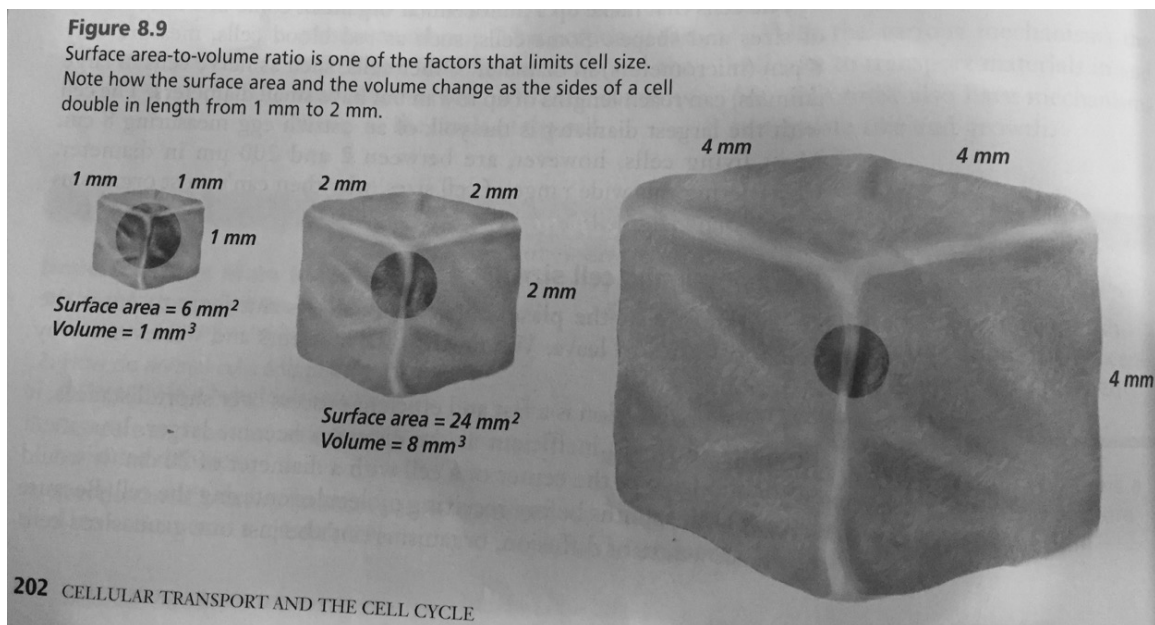


Figure 11:G202

A question we will take up in the discussion is whether deconstructing analogies like this to reveal weaknesses simply represents nit-picking that is not relevant for high

school biology students or whether limitations in analogies like these are bona fide problems for students learning biology that we need to somehow address. It is easy to Monday morning quarterback evolution – to believe that one has spotted the answer for a particular natural phenomenon based on an evolutionary logic, but like all scientific research this has the danger of falling victim for ad hoc hypotheses. There is likely some truth in what these textbook authors are saying, but biologists should be cautious in making these types of inferences without further support.

Discussion

I have provided numerous examples of pedagogical metaphors in the text and suggested these metaphors can mislead students in important ways. I would now like to discuss some other potential ramifications of the particular class of metaphors I call ‘reinforcing metaphors’ before offering some ideas and suggestions on new directions for pedagogical metaphors in biology.

New Directions for Pedagogical Metaphors

Reviewing Metaphors for Obsolescence, Cultural Assumptions and Inaccuracies

I have presented a number of examples in the previous chapters that suggest metaphors and analogies are not updated or reviewed as frequently and closely as other subject matter and may become antiquated or not in keeping with current scientific ideas. ‘Bucket brigades’ to illustrate electron transfer, ‘accordions’ to explain the folding of the endoplasmic reticulum, human ‘street sweepers’ to describe cilia action are some of the instances where one gets the impression these metaphors and analogies were first developed in the 1950s. They may have been effective analogies when they were developed – they are just arcane for today’s students and not helpful as the source analogue is likely as unfamiliar to the student as the target. Other metaphors contain simple errors such as the math underlying the Glencoe clock model and the calculation for total genome size. In these instances, even if the metaphors are attempting to convey factual material the metaphors may be regarded as purely illustrative, and hence don’t receive careful review.

There are many more current metaphors in circulation in the popular science literature to explain biology subjects that could easily be adopted in the texts. Gillings (2011), for instance, presents a case for using the development of language as a potentially helpful analogy for students to understand evolution: Language also develops complexity without an end-goal and many of the features of language development map nicely against concepts in evolution. I have summarized some of these novel mappings in the table 5 below:

Language example	Biology Correlate
Spelling changes over time ¹	Mutation and selection
Pronunciation changes, accents and dialects ¹	Neutral drift
Abrupt changes in language – spelling in SMS or Twitter ¹	Punctuated equilibrium
Words coming in from other languages ¹	lateral gene transfer
New words with new meanings (e.g. ‘Frankenfood’) ¹	Recombination events
Diacritical markers used in other languages to alter transcription ² (e.g. Don’t read this)	Methylation of DNA
Differential utility of different letters as in the game Scrabble ²	Wobbly base pairing
Story elements ‘Once upon a time’, ‘The End’.	Start and stop codons
Synonyms (e.g. “great” “wonderful” “fabulous”)	Alternative codons specifying the same amino acid

¹Adapted from Gillings (2011). ² Adapted from Rutherford (2013)

Using the development of language as a pedagogical tool for teaching about evolution seems particularly compelling given all of the analogies the authors of the textbooks already use in communicating genetic concepts. The language analogy then, properly reformed to not imply determinism, could bridge topics on genetics and evolution (i.e. “In the last chapter, we talked about “reading” the genetic code, in this chapter we want to describe how genes and gene combinations can change, just as languages change”). Furthermore, the examples of spelling changes to illustrate mutation and abrupt changes in SMS and Tweets spelling are easy to understand and provide an

entry point for students who may otherwise be intimidated by phrases and concepts such as ‘lateral gene transfer’ and ‘punctuated equilibrium’. What student isn’t familiar with LOL, b/c, b4 and the rest of the SMS/Twitter lexicon?

