3. The Nature and Meaning of Information in Biology, Psychology, and Culture

3.1 DNA and the Genetic Code

DNA and the genetic code are the foundation of life and are classic examples of symbolic information. The medium for storing symbols is DNA, which consists of long sequences of certain chemical compounds called nucleotides that can be of four types: A, C, G, and U (Pollard & Earnshaw, 2008; Yockey, 2005). Each sequential group of three nucleotides is a symbol for an amino acid. This is essentially digital information similar to the sequence of binary electronic states used to store data in computers. Three nucleotides with four possible types for each can code 64 different items. However, there are only 20 amino acids to be coded and some are coded redundantly. For example, CGG, CGC, CGU, and CGA all code arginine, and only UGG codes for tryptophan (Pollard & Earnshaw, 2008; Yockey, 2005). Proteins constructed from amino acids in the sequences specified by DNA are the basis for life as we know it.

The interpretational infrastructure for the symbols in DNA consists of a complicated, integrated network of biochemical processes for storing and duplicating DNA, determining which sections of DNA should be utilized at a particular point in time, reading the sequences, constructing the corresponding proteins, and making error corrections (Pollard & Earnshaw, 2008). Each new generation must have the same interpretation of the symbols in the DNA. This applies to the reproduction of individual cells as well as the reproduction of an organism. As Harold noted "… sequences are just strings of symbols without intrinsic significance. At the end of the day, the object of the genetic exercise is to specify the shape of a protein that performs a biological function" (Harold, 2001, p. 50).

As expected, this interpretational infrastructure involves many other layers of information processing. Control mechanisms and error handling are particularly important.

"Living cells are dynamic, constantly undergoing changes in composition or activity in response to external stimuli, nutrient availability, and internal signals. … The supply of each of thousands of proteins is controlled by a hierarchy of mechanisms. … Molecular feedback loops regulate all of these processes to ensure the proper level of each cellular constituent" (Pollard & Earnshaw, 2008, pp. 9-10). "The use of multiple, unrelated, and redundant regulatory devices is quite typical … Control circuits … are more elaborate than the processes which are regulated" (Harold, 2001, p. 53).

Reproduction of a living cell occurs when a cell divides into two cells. Both cells include a copy of the DNA and a copy of the surrounding components of the cell that are part of the interpretational infrastructure for the DNA. The interpretational infrastructure also includes environmental factors that influence the development of an organism and that cause natural selection for evolution. The variations and adaptations that underlie evolution occur when the symbols in DNA are altered through sexual reproduction or through other mechanisms. "Open-ended evolution" results from genetic symbolic information processing (Pattee, 2007) and is a manifestation of creativity in living systems.

All known living cells, from bacteria to the cells in humans, use essentially the same genetic code for mapping DNA to amino acids (Pollard & Earnshaw, 2008). At the same time, this mapping appears to be arbitrary like the meanings assigned to symbols in other types of information (e.g., CGG could have been used equally well for tryptophan as for arginine). These findings are generally taken as evidence that all life on earth evolved from one ancestor. If life spontaneously originated at different times, different genetic codes for constructing proteins would be expected, much like the different spoken (and computer) languages that have emerged.

3.2 Perception for Single Cells

A single living cell is the basic unit of life. Each cell has a membrane that defines its boundaries and separates it from the environment. The cell takes in nutrients, releases waste products, and reproduces.

Individual cells perceive and respond to environmental factors. "Free-living organisms, such as yeast and bacteria, respond to changes in temperature, osmotic stress, and nutrients by synthesizing the proteins that are required to optimize their survival. Motile cells respond to chemicals by migrating toward attractants and away from repellants" (Pollard & Earnshaw, 2008, p. 425).

Cells have receptors that respond to specific environmental factors by releasing certain chemicals inside the cell. The chemicals released inside the cell represent or signify the environmental conditions and affect various processes within the cell. "This *transduction* step converts one type of signal (stimulus) into another signal (messenger) and commonly amplifies the signal. … Signaling pathways regulate virtually all cellular processes" (Pollard & Earnshaw, 2008, p. 426). The receptors can be either on the outside surface of a cell or inside the cell to respond to internal conditions. The signaling pathways are very complicated, typically branching and converging multiple times with positive and negative feedback loops and with interactions with other signaling pathways.

The signaling pathways within a cell appear to involve a merging of and transition between symbolic information processes and directly causal processes. Aspects of the pathways appear to be symbolic in nature with arbitrary signal processes. However, many other aspects of the pathways are directly causal chemical processes that are not arbitrary in nature (Pollard & Earnshaw, 2008, pp. 425-512). These complex signaling pathways control cell behavior and are the interpretational infrastructure for responding to environmental conditions.

