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CHAPTER 2

Social metaphors in cellular and molecular biology

Theodore L. Brown | University of Illinois, Urbana-Champaign

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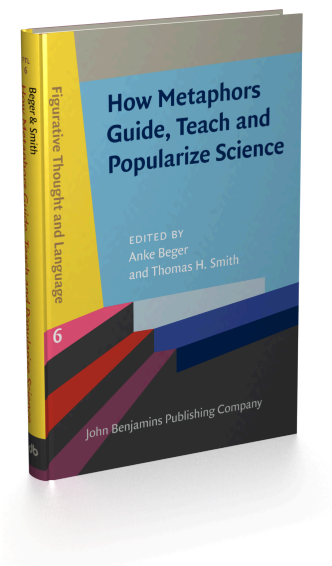

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CHAPTER 2

Social metaphors in cellular and molecular biology

Theodore L. Brown
University of Illinois, Urbana-Champaign

Consistent with conceptual metaphor theory (CMT), metaphor use in biology is characterized by three overarching metaphorical themes: The Semiotic Metaphor, Teleology and Emergence/Supervenience. These themes are applied in analyzing metaphor use in the study of cellular systems. Use of metaphors drawn from social domains is extensive and systematic. In science teaching, attention should be paid to *how* scientists acquire and evaluate new knowledge, and convey new findings. *Abductive inference* as a means of arriving at a best explanation is of great pedagogical value. Abductive inference depends upon metaphors grounded in embodied and social conceptual frameworks. Explicit acknowledgment of metaphorical usage in science teaching illuminates the path from scientific observations toward robust theories.

Keywords: Conceptual Metaphor Theory, Semiotic Metaphor, Teleology, Emergence, complexity theory, supervenience, quorum sensing, deliberate metaphor, abductive inference, inference to the best explanation

Introduction

The fields of cellular and molecular biology are remarkable for the variety and complexity of the metaphors employed as explanatory devices in describing and explaining laboratory results. In the related domains of chemistry and biochemistry, explanatory metaphors are heavily drawn from the physical domains, and based on embodied conceptions of the world. By contrast, we find that in cellular and molecular biology, the explanatory metaphors are often based on experiences in social domains. I aim to show here that these facts are consistent with expectations based on Conceptual Metaphor Theory (CMT) (Lakoff & Johnson, 1980; Kövecses, 2010). As I illustrate in this essay, the uses of social metaphors in cellular and molecular biology are so numerous, interrelated and internally coherent as

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to constitute powerful evidence in their own right for the efficacy of CMT in accounting for metaphor production in this domain of science. To understand why this is the case we must begin with a general consideration of metaphors' roles in scientific practice.

Metaphors are essential features of scientific practice; they are not in the least optional or merely decorative. They permeate all aspects of science, ranging from observation, data acquisition and analysis, hypothesis formation, explanation, experimental design and theory formation to scientific communication at all levels. It behooves us then to ask what purposes they serve in all these varied activities.

Science can be described as the systematic acquisition of knowledge based on experimentation, hypothesis formation and observation. To practice science we must use our senses, and any extensions of them we may contrive in order to enlarge on our observational capacities. Secondly, we must describe and explain what has been observed. In broad terms, a good explanation is capable of accounting for many different phenomena using a restricted number of assertions as to their causes. The sciences involve special vocabularies, but in other respects, the explanatory language that scientists use to talk about their observations is not greatly different from that used in ordinary discourse. Metaphors often serve as explanatory devices in general discourse; similarly, the language of scientists is laden with metaphors.

Conceptual Metaphor theory (CMT) holds that our everyday speech reflects deep-seated conceptual understandings that derive from concrete experiences and feelings. The so-called conventional metaphors with which our everyday language is peppered are reflective both of physical experiences garnered from living in the world, and experiential gestalts that derive from social experiences and understandings.[1]

In their seminal book, *Metaphors We Live By*, George Lakoff and Mark Johnson devote an important section to *Indirect Understanding*.

> [W]e have seen throughout this work that many aspects of our experience cannot be clearly delineated in terms of the naturally emergent dimensions of our experience. This is typically the case for human emotions, abstract concepts, mental activity, time, work, human institutions, social practices, etc. and even for physical objects that have no inherent boundaries or orientations. Though most of these can be *experienced* directly, none of them can be fully comprehended on their own terms. Instead we must understand them in terms of other entities and experiences, typically other *kinds* of entities and experiences
>
> (Lakoff & Johnson, 1980, p. 171).

1. I will not attempt here a review of the theory of Conceptual Metaphor. See Lakoff, G. & Johnson, M. (1980), Kövecses, Z. (2010), and a brief account in Brown, T. L. (2003).

The situation described by Lakoff and Johnson is just the sort that occurs regularly in the everyday work of life scientists as they observe nature, whether it be at the macro level, as in observing the behavior of an animal, or at the micro level, as in following the growth of cell colonies or the changing concentrations of a particular molecule or group of molecules within a cell. CMT is key to understanding how the scientist is thinking; her aim is not merely to describe direct experience, but to provide a causal account of it. The scientist is in this way more or less forced to turn to a metaphorical description, one that gives form and direction to the account by calling upon experiences in domains far removed from the system under investigation. Very often the experiences most apropos are drawn from one or another aspect of human social life. Thus, experiential gestalts are commonly employed (Lakoff, & Johnson, 1980, Chapter 15). The vast number of examples of such metaphors, and the details of these metaphorical mappings in science, represents a powerful argument in support of the tenets of CMT, the most central of which are:

- metaphors are matters of thought, not merely of language.
- we employ inference patterns from one conceptual domain of thought to reason about another domain.
- the systematic correspondences we establish across domains are metaphorical mappings, which are shaped and constrained by our bodily and social experiences in the world.

Conceptual metaphor theory has been spectacularly successful in revealing how a host of abstract ideas dealt with in daily life, such as time, love, inflation or marriage, are conceptualized in terms drawn from our direct physical *and* social experiences. Lakoff and Johnson give the example of how we think and speak about the idea of LOVE:

> Certain concepts are structured almost entirely metaphorically. The concept LOVE, for example, is structured mostly in metaphorical terms: LOVE IS A JOURNEY, LOVE IS A PATIENT, LOVE IS A PHYSICAL FORCE, LOVE IS MADNESS, LOVE IS WAR, etc. (Lakoff & Johnson, 1980: p. 85)[2]

The complexity inherent in a complicated emotion and state of being such as romantic love cannot be captured adequately by the core, subconscious concepts derived solely from direct physical experience. More complex and nuanced conceptual frameworks needed are derived from our ability to recognize *whole patterns* in our experiences of daily life; for example, that of a journey. Two people in love might be spoken of as taking a journey together, one that follows over

2. We adhere to the common convention of using caps to denote conceptual metaphors. They typically apply to a broad range of specific instantiations of the primary metaphor.

time along a certain pathway, in which there might be ups and downs, filled with destinations, and events in which planning ahead might be a good idea, and so on. Thus, our everyday language dealing with romantic love is heavily sprinkled with what Lakoff and Johnson term *conventional metaphors,* examples such as:

> We'll just have to *go* our separate *ways*.
> Those two have *come a long way* together.
> They've been married now for 40 years; at times the *road* has been a bit *bumpy*.
> Our love affair is *on the rocks*.
> This relationship has *gone way off course*.
> I've fallen in love, but we seem to be *going in different directions*.

All of these expressions are instances of conventional metaphors based on the conceptual metaphor, LOVE IS A JOURNEY. The referents for these metaphors are *experiential gestalts*, basic units of perception in which a collection of physical and social experiences together form a set of related elements. Johnson (1987) discusses the *image schema* as a recurring structure arising from cognitive processes which establish patterns of understanding and reasoning. Image schemas are formed by a complex of bodily interactions, linguistic experience, and learned content (ibid.) and often form the basis of more complex conceptual metaphors, such as LOVE IS A JOURNEY, where the PATH-GOAL schema underlies the more elaborate domain JOURNEY. The conceptual metaphor LOVE IS A JOURNEY is more complex than an image schema as it involves mapping aspects of widely experienced experiential gestalts, journeys, which have both physical and social components, onto the intensely social experience of love.