In trying to develop metaphors and analogies, we need to think about what high school students already understand. For instance, the game Minecraft has hundreds of millions of players worldwide – many of whom are adolescents. Interestingly, new game features are often created through tinkering and hacking as gamers only have access to a certain repertoire of modifiable game elements – it would be easy to provide numerous examples of how gamers have solved certain problems using improbable combinations of game elements just as evolution through natural selection has stumbled on solutions that would not seem obvious at first glance (Thompson, 2016). The point is, whether we are using Facebook and Instagram to illustrate biological networks, Minecraft to describe evolutionary tinkering or SMS and Twitter spelling to introduce the topic of punctuated equilibrium and neutral drift, we are utilizing what students arrive in biology class already understanding.

Target acquisition versus target exploration

Much of the educational literature on metaphors concerns how metaphors can aid a student in learning a target concept. This perspective on pedagogical metaphor is exemplified by Genter’s original structure-mapping theory, its later instantiations and Glynn’s (1991) Teaching-With-Metaphors framework (Gentner 2002; Gentner and Colhoun, 2010). There is certainly a place for these types of metaphors in biology education. However, there is also a place for metaphors where the pedagogical goal is not a strict alignment between features in a source and target analogue but instead for

students to explore a target phenomenon or a facet of a target phenomenon. To give an example of what I mean by this I have taken an example originally proposed by the evolutionary biologist Richard Lewontin (1991) and recast it as a pedagogical metaphor that could reasonably be included in a textbook.

“You may have heard people in the media talking about the importance of nature and nurture and debating which of the two is more central in how a person develops. You may have heard some people say, “it’s 75% nature” and another person disagreeing, “no, its mostly nurture”. To understand why that approach to understanding development is not helpful to biologists, imagine someone who has never seen a brick house asking you whether the bricks or mortar were more important. You could answer that the house is mostly brick, and some mortar, or that it is about even between bricks and mortar. In doing so, however, what you would be missing is the *pattern* of the house in which each layer of brick *alternates* with a layer of mortar. In the same way, at each point in an organism’s development there is an interaction between the genes and the environment. Biologists seek to understand all of the different *processes* in which genes and the environment interact in the growth of an organism from an embryo to an adult.”

This analogy could undoubtedly be refined further, but the point is the analogy is not attempting to map all of the interactions between genes and the environment through reference to a house. What it is trying to do is show why an attempt to neatly partition the proportion of an organism’s development to nature and nurture is an unhelpful exercise. The analogy stills fulfills the role of making the text friendlier and sets up the content of the section but bypasses the difficult task of crafting an analogy familiar and useful to students that depicts the massive repertoire of gene-environment feedbacks that have been discovered by biologists.

There are many other examples one could provide where metaphors and analogies are orientated towards reflection rather than mapping per se. This is appropriate as there are biological phenomena where it is unlikely for us to ever come up with a good analogy – imagine for instance coming up with an analogy that maps well to the intricacies of

photosynthesis or the Krebs cycle! Additionally, metaphors and analogies can spur debate: To take an example that would be perhaps too contentious for a typical high-school class, Moore and Moore (2013) suggest that efforts to repair damaged ecosystems are like parents who are always intervening to get their kids out of trouble. Although these actions may seem helpful at first, both perpetuate the underlying problem by limiting the immediate experience of consequences and the learning that could have taken place. In the target analogy, if we could really see the damage wrought on nature in our desire to attain cheap energy, we would rethink our resource extraction and energy policies.

Again, the issue is not the correctness or incorrectness of the underlying analogy. The value is that the analogy spurs reflection for students and the reflective process itself is valuable.

Better Metaphors as for Process

One of the criticisms of current biology curricula is that it is heavy on scientific content and light on the discovery process (Duncan, Lubman and Hoskins, 2011). These authors find that the percentage of figures that illustrate a research study is less than 10% and sometimes absent all together in biology textbooks. This is a problem because for most practicing scientists a good understanding of research methods is more important than mastery of the entire biology corpus. This critique dovetails with the subject of metaphors as scientists have suggested, “metaphorical reasoning is at the very core of what scientists do when they design experiments, make discoveries, formulate theories and models, and describe their results to others.” (Brown, 2003 pg. X) This is an argument that gains credence with Dunbar’s (2000) empirical investigations for how

scientists reason and Gentner (2002) and Nersessian's (2008) careful historical analysis of analogical reasoning underlying important discoveries in science. It turns out metaphor and analogy are essential in how scientists propose a new hypothesis to investigate, design an experiment as well as try to understand an unexpected result. These scientists don't compare a cell with a factory, but instead compare known biological phenomena to understand novel phenomena (i.e. "maybe gene X is mediated in the same way as gene Y in suppressing tumors", "maybe gravity operates like light"). To this end, including exercises in analogical reasoning as part of the process of scientific discovery would advance both the goals of incorporating more scientific process in texts and using analogy to foster learning. Although there are hints of this in some of the analogies in the problem sets, what is really required here is either historical or contemporary accounts of discovery in science that relied on analogical reasoning or carefully designed exercises where students are tasked with generating hypotheses on novel phenomena based on extrapolating from prior findings.

Metaphors for Understanding Causality

Grotzer and Basca's (2003) work explores fostering student understanding of causality in ecological concepts. Here it is worth noting that some of the dominant metaphors in the ecology chapters of the textbooks such as "webs", "chains" and "pyramids" that are used to describe predator-prey relationships are static metaphors. The metaphorical target of "webs", "chains" and "pyramids" exist at all points simultaneously whereas their metaphorical targets are non-static and dynamic. This is a case where authors need to simply point out the limitations of the metaphor (e.g. "unlike a spider web, in a food web each strand in the web can influence others over time and be influenced by them. So food webs can also be thought of as ripples made when a rock is

thrown into a small pond where the population size of predators and prey are constantly influencing one another”).

Metaphors for Systems Biology

Imagine someone trying to explain what a basketball is to a person unfamiliar with basketballs. The knowledgeable party begins by saying a basketball is spherical like an orange. Unlike an orange however, it is typically made of leather or synthetic leather, which is a product derived from petroleum. This is the exterior layer of the ball. The next layer is made of rubber - synthetic or naturally derived from the rubber tree (*Hevea brasiliensis*). The ball has 8 major groups of leather created by three lateral and one vertical strand of visible rubber segmenting the ball into 8 patches of roughly equal area.

The ball has a hole in it that can be missed on casual inspection. A needle can be inserted into this hole and air can be added to the basketball under pressure. Typically the balls are inflated to 7.5 and 8.5 pounds per square inch and it is the air pressure that gives it its characteristic shape. When the ball is dropped its potential energy is converted via gravitational force to kinetic energy. The elasticity of the ball (its air pressure and the material properties of rubber) then allows the kinetic energy to be re-converted into potential energy as the ball responds to deformation. Of course, due to sources of friction the ball does not go as high as originally dropped.

As our expert continues to lecture our basketball neophyte on the properties of basketballs, eventually some onlooker familiar with the game of basketball may decide to interject. This newcomer wants to point out that the basketball is an important object in the *game* of basketball and it is hard to really understand a basketball without understanding the game in which it is the primary object. In fact, many of the properties of the basketball can best be understood in reference to the game — grooves in the

basketball are not simply intrinsic characteristics of the basketball with no apparent explanation but make it easier to catch and palm. The air pressure in the ball that is calibrated to 7.5 to 8.5 pounds is optimal for the sport; not so bouncy that it flies off the rim, not so deflated that it is hard to dribble. Even the size of the basketball at 9” diameter is exactly half the size of the diameter of the rim – surely not a coincidence.

In short the new participant to the conversation wants to highlight the relational properties of the basketball – that is, the game in which it is embedded. Whether consciously or not, this person believes that it is only under by understanding this context can a basketball really can be understood.

In biology texts however, most of the metaphors and analogies textbook authors use in describing cells, bacteria, protists and viruses focus on the internal characteristics of these organisms without referencing the microecology. Thus, unlike cells in our bodies that function as part of “a winning baseball team” (ML, 215) bacteria, viruses and protists tend to be loners and metaphorical references highlight internal structural components.

Even in the eukaryotic ‘cell as factory’ analogy discussed at length there is no indication in that very elaborate analogy that the factory exists in relation to other actors in the system. There are no vendors that supply it with parts and there are no customers buying their products. There are no competitors offering the same products or substitute goods, there are no joint ventures, no outsourcing, no mergers and acquisitions. In short, the factory in Miller and Levine seems to operate irrespective of external factors. It produces its products regardless of the environmental situation and is not adaptive to external circumstances. In metaphors for bacteria, protists and viruses as well, unless they are ‘invading’ or ‘attacking’ they are effectively on their own.

Within the main of biology the shift to focusing on relation in the smallest of creatures is now evident in the huge interest and activity in topics such as the human biome and bacterial biofilms, or communities of bacteria that exhibit structure and relationship. These biofilms may not be quite a winning team, but they are certainly a community that exhibits metabolic co-dependence and “resolves the social conflict between cooperation (protection) and competition (starvation) through oscillations” (Liu et al., 2015). Interestingly enough, these communities relational properties help explain why various antibiotics and chemical treatments that can destroy individual bacteria abstracted for experiments often strengthen bacterial communities *in situ* (2015). Thus, there are also pragmatic and clinical reasons to pay attention to relational patterns.

More philosophically, at smaller and smaller levels of phenomena, it would seem that things are equally or even more dependent on relation for existence. The virus is not considered ‘alive’ by the definition of life presented by the textbooks and in the main of biology as it lacks the ability to ‘independently’ reproduce. It remains inert in isolation unless it is coupled with a cell. It may not, when isolated in its own petri dish be considered alive, but it exists as a functioning and sometimes essential component in many living systems. Some of these interactions are not just convenient business relationships that can be easily dropped, but long-term alliances. We can recognize this for well-known symbiotic relationships such as the clown fish and sea anemone that are co-adapted and mutually dependent in multiple ways but sometimes we have a harder time considering the bacteria that colonize our mouths and break down sugar to be

integral to our overall existence.⁸ It turns out the very notion of ‘single celled organisms’ that is so central to the structure of biology texts is likely an inaccuracy. Journal articles on the subject talk about bacterial ‘quorum sensing’, microorganism ‘consortia’ consisting of hundreds of interdependent bacterial and viral species, ‘police’ that enforce rules for the collective to keep ‘cheaters’ in check (Wingreen and Levin, 2006). In short, co-dependence is not the exception as presented; it is the rule.

That this relational necessity persists at smaller levels of phenomena is perhaps part of a paradigm shift that has occurred in biology. At the extreme, despite our best efforts to separate parts out, nature wants to relate and cohere – we can break apart quarks to form mesons, but only for a trillionth of a trillionth of a second before the mesons reform as quarks and the quarks reunite as ‘families’ (Roszak 1999b). Meson bachelors and bachelorettes do not endure in the wild.

In examining the interior workings of a cell students should not lose sight of the fact that cells exist in communities or even societies that exhibit organization, structure and relationship. Going back to the *cell as machine* image of watch gears presented in Glencoe, if you take apart the gears and lay them on the table, little happens save chemical oxidation processes. Should you, in fact, break apart a gear there would be no meaningful sub-structure of the machine itself yet nature seems to showcase organization and structure at every hierarchical level. Thus, a subtle but potentially far-reaching limitation of machine metaphors is that nature may not ever reduce to discrete and independent parts that can be understood separately from one another.

⁸ It has been put forward that because microorganisms have more rapid rates of reproduction, they support fast accommodation of changing environments for their symbiotic hosts (Jablonka, 2014).

Students frequently misunderstand the nested structure of biological systems and hence this is an important topic to incorporate in biology texts (Wilensky and Resnick, 1999). Additionally, an emphasis on systems biology is in keeping with the times: a simple search on Pubmed reveals that articles with ‘systems biology’ in the title now account for over 10,000 published articles a year and more than 90% of the articles on ‘systems biology’ are from the last 10 years.

Although the texts describe how the part can affect the whole they rarely (if ever) illustrate how causal influences can be bi-directional or how any part can be arbitrarily examined as a whole or as a part (i.e. a cell can be part of an organelle as well as the whole of its components). Below is an illustrative analogy for helping students understand the nested nature of biological systems:

You have probably heard local and national politicians giving speeches to their constituents. Local politicians may talk about subjects like priorities for the school board, a new housing project or the need for better bike paths in the community. National politicians may instead be talking about the US economy and how to increase jobs, what to do about the national debt and what the US should be doing to help promote peace in the world. National politicians rarely talk about creating bike paths and local politicians usually don’t talk about trade imbalances with another country. In the same way, when we are studying ecology we mostly discuss organisms and how they interact. We don’t usually discuss an organism’s cellular structure in ecology even though, of course, organisms are made of cells.