Conventional metaphors that abound in everyday speech are used in science in much the same ways as in other areas of discourse. But, importantly, scientific discourse is permeated with the use of metaphors created to aid in describing and explaining new observations. We begin with a few comments on characteristic features of explanation in biology.

Over-arching metaphors in biology

While biology is the study of living systems, the scientist utilizes knowledge of chemistry and physics to understand any living system. It is important to keep in mind the distinction between a living organism on the one hand, and the interactions of living organisms with inanimate matter on the other. The viability of a biological system depends on appropriate surroundings, and passage of matter and energy across interfaces the system establishes with the surroundings. However, it is not always clear where the boundary for a system of interest should be drawn.

Further, while an entity such as a cell can be said to live, the cell itself is packed with a host of molecules and subsystems that in themselves are not living. We need metaphors to describe the processes that make the cell a living thing that are more complex than we normally require to describe properties of the simpler components that lie within the cell.

Thus, for example, a cell is sometimes described metaphorically as a factory (described in more detail below) (Alberts, 1998; Brown, 2003, Chapter 8). The metaphor engages subsidiary metaphors involving transport, energy, quality control and others that map onto processes occurring within the cell. In this example and in countless others, scientists draw upon experiential gestalts drawn from everyday social life in interpreting what is going on at the molecular level within the cell.

Because of their complexity, the biological sciences present special challenges to anyone who seeks to comprehend the full range and nature of metaphorical usages. It is helpful to keep in mind three fundamental metaphorical constructs that are more or less constant features of scientific thought in this domain:

- The semiotic metaphor
- Teleology
- Emergence and Supervenience

Each of these constructs represents a general conceptual metaphor that is instantiated in a variety of ways, as will be evident in the discussions that follow.

The semiotic metaphor

The language of biological explanation is replete with references to communication, in systems ranging from groups of mammals to colonies of cells. At all levels of scale, for change to proceed in an orderly way, biological systems require communication – some form or other of signaling. Because signaling and communication are important aspects of human cultural life, the metaphors employed in biological explanation draw heavily from social aspects of human culture. For example, at the macro level scientists talk about the mating behaviors of birds in terms borrowed from human relationships. At a different level the social structure of a beehive is understood in terms appropriated from language describing human societies. At the molecular and cellular level we find heavy use of terms such as "the genetic code", "messenger RNA", and "cell signaling". These examples and a host of others fit within the framework of a general *semiotic metaphor*: BIOLOGICAL PROCESSES ARE COMMUNICATION. Not surprisingly, there is a substantial literature dealing with the various ramifications of biological communication; how it can be understood, and how we can talk about it (Emmeche & Hoffmeyer, 1991). I will be discussing several examples in what follows.

Teleology

Teleology, a conceptual metaphor with a long history, is of the form CAUSATION IS ACTION TO ACHIEVE A PURPOSE (Lakoff & Johnson, 1999, p. 217). Both Plato and Aristotle argued for the existence of a telos; that each process or change we see in nature is the result of some entity moving toward a natural end. They did not attribute these ends to some external agency such as a god, nor did they imagine that mental activity is inherent in things. Rather, the end of a thing is internal, a part of its essence. The Aristotelian idea that things have inherent natural ends, which he called final causes, persisted in the writings of medieval scholars. At times, their language was explicitly metaphorical, and even fanciful. The alchemist, for example, might attribute the reaction of an acid with a base to a desire of the two reagents to mate. But Francis Bacon, writing in the early decades of the seventeenth century, advocated an empirical, inductive approach that emphasized experimentation, from which he wished to exclude teleology; that is, any talk of final causes. Analytic philosophy was a dominant current of thought throughout most of the twentieth century, during which time most philosophers of science rejected leanings toward teleological explanations.

Teleology is traditionally thought of as the imputation of purpose and ends to the behavior of entities that we have no reason to expect should be capable of independent volitional action. Though it is a contested notion, teleology has long been a persistent feature of biological explanation (Mayr, 1992; Dawkins, 1986; Allen, 2009). The kinds of purposes we associate with a human's actions are often also attributed to the behaviors of mammals, birds and bees. For example, we talk of a bird pair working together to make a nest *for the purpose* of rearing young. More remarkably, though, *purposeful action* is spoken of as inherent in living organisms at *all* levels, from insects and plants to single-cell organisms. The advent of Darwinism stimulated wide-spread use of teleological language. Statements implying that *nature has goals*, for example, that the behavior of a species is motivated by a *drive for survival*, appear teleological. Darwin was accused of harboring such ideas, though in fact he abandoned literal teleological language soon after concluding that natural selection, blind to any purpose, is the dominant mechanism of evolutionary change. Here is Darwin on the subject in the first edition of *The Origin of Species:*

> [N]atural selection is daily and hourly scrutinizing throughout the world, every variation, even the slightest; rejecting that which is bad, preserving and adding up all that is good, silently and insensibly working … (Darwin, 1859, p. 84)

In later editions of *The Origins* Darwin inserted a prefatory phrase: "It may be metaphorically said …".

Not every philosopher of biology is convinced that teleological explanation is invalid. The philosophical arguments surrounding the status of teleology in natural selection in particular are many and varied (see the following section on Metaphor and Evolution). In what follows it will become clear that teleological forms of explanation are virtually ubiquitous in biological accounts, particularly as they apply to the world of microorganisms and other cellular level processes. Unless the context indicates a literal intent, they can be understood as generally unproblematic examples of conceptual metaphors.

Emergence and Supervenience

From the beginnings of Western science, scientists and philosophers who concerned themselves with living systems puzzled how the special properties of living systems could arise from the inanimate matter that constitutes them. *Vitalism* posited a primitive substance or principle abiding in the organism that guided the vital processes ranging from embryonic development through the life cycle. With the advent of modern science, and most especially from the nineteenth century forward, vitalism gave way to other attempts to account for vital processes in nature in terms of something irreducible. John Stewart Mill, for example, wrote:

> To whatever degree we might imagine our knowledge of the properties of the several ingredients of a living body to be extended and perfected, it is certain that no mere summing up of the separate actions of those elements will ever amount to the action of the living body itself (Mill, 1843, Chapter 6)

Mill was one of the early emergentists, those who believed complex physical and chemical processes could give rise to *emergent* properties not *a priori* predictable from the constituent components, and not reducible to them by the laws of chemistry and physics. From the perspective of CMT, emergence can be thought of as a form of container metaphor, in which new properties emerge in a container that holds (a) the constituent parts of a system, (b) the laws that govern their interactions and (c) just those properties of the constituent parts that are predictable from the laws of chemistry and physics. The emergent system in effect is a new, larger container. To quote John Holland, a contemporary pioneer of emergence theory:

> We are everywhere confronted with emergence in complex adaptive systems – ant colonies, networks of neurons, the immune system, the Internet, and the global economy, to name a few – where the behavior of the whole is much more complex than the behavior of the parts (Holland, 1998, p. 2)

Emergence theory fell out of favor with the advent of neo darwinism, with its emphasis on molecular genetics, which gave rise to strongly reductionist views of biology. It smacked of teleology at a time when any hint of it was regarded unfavorably, of vitalism in disguise. In recent decades, however, the development of complexity theory has given emergence a new lease on life (Deacon, 2013; Holland, 1998; Johnson, 2001; Lineweaver, Davies, & Ruse, 2013).