The point of the example is to equip students with metacognitive strategies in realizing that they are presently focusing on a particular system level and that the system is connected with other system levels. To take this point one step further ecologists recognize that “interactions among individuals lead to ecosystem-level networks that, in turn, shape community assembly, stability, and robustness (weitz, 2007 pg. 11). To go back to the government analogy, long ago in the past there were no national

governments: yet although national governments emerged from local constituencies they nonetheless shape local politics. Thus, these emergent systems are not simply a passive recipient of local politics but are also able to causally impact their forming constituencies.

Conclusion

The title of my thesis, “the baby and the bathwater” is in reference to the familiar adage about not throwing out the baby with the bathwater or throwing out the good with the bad. I do not believe the solution to problematic metaphors in biology education is to get rid of metaphors and analogies altogether – there are too many good reasons for their inclusion. That metaphors are often seen as primarily textual adornments promoting ‘friendliness’ and hence not given the same level of scrutiny as other parts of the text seems rooted in the idea that metaphors are optional features of language rather than integral phenomena of thinking (Singer, 1986; Gibbs, 1999). As we saw, there are many examples of simplistic metaphors and analogies in the text that have a limited pedagogical function beyond friendliness. If we accept that metaphors structure our thinking and are essential in our learning, we may demand more of our pedagogical metaphors.

I have further argued that a one-size fits-all approach to classifying metaphors and analogies in biology textbooks glosses over the variations in metaphors that escape the coding structure. Not all metaphors and analogies are created equal and a given metaphor’s potential for instructing or misleading students is also not equal. I would suggest the reinforcing metaphors I have identified demand critical review and we get rid of clock and factory metaphors for cells, blueprints for genes and tone down the rhetoric of competition and economic metaphors. There is simply too much historical baggage

with these ideas and they are not in keeping with our current understanding of evolution, genetics and systems biology. Furthermore it is possible some of these metaphors perpetuate an unnecessary reluctance on the part of students and teachers to want to understand the topic of evolution by natural selection and utilize it as a scaffold for other topics in biology.

For metaphors that contain potentially important limitations but aren't so ideologically loaded, there is also an opportunity to return to the metaphors that have been introduced as advanced organizers early in the chapter and have students once again consider the metaphor to help the student consolidate what he or she has learned. Textbook authors can prompt, "At the start of the chapter we introduced the idea of thinking about X as being like Y. Based on what you have learned, can you now think of any ways in which a X is different than a Y?" This approach preserves metaphors as helpful entrées to the subject while prompting students in deconstructing the scaffold to reveal its inevitable limitations. In all of this, we should let go of the laudable but unrealistic goal of always creating an analogy that maps well to a biological target with a complex underlying structure.. Having students become adroit in metaphorical and analogical thinking is likely more important than hunting for perfection in the structural alignment between source and target when the targets are complicated.

In most cases, these recommendations are relatively easy to implement: textbooks get routinely updated and an updating of the corresponding metaphors should be easy. In some cases, the medium of textbooks may be limited for exploring the most interesting analogies and classroom activities and other pedagogical materials may be better vehicles for students to engage with some of these analogies.

As Wittenstein (2010) counseled “Philosophy is the battle against the bewitchment of our intelligence by means of our language” and clearly metaphors and analogies can mislead in overt and subtle ways. Yet, ‘battling’ to eradicate metaphors and analogies in biology may be as misguided as ‘battling’ to eradicate bacteria and viruses in the world; they are here to stay and in classroom settings their use demands our careful and creative attention.

References

- Behe, M. J. (1996). *Darwin's black box: The biochemical challenge to evolution*. Simon and Schuster. Retrieved from Google Scholar.
- Berkman, M. B., and Plutzer, E. (2011a). Defeating creationism in the courtroom, but not in the classroom. *Science*, 331(6016), 404. Retrieved from Google Scholar.
- Berkman, M. B., and Plutzer, E. (2011b). Defeating creationism in the courtroom, but not in the classroom. *Science*, 331(6016), 404. Retrieved from Google Scholar.
- Blanchette, I., and Dunbar, K. (2002). Representational change and analogy: How analogical inferences alter target representations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28(4), 672. doi:10.1037//0278-7393.28.4.672
- Bordon, Y. (2015). Microbiota: A viral understudy for commensal bacteria. *Nature Reviews Immunology*, 15(1), 4-4. Retrieved from Google Scholar.
- Bright, C. (1999). Invasive species: Pathogens of globalization. *Foreign Policy*, 50-64. Retrieved from Google Scholar.
- Brown, T. L. (2003). *Making truth : Metaphor in science*. Urbana: University of Illinois Press.

- Camp, E. (2006). Metaphor in the mind: The cognition of metaphor1. *Philosophy Compass*, 1(2), 154-170. Retrieved from Google Scholar.
- Carson, R. (1962). *Silent spring*. Houghton Mifflin Harcourt. Retrieved from Google Scholar.
- Ciliberti, S., Martin, O. C., and Wagner, A. (2007). Innovation and robustness in complex regulatory gene networks. *Proceedings of the National Academy of Sciences of the United States of America*, 104(34), 13591-6. doi:10.1073/pnas.0705396104
- Dawkins, R. (1996). *River out of eden: A darwinian view of life*. Basic books. Retrieved from Google Scholar.
- Dawkins, R. (1997). *Climbing mount improbable*. WW Norton and Company. Retrieved from Google Scholar.
- Dawkins, R., and Wong, Y. (2005). *The ancestor's tale: A pilgrimage to the dawn of evolution*. Houghton Mifflin Harcourt. Retrieved from Google Scholar.
- Dawkins, R. (2015). *Brief candle in the dark : My life in science*. Retrieved from Library of Congress or OCLC Worldcat.
- Dennett, D. C. (2013). *Intuition pumps and other tools for thinking*. WW Norton and Company. Retrieved from Google Scholar.
- Diamond, J. (1993). *The third chimpanzee*. Harper Perennial Library New York:.. Retrieved from Google Scholar.
- Dijksterhuis, E. J. (1986). *The mechanization of the world picture : Pythagoras to newton*. Princeton, N.J.: Princeton University Press.
- Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science Education*, 75(6), 649-672. doi:10.1002/sci.3730750606

Feynman, R. P., Leighton, R. B., and Sands, M. (2011). *Six easy pieces: Essentials of physics explained by its most brilliant teacher*. Basic Books. Retrieved from Google Scholar.

Forceville, S. (2008). Metaphors in pictures and multimodal representations. In R. Gibbs (Ed.), *The cambridge handbook of metaphor and thought*. Cambridge University Press.

Franke, N., Poetz, M. K., and Schreier, M. (2013). Integrating problem solvers from analogous markets in new product ideation. *Management Science*, 60(4), 1063-1081. Retrieved from Google Scholar.

Gawande, A. (2014). *Being mortal: Medicine and what matters in the end*. Macmillan. Retrieved from Google Scholar.

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science*, 7(2), 155-170. Retrieved from Google Scholar.

Gentner, D., and Markman, A. B. (1997). Structure mapping in analogy and similarity. *American Psychologist*, 52(1), 45. Retrieved from Google Scholar.

Gentner, D. (2002). Analogy in scientific discovery: The case of johannes kepler. In N. Nersessian and L. Magnani (Eds.), *Model-based reasoning: Science, technology, values* (pp. 21-39). New York: Kluwer Academic/Plenum Publisher.

Geary, J. (2011). *I is an other: The secret life of metaphor and how it shapes the way we see the world*. Harper Collins. Retrieved from Google Scholar.

Gentner, D., and Colhoun, J. (2010). Analogical processes in human thinking and learning. In *Towards a theory of thinking* (pp. 35-48). Springer Berlin Heidelberg.

doi:10.1007/978-3-642-03129-8_3

- Gentner, D., and Wolff, P. (2000). Metaphor and knowledge change. In E. Dietrich and A. Markman (Eds.), *Cognitive dynamics: Conceptual change in humans and machines* (pp. 295-342). Mahwah NJ: Lawrence Erlbaum Associates.
- Gillings, M. R. (2012). How evolution generates complexity without design: Language as an instructional metaphor. *Evolution; International Journal of Organic Evolution*, 66(3), 617-22. doi:10.1111/j.1558-5646.2011.01511.x
- Glucksberg, S., and Keysar, B. (1990). Understanding metaphorical comparisons: Beyond similarity. *Psychological Review*, 97(1), 3. Retrieved from Google Scholar
- Glucksberg, S. (2008). How metaphors create categories - quickly. In R. Gibbs (Ed.), *The cambridge handbook of metaphor and thought*. Cambridge University Press.
- Gould, S. J. (1987). *The flamingo's smile: Reflections in natural history*. WW Norton and Company. Retrieved from Google Scholar.
- Grotzer, T. A., and Basca, B. B. (2003). Helping students to grasp the underlying causal structures when learning about ecosystems: How does it impact understanding. *Journal of Biological Education*, 38(1), 16-29. Retrieved from Google Scholar.
- Hawking, S., and Jackson, M. (1993). *A brief history of time*. Dove Audio. Retrieved from Google Scholar.
- Hauser, D. J., and Schwarz, N. (2015). The war on prevention: Bellicose cancer metaphors hurt (some) prevention intentions. *Personality and Social Psychology Bulletin*, 41(1), 66-77. doi:10.1177/0146167214557006
- Hewitt, J. K. (2012). Editorial policy on candidate gene association and candidate gene-environment interaction studies of complex traits. *Behavior Genetics*, 42(1), 1-2. doi:10.1007/s10519-011-9504-z

Hills, D. (2012). *Metaphor*. The Stanford Encyclopedia of Philosophy. Retrieved from <http://plato.stanford.edu/archives/win2012/entries/metaphor/>

Holstermann, N., Ainley, M., Grube, D., Roick, T., and Bögeholz, S. (2012). The specific relationship between disgust and interest: Relevance during biology class dissections and gender differences. *Learning and Instruction*, 22(3), 185-192. Retrieved from Google Scholar.

Jablonka, E., Lamb, M. J., and Zeligowski, A. (2014). *Evolution in four dimensions, revised edition: Genetic, epigenetic, behavioral, and symbolic variation in the history of life*. MIT press. Retrieved from Google Scholar.

Jacob, F. (1977). Evolution and tinkering. Retrieved from Google Scholar.

The Teaching with Analogies Model. (1989). The teaching with analogies model. In K. D. Muth and S. Glynn (Eds.), *Children's comprehension of text : Research into practice*. Newark, Del.: International Reading Association.

Kahneman, D. (2011). *Thinking, fast and slow*. Macmillan. Retrieved from Google Scholar.

Kauffman, S. (2007). Beyond reductionism: Reinventing the sacred. *Zygon*, 42(4).

Keddy, P. A. (2001). *Competition*. Dordrecht: Springer Netherlands : Imprint : Springer. doi:1402002297

Kelemen, D., and Rosset, E. (2009). The human function compunction: Teleological explanation in adults. *Cognition*, 111(1), 138-43. doi:10.1016/j.cognition.2009.01.001

Kelemen, D., Callanan, M. A., Casler, K., and Pérez-Granados, D. R. (2005). Why things happen: Teleological explanation in parent-child conversations. *Developmental Psychology*, 41(1), 251-64. doi:10.1037/0012-1649.41.1.251

- Lakoff, G., and Johnson, M. (2008). *Metaphors we live by*. University of Chicago press. Retrieved from Google Scholar.
- Larson, B. M. (2005). The war of the roses: Demilitarizing invasion biology. *Frontiers in Ecology and the Environment*, 3(9), 495-500. Retrieved from Google Scholar.
- Larson, B. (2011). *Metaphors for environmental sustainability: Redefining our relationship with nature*. Yale University Press. Retrieved from Google Scholar.
- Leonard, T. C. (2008). Richard H. Thaler, Cass R. Sunstein, nudge: Improving decisions about health, wealth, and happiness. *Constitutional Political Economy*, 19(4), 356-360. Retrieved from Google Scholar.
- Lewontin, R. (1996). *Biology as ideology: The doctrine of DNA*. House of Anansi. Retrieved from Google Scholar.
- Liu, J., Prindle, A., Humphries, J., Gabalda-Sagarra, M., Asally, M., Lee, D. D., . . . Süel, G. M. (2015). Metabolic co-dependence gives rise to collective oscillations within biofilms. *Nature*. doi:10.1038/nature14660
- Martin, E. (1991). The egg and the sperm: How science has constructed a romance based on stereotypical male-female roles. *Signs*, 16(3), 485-501. Retrieved from Google Scholar.
- Medawar, P. (1965). Two conceptions of science. Henry Tizard Memorial Lecture.
- Mindell, D. P. (2013). The tree of life: Metaphor, model, and heuristic device. *Syst Biol*, 62(3), 479-89. doi:10.1093/sysbio/sys115
- Moore, K. D., and Moore, J. W. (2013). Ecological restoration and enabling behavior: A new metaphorical lens? *Conservation Letters*, 6(1), 1-5. Retrieved from Google Scholar.