In complexity theory the dynamic interactions among many parts of a complex system are at times unpredictable, even though the system at all times behaves deterministically. Small changes in initial conditions, for example, may cause large changes in later behavior of the system. As an example, we can understand the physics and chemistry of a tropical storm, but what small, local event sets in motion formation of the storm in the first place, and determines its course?

The tropical storm example illustrates that emergence in complex systems is associated with processes of self-organization. Jeffrey Goldstein refers to emergence as "the arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems." (Goldstein, 1999). Note the use of the word *arising*. Emergence involves the formation of new and more complex properties, which are seen as higher level than those from which they emerge, consistent with the conceptual metaphor MORE ORGANIZED IS HIGHER. Goldstein lists several common characteristics of emergent systems: (1) radical novelty; features not previously observed in the system; (2) coherence or correlation (meaning integrated wholes that maintain themselves over some period of time); (3) presence of a global or macro "level" (i.e., there is some property of wholeness); (4) being the product of a dynamical process (it evolves over time); and (5) being "ostensive" (it can be perceived). In summary, one can state the conceptual metaphor for emergence as: EMERGENCE IS THE APPEARANCE IN A SYSTEM OF COMPLEXITY NOT POSSESSED BY, AND INDEPENDENT OF, THE COMPONENTS FROM WHICH IT IS FORMED.

Finally, the system evinces "supervenience", or downward causation. This means that higher levels of organization act causally on lower levels. The expression "downward causation" provides another example from CMT of an orientational metaphor. Levels of organization are categorized in terms of a vertical structure, with the most general at the highest levels, and supervening on those below it

An example credited to the famous psychobiologist R. W. Sperry, illustrates the foregoing descriptions of emergence and supervenience, albeit with respect to a system that owes its contents and structure to human agency (Sperry, 1991). Imagine a cart wheel rolling downhill. The cart wheel itself has properties emergent on its constituent parts, consisting of the rim, the axle, the spokes and so forth. That is, it owes its characteristic properties as a wheel to the manner in which the constituent parts are organized to make the whole. One can think of the cart wheel as an organization of matter at various levels, ranging at the lowest from the atoms and molecules upward to the parts that are wooden, or metallic. At a higher level, there are the various constituents in their recognizable forms. The highest level for our purposes is the wheel itself, which possesses physical properties that exist just because all the components form an organized whole. Those properties supervene on the lower level properties, in that they determine certain behaviors of the wheel that would not exist were it not for that organization. They are said to exert a "downward causation" on the components. When the wheel rolls down the hill, all of the components and all of the atoms and molecules of the wheel are subject to the event, which is possible only because of the supervening organization.

Metaphor and evolution

There is no subject in modern biology that can be talked about, explored or related to other topics in any depth without reference, direct or indirect, to evolution. The fact of biological evolution permeates all thoughts of biology. Yet, ironically, evolution is not a completely understood and agreed-upon subject, even by those who are steeped in biological understandings, to say nothing of those who view evolution as a challenge to their religious beliefs or cultural inclinations. The divergence of beliefs regarding evolution is evident in differing views of its teleological underpinnings. We could start in many places, but let's begin with someone of recent notoriety. Thomas Nagle is not convinced that there is a purely materialistic, reductionist pathway to eventually understanding what makes human beings thinkers. The blurb on his 2012 book jacket contains this bit of text:

> Since minds are features of biological systems that have developed through evolution, the standard materialist version of evolutionary biology is fundamentally incomplete. And the cosmological history that led to the origin of life and the coming into existence of the conditions for evolution cannot be a merely materialist history, either. An adequate conception of nature would have to explain the appearance in the universe of materially irreducible conscious minds, as such. (Nagle, 2012)

Nagle argues that there is something missing in the conventional model espoused by evolutionary biologists. He hypothesizes a "natural teleology", an internal logic in the world's workings that impels matter from inanimate to living, from simple toward the more complex, from mere chemistry to consciousness. In the short space of 144 pages he doesn't get very far toward explaining what this might be, but it is doubtful that a much longer book would mollify the likes of Richard Dawkins, Steven Pinker or Daniel Dennett, who firmly believe that nature has no goals, direction or inevitable outcome. To a man, they were scornful of Nagle's book, as were most other evolutionary biologists.

The use of teleological language is commonplace in the biological literature. It is tempting to think of evolution as a mechanism, as purposeful. But toward what purpose? Which variations are bad and which good? The criterion of importance for Darwin was fitness for survival. Fast forwarding to the present, in a recent issue of the journal *Science*, A. N. Burdett criticized the following passage from an earlier issue of the journal concerning the iridescent fruit of an herb: "The fruit's dazzling display may have evolved to capitalize on the birds' attraction to sparkly objects, or to trick them into eating something that looks like a blueberry without going to the trouble of actually making juicy flesh" (Burdett, 2012). Burdett pointed out that if our current understanding of biology is correct, nothing evolves to do a specific task; such intimations of purpose are fanciful at best.

It should not be surprising that Darwin and the author of the paper criticized by Burdett resorted to such teleological language; humans have been conditioned throughout evolutionary development to account for things that occur in the world in terms of causal agents. Each of us learns such accounting from our earliest personal experiences and the influences of human culture. Not surprisingly, causation is a key element in CMT. Lakoff and Johnson suggest that causation is best understood as an experiential gestalt, possessing multiple possible features and common to all human experience (Lakoff & Johnson, 1980, Chapter 14). Isn't it to be expected that natural selection might be interpreted in terms of progression toward some goal? As Bernd Rosslenbroich explains, it is difficult to expunge from the language of evolutionary biology terms that smack of "progress" (Rosslenbroich, 2006).

Many scientists interested in complexity theory believe that there exist natural processes that inevitably move nature toward more complex, self-sustaining reactions that in turn convert more primitive raw materials into increasingly complex structures. Stuart Kauffman aims to show that the transition from mere chemistry to something self-sustaining in its interactions with the surroundings is possible and in fact inevitable. He contends that complexity itself triggers self-organization, or what he calls "order for free". The operative conceptual metaphor is COMPLEXITY IS SPONTANEOUS MOVEMENT TOWARD SELF-ORGANIZATION. He argues that if enough different molecules pass a certain threshold of complexity, they begin to self-organize into a new entity – a living cell (Kauffman, 1996). Available energy, be it sunlight, thermal energy of the surroundings or some chemical process, drives simpler structures toward more complex ones.

In complexity theory there is no purpose or intent involved, no goal-directed activity. Self-organization just happens, consistently with the laws of physics and chemistry. But the metaphorical language employed in complexity theory as it applies to biology is imbued with sensibilities of progress, improvement and attainment of "higher" order, because that is the way we have learned to view the world. Metaphors frame the world in "as though" terms. In complexity theory it is "as though" there were a purposeful drive toward higher order. The theory is a prime example of how teleology works: self-organization is the result of random processes but we are conditioned by our evolutionary development to view change in terms of entrenched conceptual metaphors such as PROGRESS IS A JOURNEY AND CAUSATION IS PURPOSEFUL.

Social metaphors in biology

Social metaphors of the sort exemplified by a conceptual metaphor such as LOVE IS A JOURNEY are commonplace in biology because the subjects of study are so often diverse and complex. A rigorously reductionist approach cannot yield an adequate description of even the simplest organisms. The interactions between all the molecular-level components of even a single-cell organism are vast in number, and intertwined in ways that give rise to signature emergent properties not attributable to any particular piece of the whole. Modeling a biological system from a reductionist perspective, solely in terms of molecular level physical and chemical processes, would limit the scientist to a set of conceptual metaphors based upon embodied experiences with the physical world. But that metaphorical repertoire does not provide a sufficiently broad framework for understanding the ways in which the system's multiple components interrelate. To grasp the complexity of biological systems, the scientist is moved to employ metaphorical concepts commensurate with that complexity. These are found among experiential gestalts formed from everyday life experiences in the social world.

We are not surprised to find social metaphors regularly appearing in hypotheses and theories relating to the behaviors of creatures such as squirrels and birds. One can also imagine that the "waggle dance" of forager honeybees is a means of communicating between colony mates, or that worker ants communicate with, or induce behaviors in one another in various ways. It is less obvious that the properties of bacterial colonies observed through a microscope, or the plaque that forms on human teeth, or the film that repeatedly forms around the drain in a kitchen sink should bring to mind a social activity. Yet remarkably, metaphorical language couched in terms of social behavior observed in human society is ubiquitous in scientific literature dealing with the microbial fauna responsible for these processes. To provide an adequate understanding of these metaphors, we must know something about the properties of cells.

Cellular systems

Cells, as living entities, can be considered in terms of three broad categories: *structure*, *processes* and *communication*. Scientists reason about each of these aspects in terms of distinct sets of metaphors. In the domain of *structure*, the cell has a distinct boundary, defined by the cell membrane, and a variety of parts and internal structural elements. The metaphors employed in assigning functional roles to these structural elements are drawn from macroscopic experiences with structured entities such as walls, supporting structures such as pillars, containers of varying shapes, and so on.

Cellular *processes* involve a host of chemical reactions and coordinated movements. Some processes are continuous, others are turned on and off at appropriate stages in the life of the cell. Many occur entirely within the cell, others involve movements of materials through the cell wall. I have written elsewhere about the kinds of metaphors employed in conceptualizing and describing cellular processes (Brown, 2003, Chapter 8). Picturing the cell as a factory is a popular pedagogical device (for example, Cell as a Factory, 2015). Multiple input and output processes occur, raw materials are consumed, products are formed, quality control measures are exercised, and materials are transported from one place to another. The factory metaphor is not merely occasional bits of colorful language; it and similar metaphors constitute the lingua franca of cellular biology as pedagogical devices and in describing novel research results. To illustrate, the term "protein quality control in cells", which appeared in the scientific literature for the first time only in 1989, is now a commonplace. An internet search using the phrase as a search term yields upwards of twenty million results. It is important to emphasize that this metaphor has not thereby become "dead" in the literary sense. Productive scientific metaphors grow in usage as elaborations are added and experimental evidence leads to new instances in which the metaphor operates. Thus, it is continually being evaluated and reinterpreted in light of new observational results.

The third, and for our present interests most important, facet of cellular life is *communication*. Cells, of whatever kind, normally do not exist in isolation. Many of the processes that constitute the life of the cell occur in response to changes within the cell or outside in the surrounding medium. Cells affect one another by releasing chemicals into their environments, to be detected by other cells in the vicinity, or through detection of molecules in their environments. Such processes, involving small molecules such as hormones, are recognized as a form of intercellular communication, referred to as *cell signaling*.

As a productive general metaphor, cell signaling entails many questions that call for further experimentation. For example, if the communication involves release and detection of a small molecule, what key properties must the "messenger" molecule possess? What triggers its release? How is it detected by the receiving entity? What processes are involved in converting the signal represented by the messenger molecule into a particular kind of signal that has consequences inside the cell? In work for which he received the Nobel Prize in Physiology or Medicine in 1971, Earl Sutherland showed that communication *between* cells involves a molecule ("the first messenger") that is converted to a second signaling molecule that acts *inside* the cell ("the second messenger"). That very productive metaphorical model inspired the 1994 Nobel Prize winning discovery by Alfred Gilman and Martin Rodbell of a special group of proteins, called G-proteins, that act as signal transducers. They convert the first messenger signal at the cell surface into a second messenger signal inside the cell.

Cell signaling has become an important subject within molecular and cellular biology. In a myriad of contexts, scientists draw upon their knowledge of the macroscopic world of communication to explain aspects of the microscopic biological world. I want to focus here on a particularly illustrative case: the metaphors for communication between bacterial cells.

Bacteria

It has been only within the past few decades that humankind has become aware that microbes too small to be seen with the naked eye are everywhere about us. As Bonnie Bassler writes,

> They include archaea, fungi and protists, but overwhelmingly they are bacteria. For billions of years these invisible critters, our forefathers, have been shaping the Earth and making it a suitable place for us to live. Higher organisms – all plants, invertebrates (including insects), and vertebrates (including humans) – occupy only a sliver of the world. (Bassler, 2012, p. 67)

Bacteria are single-celled organisms of a particular kind called prokaryotic, which denotes that they do not contain a nucleus. By contrast, the cells of all multicellular organisms, the plants, animals and fungi, do contain a nucleus and are termed eukaryotic. The prokaryotes are much older in evolutionary terms than the eukaryotes. They have had to survive great changes in the planetary environment during their long existence (Woese, 1987).

Bacteria are typically only a few micrometers in length; ten thousand of them side by side might form a line about an inch in length. They were first observed by the Dutch microscopist Antonie van Leeuwenhoek in 1676, using a single-lens microscope of his own invention. During the nineteenth century Louis Pasteur, Robert Koch and others demonstrated that pathogenic bacteria were the causes of many diseases. There ensued a prolonged war against bacterial pathogens which continues unabated to this day.

What was lost sight of in the focus on bacteria as pathogens is that an enormously varied and numerous world of microorganisms, mostly bacteria, pervades the entire planet, far outnumbering all other forms of life. Bacteria provide essential functions to every other species. They have made themselves at home in every niche in nature, from the deepest oceans to the hot geysers of Yellowstone National Park. Water from Lake Whillans, which lies more than 2,000 feet below the West Antarctic Ice Sheet, recently was found to harbor abundant microbial life. Each human body contains within and on it ten times more microbial cells of many different kinds than human cells. There are thousands of different species of bacteria in the human gut, and about 700 in the human mouth.

Altogether these various microbial species constitute the *human microbiome* (Buckman, 2003; Institute of Medicine, 2013). Microbes, mostly bacterial, pervade every surface and cavity of our body, and are highly specialized in terms of their interactions with our human cells. For the most part, they are benign, serving a multitude of functions essential to our lives.

How do these simple single-cell organisms thrive in all these different environments, and exhibit capacities that one would expect only from more complex, multicellular organisms? As it turns out, the answers all tie to communication.

Quorum sensing

J. Woodland Hastings, an outstanding Harvard biochemist who died in 2014, devoted most of his scientific career to the study of *bioluminescence*, the emission of visible light, by creatures such as fireflies, jellyfish and bacteria. During the 1960s, Hastings and a coworker, Ken Nealson, studied a bioluminescent marine bacterium, *Alivibrio fischeri*, that floats freely in the ocean. In these circumstances, the bacteria do not emit a characteristic glow. However, in the shallow waters off the Hawaiian Islands they exist in a symbiotic relationship with the Hawaiian Bobtail Squid, *Euprymna scolopes*, which live in those waters. The Bobtail Squid has a special light organ in its mantle. Each evening the squid selectively takes *A. fischeri* into its light-producing organ, and in the process, their concentration is much increased. When the concentration has reached a certain critical level, the bacteria collectively emit a luminescent glow. But how could these simple, single-cell organisms sense when there is a sufficient concentration of their fellows in the surroundings for them to collectively begin to glow with a discernible brightness?

Hastings and Nealson postulated that individual bacteria continuously release a signaling substance into the surrounding medium (Nealson, Platt, & Hastings, 1970). When the concentration of bacteria grows larger, the concentration of the signaling substance in their environment also increases. They further postulated that the bacteria not only release the signaling substance, they also individually detect it. When the bacteria concentrated within the squid's light-producing organ detect that the concentration of the signaling substance in the organ has surpassed a certain threshold value, they collectively and simultaneously commence luminescing. The mechanism of communication between bacterial cells postulated by Hastings and Nealson that triggers luminescence eventually came to be called *quorum sensing*.