- Nersessian, N. (2008). *Creating scientific concepts*. MIT Press. Retrieved from Google Scholar.
- Newton, L. D. (2003). The occurrence of analogies in elementary school science books. *Instructional Science*, 31(6), 353-375. Retrieved from Google Scholar.
- Olson, E. N. (2002). A genetic blueprint for growth and development of the heart. *Harvey Lectures*, 98, 41-64.
- Oppenheimer, R. (1956). Analogy in science. *American Psychologist*, 11(3), 127.
doi:10.1037/h0046760
- Orgill, M. K., and Bodner, G. M. (2006). An analysis of the effectiveness of analogy use in college-level biochemistry textbooks. *Journal of Research in Science Teaching*, 43(10), 1040-1060. Retrieved from Google Scholar.
- Ortony, A. (1979). Beyond literal similarity. *Psychological Review*, 86(3), 161. Retrieved from Google Scholar.
- Paton, R. C. (1992). Towards a metaphorical biology. *Biology and Philosophy*, 7(3), 279-294. Retrieved from Google Scholar.
- Perkins, D. N., and Grotzer, T. A. (2005). Dimensions of causal understanding: The role of complex causal models in students' understanding of science. *Studies in Science Education*, 41(1), 117-165. Retrieved from Google Scholar.
- Pigliucci, M. (2010). Genotype-phenotype mapping and the end of the 'genes as blueprint' metaphor. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 365(1540), 557-66. doi:10.1098/rstb.2009.0241

Pigliucci, M., and Boudry, M. (2011). Why machine-information metaphors are bad for science and science education. *Science and Education*, 20(5-6), 453-471. Retrieved from Google Scholar.

Pinker, S. (1999). How the mind works. *Annals of the New York Academy of Sciences*, 882(1), 119-127. Retrieved from Google Scholar.

Raymond, C. M., Singh, G. G., Benessaiah, K., Bernhardt, J. R., Levine, J., Nelson, H., . . . Chan, K. M. (2013). Ecosystem services and beyond: Using multiple metaphors to understand human--environment relationships. *BioScience*, 63(7), 536-546. Retrieved from Google Scholar.

Roszak, T. (1999a). *The gendered atom : Reflections on the sexual psychology of science*. Berkeley, Calif.: Conari Press.

Roszak, T. (1999b). *The gendered atom : Reflections on the sexual psychology of science*. Berkeley, Calif.: Conari Press.

Rutherford, A. (2013). *Creation: How science is reinventing life itself*. Penguin. Retrieved from Google Scholar.

Schrödinger, E. (1969). *What is life?: The physical aspect of the living cell*. University Press. Retrieved from Google Scholar.

Searle, J. (1979). *Expression and meaning*. Cambridge England: Cambridge University Press.

Sheldrake, R. (2012). *Science set free: 10 paths to new discovery*. Deepak Chopra. Retrieved from Google Scholar.

Sen, A. (2001). *Development as freedom*. Oxford Paperbacks. Retrieved from Google Scholar.

- Shiva, V. (1998). Reductionist science as epistemological violence. In A. Nandy (Ed.), *Science, hegemony and violence: A requiem for modernity* (pp. 232-256).
- Singer, H. (1986). Friendly texts: Description and criteria. In D. Moore, J. Readence, T. Bean, and E. Dishner (Eds.), *Reading in the content areas: Improving classroom instruction* (pp. 112-128). Dubuque, IA: Kendall/Hunt.
- Stanley, K. O. (2007). Compositional pattern producing networks: A novel abstraction of development. *Genetic Programming and Evolvable Machines*, 8(2), 131-162.
doi:10.1007/s10710-007-9028-8
- Tattersall, G. J., Andrade, D. V., and Abe, A. S. (2009). Heat exchange from the toucan bill reveals a controllable vascular thermal radiator. *Science (New York, N.Y.)*, 325(5939), 468-70. doi:10.1126/science.1175553
- Thibodeau, P. H., and Boroditsky, L. (2011). Metaphors we think with: The role of metaphor in reasoning. *PloS One*, 6(2), e16782. doi:10.1371/journal.pone.0016782
- Topham, J. R. 'Science, natural theology, and evangelicalism in the early nineteenth century: Thomas Chalmers and the evidence controversy', in D. N. Livingstone, D. G. Hart and M. A. Knoll, *Evangelicals and Science in Historical Perspective* (Oxford: 1999), 142–174.
- Thompson, C. (2016, April 14). The minecraft generation. *New York Times*.
- Toulmin, S., and Haken. (1993). From clocks to chaos: Humanizing the mechanistic world-view. In H. Karlqvist and U. Svedin (Eds.), *The machine as metaphor and tool*. Springer.
- West-Eberhard, M. J. (2003). *Developmental plasticity and evolution*. Oxford University Press. Retrieved from Google Scholar.

Vincent, J. F., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., and Pahl, A. K. (2006). Biomimetics: Its practice and theory. *Journal of the Royal Society, Interface / the Royal Society*, 3(9), 471-82. doi:10.1098/rsif.2006.0127

Weingart, P. (1995). Struggle for Existence - Selection and Retention of a Metaphor. In P. Weingart, S. Maasen, and E. Mendelsohn (Eds.), *Biology as Society - Society as Biology: Metaphors. Yearbook Sociology of the Sciences*, (Vol. XIX, pp. 127-151). Dordrecht: Kluwer.

Wilson, E. O. (2012). *The social conquest of earth*. WW Norton and Company. Retrieved from Google Scholar.