The quorum is a social construct with a long history in western culture. It can be roughly defined as the minimum number of members of a deliberative body necessary to conduct business. The most common rationale for a quorum is to prevent an unrepresentative action taken at the behest of an unduly small number of persons. Assuming the criteria are agreed upon, ascertainment of a quorum proceeds by a counting of persons and comparison with the number required, as set by the rules. Nealson, Platt and Hastings reasoned that the quorum criterion is necessary for *A. fischeri* because bioluminescence consumes considerable energy in each cell to generate the luminescent reaction. That energy would be wasted if the concentration of the bacteria were not high enough to produce sufficient overall brightness, determined by the needs of the host squid.

The quorum sensing proposal is a remarkable example of mapping what is arguably a fairly complex human social behavior onto a biological system. It could be stated as a conceptual metaphor of the form A COLONY OF *A. FISCHERI* IS A DELIBERATIVE BODY OF PEOPLE. Initially the model was widely thought to be too complex for the likes of a single cell organism. In spite of widespread skepticism, however, it prompted a search for the presumed messenger, or *autoinducer*, molecule. Ten years after Hastings and coworkers' initial proposal, the autoinducer through which *A. fischeri* communicate via quorum sensing was identified. The relationship between *A.Fischeri* and the Hawaiian Bobtail Squid is an example of *symbiosis*, defined loosely as a close and usually long term interaction between two unlike biological species. Most frequently, the interaction is mutualistic; that is, it is beneficial to both species, though in different ways. Application of the term symbiosis in biology is metaphorical; the word was first used in reference to people living together communally. Its use in the biological context is yet another example of metaphors drawn from the social domain that are mapped onto observations in the microscopic world.

The power of a conceptual metaphor is that it provides a model from which one can draw inferences. These in turn set the scientist in search of answers to new questions. For example, what advantages accrue to the bacteria by residence in the light-producing organ of the squid? One possible answer is, they get fed. Prompted by the metaphorical model the scientist can search out the pathways and details of how the squid provides metabolic energy for the bacteria in the light organ. But what in this arrangement works to the benefit of the squid? The metaphor of symbiosis leads the scientist to reason that the luminescence provides protection from predators. Detailed studies have revealed that when the bacteria luminesce during the night, while the squid are active, their emitted light, radiated downwards, matches the moonlight level, and thus masks the squid's shadow from predators and prey, which lie below. The symbiotic relationship between *A.Fischeri* and the squid is a product of many evolutionary adaptations. The model that neatly accounts for all of the observations together is a beautifully coherent collection of social metaphors.

For nearly twenty years the system of *A. fischeri* and its interactions with the Hawaiian Bobtail Squib, and one or two others, were regarded as rare examples of quorum sensing. More recently it has become clear that quorum sensing is a fundamental feature of the microbial world (Antunes & Ferriera, 2009; Bassler & Losick, 2006; Gray, 1997; Greenberg, 1997; Lerat & Moran, 2004). We know now that it is the single most powerful tool that enables bacteria to rise above their status as single cell organisms and develop a broad repertoire of behaviors. The language scientists use to describe quorum sensing, and multiple embellishments of the initial idea, is rich in metaphors dealing with communication, but it also incorporates other concepts drawn from human social behavior, such as "public goods", "cooperativity", "cheating" and "vigilance" (Drescher, Nadell, Stone, Wingren, & Bassler, 2014). To illustrate the range and importance of the metaphors employed, I discuss two quite striking examples of quorum sensing. But first, we need to see how cooperation is understood to work in cellular and molecular systems.

Cooperation

The concept of cooperation is central to understanding the behaviors of biological systems at all levels, from assemblies of single cell organisms to human societies. As applied to human behavior the standard dictionary definition might be: Cooperation is common effort or the association of persons for common benefit. Cooperation can be viewed also in the world of plants and microscopic organisms, as via the conceptual metaphor CONCERTED CAUSAL ACTION IS COOPERATION. Consider an example from the world of plants in which the components are as devoid of conscious intent or purpose as could be imagined (Denison & Muller, 2016).

Most plant species depend on bacteria called rhizobia that grow symbiotically as nodules on the plant's roots. The rhizobia help the plant acquire nutrients, such as phosphorus and nitrogen, which it would not otherwise be able to assimilate. The plant-rhizobium relationship is symbiotic, in that the rhizobia depend on the plant to provide energy-rich molecules they need to grow and reproduce, and the rhizobia supply the plant with otherwise inaccessible minerals: a clear case of cooperation (Tiers, Rousseau, West, & Denison, 2003).

Although the word symbiosis, derived from the Greek language, means to live together, in biology symbiosis usually is taken to mean something more: a relationship of mutual benefit or dependence. We humans tend to think of such relationships in teleological terms. It turns out that each plant hosts several different strains of rhizobia as nodules on its roots. Each strain divides its resources between supporting its own reproduction and contributing to the "public good" of host-plant vitality.

This sets up the possibility that a particular strain of rhizobia could "cheat", by diverting excessive resources to its own reproduction, and thus outcompete other strains. This is where the concept of supervenience comes into play. Experimental studies have demonstrated that plants have evolved ways to prevent this sort of one-way resource grab. They can shut off the oxygen supply to that nodule, and thus limit its capacity to reproduce. That is to say, plants can supervene on their bacterial symbionts by sensing the activities of the bacteria. They can "impose sanctions" by limiting the supply of energy in the form of molecular food to nodules that supply them with insufficient nutrients.

The following sentences from the abstract of a paper by Tiers and colleagues illustrate the pervasiveness of conceptual metaphors such as: EXCESS CONSUMPTION OF RESOURCES BY A SYMBIONT IS CHEATING and HOST RESPONSE TO NUTRIENT LOSS IS PENALIZING CHEATERS. Note also that the abstract supplies several examples of supervenience, in the form of metaphorically PURPOSEFUL ACTIONS: monitoring, penalizing, and stabilizing:

> Explaining mutualistic cooperation between species remains one of the greatest problems for evolutionary biology. Why do symbionts provide costly services to a host, indirectly benefiting competitors sharing the same individual host? Host monitoring of symbiont performance and the imposition of sanctions on 'cheats' could stabilize mutualism. Here we show that soybeans penalize rhizobia that fail to fix N_2 inside their root nodules. (Tiers, Rousseau, West, & Denison, 2003)

This passage is illustrative of the three central tenets of CMT mentioned in the introduction:

- Metaphors are matters of thought, not merely of language
- We employ inference patterns from one conceptual domain of thought to reason about another domain.

– The systematic correspondences we establish across domains are metaphorical mappings, which are shaped and constrained by our bodily and social experiences in the world.

The examples that follow provide further support these tenets of CMT in diverse biological systems.

Virulence

From an evolutionary perspective, quorum sensing ensures that certain essential functions are executed when and only when the colony has reached an appropriate number. This process enables the very small and vulnerable bacterial cells to amass sufficient capacity and protection. By acting in concert under the influence of quorum sensing the bacterial colony takes on capacities of a larger, more complex entity. A striking example of this is *virulence*.

It is common to use the conceptual metaphor OVERCOMING ILLNESS IS WARFARE in talking about illnesses, ranging from head colds to cancer or Alzheimer's. Thus, a sick person is "battling a bad cold" or "fighting a losing battle against lung cancer". In the same way, harmful microscopic organisms, such as a flu virus or streptococcus bacterial infection are conceptualized as enemies that invade the body, to be killed with agents such as antiviral agents or antibiotics. The invasive agents may be understood metaphorically as employing warfare tactics, such as camouflage, mounting protective armor, or evading contact with the drug.

The term virulence in relation to bacteria denotes a dangerous, potentially deadly agent capable of spreading quickly. When a particular bacterium invades a human body, it may initially lack the numbers to cause significant damage to the host. However by multiplying in the usual way without releasing any damaging virulence factors, a substantial bacterial colony eventually forms. At an appropriate stage of colony growth, as determined by a quorum sensing mechanism, the hitherto inoffensive bacteria simultaneously release one or more virulence factors, so-called effector proteins, through a special secretion system. These proteins are sufficiently abundant to overwhelm the host's defenses, by binding to host antibodies or through some other mechanism. The invading bacterium is thus able to multiply rapidly, and the characteristic symptoms of a proliferating infection set in. For example, the bacterium *Staphylococcus aureus* is a member of the human microbiota, found in approximately 30 percent of the human population. Although this widespread distribution suggests that it is innocuous in humans, *S. aureus* is a very dangerous opportunistic pathogen, one that has become associated with antibiotic resistance. But it becomes virulent only under certain conditions, utilizing one or more quorum sensing systems that eventually activate a set of virulence genes (Antunes, Ferriera, Buckner, & Finlay, 2010).

Scientists studying virulence in a wide range of bacterial systems have learned that it involves many related processes (National Academies Press, 2012). In some cases, invading bacteria produce a fractional mutant version that lacks a typical full virulence. The mutant cells do not pay the full metabolic costs of generating the virulence factor, yet they nevertheless share in the benefits of the virulence factors released by the other bacteria. Here again, in explaining such systems, scientists have labeled the mutant forms metaphorically, as "cheaters"; they benefit from the "public good" provided by the "cooperators" without paying their way. Other variants of this kind of explanatory language have been observed. They illustrate the ways in which the behaviors of microscopic systems are metaphorically conceptualized in terms of social roles drawn from the familiar everyday world. Matters are frequently made more complex by the fact that the cellular medium is populated with many different species of bacteria and other active molecular species. Survival depends on being able to communicate in different ways with cooperating and non-cooperating others, and behave accordingly. Scientists employ a variety of social metaphors in building explanatory models that reflect these complex bacterial colonies.

Biofilms

Anyone who has visited a dental office to have their teeth cleaned has experienced the consequences of biofilm formation. A major task of the dental hygienist is to remove accumulated dental plaque. This hard, complex polymeric material on teeth is a protective mantle for many layers of bacteria. The bacteria opportunistically take advantage of the nutrients available in the mouth, but are typically not pathogenic strains. The first colonizers in forming a dental plaque exploit substances in saliva that allow them to adhere to the tooth surface. These early colonizers emit substances enabling other bacteria to adhere to the first layers. At some point, a quorum sensing process comes into play. When a sufficient collection of cells is present, as detected through inter-cell communication, some or all of the bacterial cells simultaneously release a variety of chemicals that combine with other substances from the immediate environment to form a polymeric matrix that covers all the cells and acts as a shield. The matrix begins to harden after about 48 hours. After several days, it has become tartar, a hard material that is difficult to remove. While the bacteria living in the plaque don't generally produce toxic substances, they lead to acid formation through their consumption of fermentable sugars in the mouth, thus contributing to tooth decay. Plaque can also contribute to gum disease.

Dental plaque is but one of many examples of biofilms, complex aggregations usually made up of multiple bacterial species. They thrive on nearly every surface, from kitchen sinks to doorknobs to the linings of our stomachs and the surfaces of hip replacements. Depending on their location, the biofilms protect the bacteria from ultraviolet radiation, dehydration, cleansing agents and toxins such as antibiotics. Biofilms can contain many species of infectious strains of bacteria that are serious problems in medical settings - for example on the surfaces of implanted medical devices, or in the respiratory system. Biofilms are organized in much the manner of a human community, with individual species (metaphorically) taking on particular tasks. The environment surrounding each cell therefore contains a great variety of signaling (autoinducer) molecules. Some are specific to an individual species, others are involved in interspecies signaling. The following passage, like many others in the scientific literature, reveals the extent to which scientists conceptualize processes in the bacterial world in terms of experiential gestalts of considerable complexity drawn from the social world:

> Every quorum-sensing bacterium has multiple quorum-sensing circuits. That is, bacteria are multilingual, and they converse using a rich chemical lexicon. Beyond simply counting, bacteria use different quorum-sensing molecules to distinguish between self and non-self, and they decode blends of autoinducer molecules to extract information about the ratio of different species present.[B]acteria employ a chemical vocabulary composed of molecules that identify self, non-self but closely related, and non-related. In essence they can determine "you are my sibling", or "you are my cousin", or "you are not family." (Bassler, 2012)

Notice in these descriptions of bacterial systems two important threads drawn from our prior discussions: (a) There are multiple examples of the semiotic metaphor; communication is ubiquitous; (b) New properties emerge from the behaviors of the simplest assemblies of bacteria as they communicate, form new structures, and through interactions with other species generate still higher levels of organization with new properties. Emergence / supervenience is a powerful metaphor that organizes the scientist's understanding of a complex system in terms of simpler constituents.

The social conceptual frames I have described, and many others like them, are not the detailed content of the scientist's understanding of the biology involved, but rather provide a general framework for understanding and generating hypotheses. The goals of research in this area are to understand bacterial behaviors in terms of molecular components and microscopic level constructions. Thus, for example, scientists strive to know the molecular structures of the autoinducer molecules, and to understand how variations in their structures arise and govern cellular responses. One might therefore think of the social metaphors as overarching representations of how the molecular-level processes are governed and relate to one another. They provide essential high level interpretive views of what may be going on in the system, as it seems to the scientist. Most importantly, the metaphorical representations inspire and guide searches for the cellular and molecular actors.

We can see in the examples presented how the three meta-metaphors alluded to earlier (the semiotic metaphor, teleology, and emergence/supervenience) encompass the gamut of metaphors in biology. The semiotic metaphor is obviously the overarching concept in quorum sensing. It is at work also in helping the scientist understand interspecies communication. Teleological language is commonplace throughout the examples I have cited. Emergence is seen in the idea that collectives of simpler entities – from flocks of birds and beehives to bacterial colonies – possess emergent properties not possessed by individuals. Supervenience is evident in the ways in which the behaviors of individuals in collectives are constrained in highly structured ways. The systematicity of the metaphors encountered, their evident origins in experiential gestalts from the social lives of scientists, and their efficacy in generating productive new directions for research, are all accounted for by CMT, and provide strong support for the theory.

The explanatory language used in biology is consistent with the idea that a conceptual understanding of the natural world is the product of both embodied and social experience. However "right" any explanation may seem once established, no single metaphor or collection of them can be an objective representation of "truth" in science. The success of CMT in accounting for scientific explanation enlightens us about our human capacities for understanding the natural world. But we see also that our capacities are limited by the conceptual frameworks possible given our embodied experiences in the physical world together with experiential gestalts derived from our personal and cultural lives.

Conceptual metaphors, abduction and science education

Science educators are perennially concerned with the most effective methods for imparting information about the natural world. Much of the discussion has to do with specifics of what *content* should be taught in any particular discipline. Too often, however science educators fail to address questions of how scientists acquire new knowledge, and the means by which new scientific findings are disseminated, evaluated and eventually accepted or rejected by other scientists. The roles of metaphorical thought are often neglected altogether, as are the processes by which judgments are made regarding new hypotheses and models. Students are left without a sense of how to judge the reliability of scientific claims.

There is no general agreement on a single best way to study the natural world. The objects of study vary greatly and the tools available are variable and subject to continual change. Philosophers of science have attempted to define rules and criteria that can best ensure that the conclusions reached through processes of data-gathering, analysis and reasoning lead to the best possible account of nature, an account that comes as close as possible to "true". Although he is seldom given credit for it, Charles S. Peirce (1857–1914), an American scientist and philosopher, proposed an internally self-consistent approach sometimes referred to as the Pragmatic Theory of Truth. Peirce was a remarkable, brilliant and strange person. Over his lifetime he made important contributions to logic (his major interest), chemistry and other physical sciences, economics, and a broad range of topics in the social sciences. He is considered the father of Pragmatism, a distinctly American contribution to philosophy. However, Peirce was eccentric and difficult, with the result that he was underappreciated during his lifetime. A great deal of his voluminous writing was lost or is only now being discovered (Burch, 2014).