Wingreen, N. S., and Levin, S. A. (2006). Cooperation among microorganisms. *PLoS Biology*, 4(9), e299. Retrieved from Google Scholar.

Wittgenstein, L. (2010). *Philosophical investigations*. John Wiley and Sons. Retrieved from Google Scholar.

Woyke, T., and Rubin, E. M. (2014). Evolution. Searching for new branches on the tree of life. *Science (New York, N.Y.)*, 346(6210), 698-9. doi:10.1126/science.1258871

Vita

Luke Shors
4020 Pillsbury Ave, Minneapolis, MN 55409 **lshors@yahoo.com**

Fellow	2012, Harvard University Center for Energy and the Environment
M.E.	2012, Harvard Graduate School of Education
M.P.H.	2005, Johns Hopkins Bloomberg School of Public Health
M.B.A.	2005, Johns Hopkins University
B.A.	2000, University of Iowa

Employment History

2014-Present	Praxik, LLC
2014	AgSolver Inc.
2014	Consultant, The World Bank
2012-2013	Consultant, The World Bank
2012-2013	Consultant, Aflac Insurance
2012	Consultant, Dahlberg - Global Development Advisors
2011-2012	Consultant, Liberian Energy Network
2010-2011	Consultant, OECD
2009-2010	Consultant, The World Bank
2009-2012	Chief Development Officer, Hybrid Power Centers, LLC
2005-2009	Senior Project Specialist, American Institutes for Research
2005	Consultant, The World Bank
2004	Consultant, Erickson Retirement Communities
2003-2004	Consultant, Center for the Assurance of Quality Health
2001-2003	Volunteer, US Peace Corps, Nepal
2000	Assistant Program Coordinator, University of Iowa program in S. India
1996-1998	Laboratory Assistant, Biology Dept., University of Iowa

Co-Founder and SVP Business Development, Praxik, LLC

Praxik is a technology company with offices in Minneapolis, MN and Ames, Ia. We have expertise in geolocation, app design, imaging, computer vision, and 3D modeling. We build custom applications to allow computer systems to gain knowledge of built environments producing useful and actionable information. We rely on inexpensive consumer devices, extending the capabilities of novel technologies such as:

- Microsoft Kinect™ 2.0
- Microsoft HoloLens™
- Google Project Tango™
- Apple iBeacons™
- Lytro™ lightfield cameras
- Occipital Structure Sensor™

These technologies combined with our proprietary software allow one to learn about the physical world. One of our first products enables anyone to take 3D pictures and scans cheaply and easily - generating highly accurate models of spaces that can be analyzed and digitally manipulated on mobile, tablet or web-based environments.

www.praxik.com

Co-Founder and Business Consultant, AgSolver Inc.

AgSolver is a software services company that combines data, models and simulations to create decision-making tools. AgSolver provides a variety of clients with tools to better manage agricultural operations.

www.agsolver.com

Consultant, World Bank (2014)

Developed protocols for case studies to support China's health reforms focusing on integrated primary care and strategic purchase of health services.

Consultant, World Bank (2012-2013)

Supported the World Bank's internal reform initiative under president Jim Yong Kim. The role of the consultancy under the direction of the VP for Change Management was to help in the development of processes and tools to support country engagement in light of World Bank twin focus on elimination of extreme poverty and reduction of poverty (promotion of 'shared prosperity').

A second consultancy involved creating a typology of health systems in the OECD using the WHO's Health Systems in Transition typology as an entry point. After conducting a literature review of comparable health systems, the purpose of the consultancy was to identify approaches for setting priorities in health for Western Balkans nations.

A third consultancy provided guidance to the Western Balkans in designing networks to create a regional initiative promoting inclusive development and employment. Responsibilities have included conducting literature reviews on relative merits of multiple IT platforms (Jive 6, Ning, etc.), interviewing stakeholders, developing surveys and focus group study protocols in consultation with a World Bank team and developing a business action plan.

Consultant, Aflac Insurance (2012-2013)

Developed a proposal on the potential business case for conducting educational seminars on the Patient Protection and Affordable Care Act.

Consultant, Dahlberg - Global Development Advisors

Dahlberg is a global consulting firm with offices in 11 countries. Work included supporting Dahlberg in developing a national school-feeding program in partnership with the Ministry of Education, Cote d'Ivoire.

Consultant, Liberian Energy Network

Less than 2% of Liberians living in rural areas have access to energy. Without a national grid in the foreseeable future, the Liberian Energy Network aims to introduce affordable solar lanterns to the base of the pyramid while simultaneously building and empowering civil society organizations. Work for LEN included developing marketing materials and business plan and identifying potential funders.

Consultant, Organization for Economic Cooperation and Development (2010-2011)

Recent scientific literature points to possibility of "fast action" mitigation strategies that could limit the risk of dangerous anthropogenic interference with the earth's climate system. Work included developing a scoping paper identifying possible avenues for OECD engagement given current institutional landscape.

Consultant, World Bank (2009-2010)

Provided support to the Latin American and Caribbean region in developing a framework for improving knowledge management approaches at the World Bank especially in regard to procedural or tacit knowledge generation and conversion in the health sector.

Chief Development Officer, Hybrid Power Centers, LLC (2009-2012).

Hybrid Power Centers, LLC has patents pending on coupling combustible and non-combustible forms of energy generation to harness synergistic effects that both lower cost of energy production and reduce greenhouse gas emissions. As Chief Development Officer, work included preparing patents, developing presentations, writing proposals for state grants as well as supporting overall strategy development.

Senior Project Specialist, American Institutes for Research

AIR's International Development Program works with a variety of clients including USAID, multi-lateral donors and private foundations. Responsibilities have included:

Project Management and Research

CHANGES2, *Monitoring and Evaluation Specialist (7/05-2009)*. Served as monitoring and evaluation director for a \$30 million-dollar USAID-funded holistic school support program in Zambia. The program had a particular emphasis on HIV/AIDS prevention education and deworming in schools.

UNICEF, *Global Evaluation of Child-Friendly Schools (12/07-6/09)*. Served as a lead evaluator of UNICEF's flagship education program, Child-Friendly Schools. Lead in creating overall research framework, cost analysis and global web-based Delphi-survey of UNICEF officials. Served as field investigator in Thailand and the Philippines.