A coherent explanation of any observation of the natural world can result only from a process of inferential reasoning. The three widely recognized forms of inference are deductive, inductive and abductive. Because Peirce was passionately interested in logic, he began by considering how these three recognized forms of argument might be coherently related in an integrated methodology. In deductive reasoning, a conclusion formed from a set of premises is *necessarily* true if the premises on which it is based are true. For example: All kangaroos are marsupials. X is a kangaroo. Therefore X is a marsupial. Ordinarily when searching for explanations, it is rarely the case that the working premises can be assumed to be necessarily true. Inferences made are therefore most usually non-necessary.

The two commonly recognized forms of non-necessary inference are induction and abduction. Peirce is generally credited with recognizing abduction as an important form of reasoning (Douven, 2011). *Inductive* inferences commonly depend on statistical data, such as the observed frequencies of occurrence of a particular feature in a given population. For example, all morbidly obese mice in a given laboratory population being studied are found to host a particular gut microbiome Y. Mouse X is morbidly obese. Therefore, mouse X hosts gut microbiome Y. The inference might not be completely logical – that is, not admitting of any other conclusion. Nonetheless, under the conditions of the experiment it is highly likely to be true. In inductive inference, the basis is normally statistical. If all the swans you or anyone you know have ever observed are white, it is reasonable to infer that all swans are white.

Abductive inference, while similar to inductive inference, differs in its underlying rationale. The emphasis is on what provides *the best explanation for the observations*. In Peirce's framework, the scientific method begins with the formation of some sort of conjecture, or hypothesis, that might account for a phenomenon or set of data. The reasoning goes that if the hypothesis is true, then the phenomenon or set of data are what we would expect to find. According to Peirce, if the abductive hypothesis passes muster, the next stage in the investigation is to employ deductive reasoning, to deduce other observable phenomena or data that should follow logically. If the second stage is successful, further and more detailed hypotheses are advanced and tested. If not, the hypotheses are modified in light of new evidence, and a loop of inferences and testing ensues. Peirce argued that the overall procedure is a form of inductive inference, in which we take the ability of the hypotheses to explain the accumulated evidence as a measure of their correctness. The process is commonly referred to as *Inference to the Best Explanation* (Lipton, 2000). Conceptual metaphors are at the heart of this, because the hypotheses or conjectures advanced are based on embodied conceptual understanding of the natural world, or concepts grounded in experiential gestalts.

Hastings and Nealson's explanation for how *A.fischeri* bacteria come to the point of luminescing in the mantle of the Hawaiian bobtail shrimp provides an illustration. Based on their observations, they formulated the hypothesis that there is a particular small molecule present in the solution containing the bacteria. When its concentration reaches a certain level, the bacteria simultaneously express genes that result in luminescence from every cell. This hypothesis, named quorum sensing, is explanatory and predictive. The abductive inference in this case is just this: If the hypothesis is true, we should be able to find the small molecule, the autoinducer, that evokes the collective response of the bacteria. The abductive inference sends the scientist in search of the elusive autoinducer, of which, up to that point, no one had an inkling. If the predictions of the quorum sensing hypothesis are found to reliably match observations, the truth value of the model is increased. Further questions and predictions arise as guided observations accumulate.

Educating students about science often consists in imposing upon them memorization of a great many facts, names and processes. Important as this may be in producing "literacy" in a particular science, the more important thing to teach students about science in general is how scientists come to possess reliable knowledge. There is no single pathway to such knowledge. Peirce's scientific method is the single most effective and commonly applied approach. The abductive inference at its heart is based on the inference structure inherent in a conceptual metaphor, grounded in the scientist's embodied and social understandings. By using conceptual metaphors the scientist arrives at contingent, testable models and theories that describe the world. They do not aim toward the unattainable goal of "absolute" truth, but toward reliability and accuracy. The world is filled with ample evidence that the scientific method when exercised this way works. Humans are able to perform amazing surgical procedures, land a complex device on a relatively tiny comet 300 million miles from Earth, and make progress in understanding the origins and progression of Alzheimer's disease. Conceptual metaphorical thought has been vital in all this progress.

Criticisms and defenses of CMT in science and science education

While CMT has been unquestionably influential in metaphor studies, it has also been criticized on various grounds by some scholars who approach metaphor theory from perspectives grounded in philosophy of language, literary theory, or linguistics (Camp, 2006; Guttenplan, 2005; McClone, 2007; Murphy, 1996). This is not an appropriate place to mount a comprehensive defense of CMT that addresses the many caveats and outright disagreements mounted against it. Gibbs and Lakoff and Johnson have addressed most of them in comprehensive, wide-ranging papers (Gibbs, 2001; Johnson & Lakoff, 2002).

It is important to emphasize that in scientific practice metaphor usage serves particular purposes. The language employed in scientific discourse often has features we associate with ordinary discourse, and we expect conventional metaphors to arise there as they would in other situations. However, conceptual metaphors such as quorum sensing, the cell as a factory, and a host of others, play essential roles in science because they are at the core of scientific explanation. Whatever may be the merits of critiques addressing how CMT can be applied more generally, the case for its efficacy in the practice of science is very strong. Here are additional considerations that should be kept in mind in evaluating CMT in this domain:

- Metaphoric usage is ubiquitous in scientific speech and writing that relates to scientific observation, creation of hypotheses and theory development. Indeed, it is difficult to find instances where metaphor is not a key element in scientific thought and communication. The patterns of metaphor usage are highly consistent with the tenets of CMT, as I have pointed out elsewhere (Brown, 2003) and illustrated further in this paper.
- It is frequently charged that the "conventional" metaphors that form the basis of our everyday thoughts and conversations are not products of our ongoing thought processes, but only linguistic conventions, metaphors that have lost their connections with the conceptual mappings that brought them into existence. Whatever the merits of such claims as regards everyday language use, and they have been rebutted (Gibbs, 2001), metaphors employed as explanations of new observations in science are nearly always novel. Furthermore, even in cases where a scientific metaphor has been in use for a long time, its conceptual import remains. For example, the metaphor of a "chaperone

protein" as one that acts to protect another protein from alteration, was freshly coined in 1978 (Brown, 2003, pp. 150–155). The metaphor proved to be highly productive, and applications of the concept spread rapidly. Today a Google search of the term "chaperone protein" returns in excess of 4 million entries. (There is, of course, considerable redundancy in this number, but it is evident that the concept of 'chaperone protein' remains actively employed long after its initial formulation.) It cannot be said that the term has become a dead metaphor, for several reasons. Most importantly, the meaning of "chaperone protein" is subject to continual revision as new findings and examples arise, and the term is applied to newly discovered systems.

– CMT accounts brilliantly for the fact that metaphors employed by scientists in accounting for scientific observations and in hypothesis formation draw upon conventional metaphors born of both the scientist's physical experiences of living in the world, and those deriving from experiential gestalts based upon social experiences and understandings. The systematicity and structural cohesiveness of metaphorical usages in science are consistent with the idea that fundamental conceptual processes are at work. For example, the metaphor of quorum sensing has been applied in a consistent manner to a host of highly varied situations in bacteriology. A well-formulated scientific metaphor is not merely a catachrestic label; it can do real work. When there exist viable cross-domain mappings, it is capable of stimulating new hypotheses and suggesting new experiments. No theory of metaphor other than CMT accounts satisfactorily for the breadth, consistency and productive roles of metaphor usage in science.

Finally, I close with a few comments on areas that appear to be ripe for further study of metaphor as it applies to science education. For some, a focus on conceptual metaphor entirely from the perspective of language and thought omits important aspects of metaphor's roles. To quote Gerard Steen:

> Metaphors are not only a matter of thought (with conceptual structures bridging conceptual domains or mental spaces) and a matter of language (with linguistic expressions in context indicating at least one aspect of such cross-domain mappings in thought), but also of communication, with linguistic expressions in context suggesting whether the metaphor has a specific value to the interlocutors as a distinct communicative (typically rhetorical) device – or not
>
> (Steen, 2015, p. 78)

All three of these dimensions of metaphor (thought, language, communication) are involved in scientific activity broadly. The focus in this paper has been largely on the roles of metaphor in the practice of science: That is, on the thought processes involved in making sense of scientifically motivated observations of things and events in the world. The evidence I have pointed to further establishes the primary role of conceptual metaphors, grounded in embodied experiences and social experiences of ordinary life, in scientific thought. Those same conceptual frameworks operate in forming the language scientists use in communicating with one another via speech or writing, and, of equal importance, in communicating to broader audiences about scientific results. However, as Steen rightly points out, the distinct dimensions, which can be roughly categorized as thought, language and communication, may produce differing patterns of thought in discourse. I offer a few comments here on the idea of *deliberate metaphor*, introduced by Steen (Steen, 2008, 2014) as it might apply to science education.

Deliberate metaphor use is the purposeful use of a metaphor as a metaphor. It often occurs in science teaching that a particular metaphor is called for to get across some insight or point of information. For example, I might say, "Imagine that a water molecule consists of a rubbery sphere connected symmetrically to two smaller rubbery spheres of equal size by rather stiff springs." This is a deliberate metaphor, in that the listener is specifically invited to set up a cross-domain mapping between a microscopic entity, a water molecule, for which we have various kinds of experimental evidence, and the physical model described in the metaphor. I might have chosen a different metaphorical model for the water molecule, for example, "Imagine that a water molecule consists of one tiny mass with a positive electrical charge of eight, and two positively charged tiny centers each with a charge of one, buried in a cloud of ten very low mass negative particles in extremely fast motion." The second deliberate metaphor demands more background knowledge on the part of the listener than the first one, but in a particular teaching situation it could be the better one to use.

It is frequently the case that the teacher needs to make a choice of one metaphor over another based on fairly complex considerations, such as the student's state of understanding of the domain under discussion, consistency with other metaphors that may have already been employed, and the particular aspect of the system demanding explanation. It is not surprising, then, that many metaphors used in science are "deliberate", and tailored to answer to particular pedagogical aims of the teacher. Consider this example drawn from a paper by Bruce Alberts dealing with the education of molecular biologists:

> …the entire cell can be viewed as a factory that contains an elaborate network of interlocking assembly lines, each of which is composed of a set of large protein machines. (Alberts, 1998)

In this example, the metaphor to which Alberts specifically calls attention is that of the cell as a factory. The short quote also contains several metaphors not specifically identified as such, including "interlocking assembly lines" and "large protein machines", that are simply entailments of the more general factory metaphor. The deliberate metaphor employed by Alberts is that of the cell as a factory. He suggests that proteins are somehow able to do machine-like work, perhaps cranking out new parts, and that this work is done in a systematic way in an organized array analogous to an assembly line.

The choice of calling attention to a metaphor, thus creating a meta-metaphorical entity, is often made to distinguish one key metaphorical model from another that might be employed in discussing the same target domain. For example, Alberts might have alternatively characterized the cell as a city, into which new substances enter and other substances pass out, in which certain proteins exercise surveillance over others, and destroy defective ones, in which strict traffic rules apply. In this frequently used metaphor for the cell, certain proteins are said to practice "triage." But Alberts chose the metaphor of the factory because he wanted to focus on proteins as machines; much of the rest of his paper is concerned with developing that notion.

While there are plenty of deliberate metaphors in science and in science pedagogy, the concepts employed in accounting for an observation or forming part of a hypothesis are typically grounded in basic conceptual understandings. Thus, we find language such as "the electron is promoted to a higher level", "the energy has a sharp minimum at 2.2 Angstroms", the term "fitness landscape" in which height represents degree of fitness, and so on. Such conventional conceptual metaphors abound in scientific discourse. Deliberate metaphors have their place as a considered choice of one metaphor over another for pedagogical reasons or possibly as a persuasive move. Deliberate metaphors are typically instantiations of a more general primary embodied metaphor or deeply grounded social metaphor. For example, Steen uses the following extract from a magazine article as an example of a deliberate metaphor: "Imagine your brain as a house filled with lights" (Steen, 2015). This metaphor makes sense only in terms of a more basic metaphor of the form: UNDERSTANDING IS SEEING. The metaphors of the cell as a factory or hospital rest on a metaphor such as LIFE IS PROCESS. Gibbs has challenged the very notion of deliberate metaphor, partly on the grounds that calling out a metaphor as such does nothing to change its relationship to the underlying primary metaphor (Gibbs, 2015, pp. 77–87). However, as I noted above, the deliberate metaphor does direct attention to one of what might be many metaphors for the target domain. For example, the brain might be imagined as a computer, a filing cabinet, consumer of energy, and so on. Deliberately calling attention to the brain as a house filled with lights may assist the listener to direct thought away from other metaphors for the brain that would be inappropriate for the application at hand. It is in this sense that deliberate metaphor as a pedagogical device has potential value.

Summary

My aim in this chapter has been to apply Conceptual Metaphor Theory (CMT) to the domain of cellular and molecular biology, in which conceptual metaphors drawn from the social domain are widely employed in reasoning about observations, forming hypotheses and generating thoughts for new experiments. Following an introduction of the central ideas of CMT, three overarching metaphors of special importance have been discussed: the Semiotic Metaphor, Teleology and Emergence and Supervenience. The centrality of these three primary conceptual metaphors to biology is demonstrated by showing their roles in discussions and theories related to evolution, a theory that underlies all of modern biology.

The study of living systems, even at the microscopic level, challenges the scientist to think in terms of metaphorical constructs that are sufficiently complex to capture a wide range of collective behaviors. In addition to drawing upon embodied experiences in the physical world, the scientist may call upon social experiences, including experiential gestalts of some complexity, in formulating hypotheses and models. The study of cellular systems that are focused on here calls upon metaphors from three source domains: structure, processes and – most importantly - communication.

Bacteria are ubiquitous unicellular organisms found throughout all living systems. These microscopic entities are too simple to exhibit complex behavior on a single-cell basis. However, intercellular communication leads to a wide range of collective behaviors, as illustrated and explained in this chapter with numerous examples. The explanatory metaphors employed to account for bacterial behaviors, formulate hypotheses and make predictions about the behaviors of the systems, are sophisticated. They call upon familiar social experiential gestalts suggested by terms such as "quorum sensing", "cooperation", "kin recognition", and "cheating". As demonstrated in this chapter, the range and systematicity of conceptual social metaphors in the language scientists employ attests to their fundamental importance in the biological sciences.

An understanding of conceptual metaphor and the roles it plays in science should be a prominent goal in all areas of science education. The most important mode of scientific reasoning, abduction, identified primarily by Charles S. Peirce, involves as a first step establishing a hypothesis, based primarily on conceptual metaphorical reasoning. Abductive reasoning consists in postulating that if a particular hypothesis regarding a system under study is true, one or more properties of the system follow. The scientist is then led to new experiments to test whether a particular predicted property is observed. If it is, the hypothesis is strengthened. If not, the hypothesis is amended or rejected. Successful accumulation of hypotheses leads to metaphorical models grounded in conceptual metaphors, a key ingredient

in developing a "best explanation." Students are not generally familiar with the notion of metaphorical thought, unaware that conventional metaphors form the basis of their everyday thought processes. Because conceptual metaphors are so central to scientific reasoning and explanation, their explicit identification – that is, use of deliberate metaphor – can help to inculcate a deeper sense of the importance of conceptual metaphors.

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