UNICEF, *Evaluation Specialist (7/07-2/09)*. Served as AIR's lead site-evaluation specialist of UNICEF's efforts to promote life skills in East Asia and the Pacific. Provided technical assistance to East Asian and Pacific countries to develop curriculum standards for Social and Emotional Learning (SEL).

World Bank, *Consultant (7/05-5/08)*. Provided technical assistance to support the World Bank's Latin America and Caribbean (LAC) health unit to understand characteristics of nurse migration from the Caribbean to the US, UK and Canada. The purpose of this research is to use the findings as a basis to develop sustainable solutions to global nursing shortages.

RISE, *Project Manager (10/07-6/08)*. Served as project manager for the \$17.5 million-dollar USAID-funded Revitalizing, Innovating, Strengthening Education (RISE) project which aims to improve education management, quality of classroom teaching and community participation in school management in regions of Kashmir impacted by the 2005 earthquake.

MCM, *Program Coordinator (10/05-2/07)*. Provided technical support to the Malawian NGO Creative Center for Community Mobilization (CRECCOM) in the design and implementation of the Mobilization Corps of Malawi program that is modeled on Teach for America. During the period of involvement the program trained over 100 Malawian youth to live in communities and provide support to students through activities such as peer counseling and establishing reading and sports clubs.

Business Development

Lead or participated in numerous successful grants to the US Government, UNICEF, the World Bank and private foundations. Lead successful effort to win largest UNICEF procurement in education sector (Global Evaluation of Child Friendly Schools). Participated in small team to win USAID's ED-LINKS education program in Pakistan (a \$100 million 5-year grant). Routinely monitored fedbizopps.gov and UN Procurements. Knowledge of Federal Acquisition Regulations.

Other Professional Experience

Consultant, World Bank, Human Resources for Health (2005).

Conducted research on the consequences of fiscal austerity measures promoted by the World Bank and IMF on the distribution of health workers in Tanzania and the constraints of decreased human resources for health in the context of the WHO's effort to scale up antiretroviral distribution for HIV/AIDS.

Consultant, Erickson Retirement Communities (2004)

As a consultant, projects for Erickson Retirement Communities included: (1) Conducting a cost-benefit evaluation of a Center for Medicare and Medicaid Services' care coordination demonstration award; (2) Creating mathematical models to estimate financial risk present in Erickson's insurance model; and (3) Surveying non-residents using conjoint-based analysis to determine market for services and facilities.

Consultant, Center for the Assurance of Quality Health (2003-2004)

The Center for the Assurance of Quality Health holds several US GOV contracts to help disseminate information related to sustainable use of antibiotics. Work included researching and developing web site content for health care providers and consumers on the dangers of antibiotic over-utilization.

Assistant Program Coordinator, University of Iowa (2000-2001)

The University of Iowa operates a study abroad program in South India. As Assistant Program Coordinator, served as a liaison between India's former Director General of Archaeology, the University of Iowa faculty and U of I students in Mysore, India. Responsibilities included providing logistical support for field trips and preparing bi-weekly evaluations for the U of I.

Laboratory Assistant, University of Iowa Department of Biology (1996-1998)

Under the direction of Dr. David Soll, helped to determine gene functionality in white blood cells by examining how mutations to specific gene sequences altered cell motility.

Selected Publications

Kurowski, C. Vujicic, M. Murakami, Y. Ono, T. **Shors, L.** and Caprio, C. *No Island is an Island: The Fragile State of Nursing in the English-Speaking Caribbean* (Submitted to Health Affairs on 1/5/12).

Kurowski, C. Murakami, Y. Ono, T. **Shors, L.** Vujicic, M. Zolfaghari, A. The Nurse Education and Labor Market in the English-Speaking CARICOM: Issues and Options for Reform (2008). World Bank. **Featured in The Economist April 8, 2010.**

Osher, D. Kelly, D. Tolani-Brown, N. **Shors, L.** Chen, C. (2009) UNICEF Child Friendly School Programming: Global Evaluation Final Report. Available at http://www.unicef.org/evaldatabase/index_51289.html

Osher, D. Utne-O'Brien, M. **Shors, L.** (2007). Strengthening Social and Emotional Learning in UNICEF's Child-Friendly Schools in East Asia and the Pacific. UNICEF East Asia and Pacific Region.

Shors, L. Chen, C. Strickland, B. (2006) USAID/Zambia CHANGES2 Program Baseline Assessment. Available for download at the Development Experience Clearinghouse at http://pdf.usaid.gov/pdf_docs/PDAC1932.pdf

Professional Presentations

Shors, L. (2012). The Potential Role of School-Based Interventions in Accelerating the Uptake and Use of Improved Cookstoves in the Developing World. Poster presented at Harvard University Student Research Conference.

Simpson, H. **Shors, L.** Emerson, A. (2007) Engaging Youth in Development: Balancing empowerment and traditional community structures. Paper presented at the Center for International Education Studies Annual Conference.

Other Experience

Teaching Fellow, Harvard Graduate School of Education (2011)

Served as a teaching fellow for the graduate course "International Health and Education". Work included facilitating class discussion and helping in developing curricular materials.

Teaching Assistant, Bloomberg School of Public Health (2004-2005)

Served twice as a teaching assistant for the graduate course "Problem Solving in Public Health" and once for the graduate course "Case Studies in Primary Health Care". Responsibilities included leading small group discussions, grading papers and providing input on curriculum.

Class Mentor, Bloomberg School of Public Health (2004)

Provided mentoring support for foreign students at the school. Liaised with staff to ensure students were referred to the proper resources as appropriate.

Volunteer, US Peace Corps, Nepal (2001-2003)

Served as a water/sanitation coordinator working with the local water sanitation unit in Parsa district and conducted trainings on health and hygiene and the construction of toilets and smokeless stoves for Nepalese health workers, community leaders and women's groups. Additionally, served in the following roles: (1) *Women in Development President*- Coordinated projects benefiting gender equity and awareness. Funded and administered over 700 scholarships for needy girls; (2) *Peace Corps Newsletter Editor-in-Chief*- Edited bi-weekly publication dedicated to the exchange of work related information among 120 volunteers; and (3) *HIV Educator*- Worked with the Australian INGO Center for Harm Reduction on programs targeted towards inter-venous drug users.

Language Skills

Proficient in Nepalese (US State Department Certified 'Advanced Mid') and Hindi, basic skills in Chinese and Kannada.