Multi-cellular organisms have many cells functioning together in a highly coordinated, interconnected manner. Different types and groups of cells provide different functions for the living organism. Communication among cells is required for coordination and regulation of the functioning of the organism.

Most cells communicate by releasing certain chemicals into the fluids around the cells, and these chemicals are detected by receptors on other cells (Bruni, 2007; Pollard & Earnshaw, 2008; Reading, 2011). The use of receptors is basically the same process as a single-cell organism responding to the environment—except the environment for a cell now includes the other cells that are part of the organism. The chemicals used for communication can be categorized into groups with different properties, such as hormones and neurotransmitters. However, such categories are not relevant for the basic principles of information processing discussed here.

"At any time, hundreds of different chemical signals may be present in the environment surrounding the cell. Each cell responds only to certain signals, however, and ignores the rest, like a person following the conversation of one or two individuals in a noisy, crowded room" (Mason, Losos, and Singer, 2011, p. 169).

This communication between cells has the properties of symbolic information processing. The fluids around cells are the media. The specific chemicals are symbols that represent conditions that require responses by other cells. The symbols are placed in the media by living systems specifically for purposes of communication. The responses to the symbols are determined by the interpretational infrastructures of recipient cells, which include sources of energy and matter that can respond disproportionately to the energy and matter of the symbols and media.

As expected for symbolic information, the meaning or function of the symbols appears to have a high degree of arbitrariness. The fact that a specific chemical can have very different effects in different cells is evidence for the arbitrary nature of the signaling chemicals. For example, epinephrine is a chemical signal that means "increased physical activity is expected." Many different effects occur in response to epinephrine, including relaxation of the smooth muscle in the air passageways in the lungs and contraction of the smooth muscle in blood vessels in the intestines. In general, "One cannot predict the type of receptor, signal transduction mechanism, or nature of the response from the chemical nature of a stimulus" (Pollard &

Earnshaw, 2008, p. 427). This variability indicates symbolic processes rather than processes that include only directly causal chemistry.

A complex organism such as an animal has a staggering amount of communication among cells. For a simple example, muscles are specialized cells that can contract to move the body. Groups of muscle cells must work together and respond to signals from the central nervous system. The muscle cells require energy and oxygen, and give off waste products including carbon dioxide. Respiration and blood circulation must be coordinated with the activity of the muscles. Most movements of the body are also coordinated with perceptions of the environment and purposeful goals for the animal. All of these interacting processes are based on communication among cells.

3.3 Perception for Multi-Cellular Organisms

With evolution, environmental receptors have become more sophisticated and the processing of signals from receptors has become much more complex. In human vision, about 130 million individual receptor cells in the eye respond to light of certain colors and intensities. The signals from these receptors are sent to several regions of the brain that detect features such as specific edges, lines, and angles, and perform integration functions, such as facial recognition or tracking movement of objects. “As you look at someone, the visual information is sent to your brain as millions of neural impulses, then constructed into its component features, and finally, in some as yet mysterious way, composed into a meaningful perceived image, which is then compared with previously stored images and recognized” (Meyers, 2005, p. 152). Extensive parallel processing and hierarchical integration are utilized in achieving this result. Again we find many layers of information processing.

The senses of hearing, smell, taste, touch, and body position are similarly based on receptors that generate signals that are processed and integrated in the brain (Meyers, 2005).

3.4 Learning

Developing the capability to learn was a very important step in evolution. The behavior of a simple living organism is determined by genetic programming of automatic responses to environmental conditions. For these organisms, adaptation to environmental changes occurs at the species level through genetic mutations and diversity in the species. When environmental changes occur, many or most individuals may die while a few with favorable genetic mutations survive and reproduce. Of course, if the environmental changes are outside the range of species diversity, the species will become extinct—as has happened for over 99 percent of the species that have existed on earth (Guttman, 2002). The ability to learn allows individual organisms to adapt to environmental changes during their lifetimes. Learning is based on identifying associations between events and/or on imitation after direct observation of others.

An implied requirement for learning is that an organism can generate variability in responses or behavior. Behavior is not limited to genetically programmed automatic responses to certain environmental stimuli. Neural mechanisms that provide variations in behavior have become increasingly sophisticated with evolution. This variability emerges from symbolic information processing.

Another implied requirement for learning is that an organism can identify and remember associations among the signals from receptors. Identifying these associations creates symbolic information and requires an interpretational infrastructure that is dynamic, as well as having memory. Similar to the processing of perceptions, learning can utilize groups or patterns of symbols to form high-level integrated symbols, such as recognizing an animal and anticipating its movements.

Self-awareness results from receptor signals from internal processes rather than from environmental conditions. This self-monitoring makes an organism able to coordinate and guide different parts of its body, and to be sensitive to changing conditions—and therefore more able to adapt.

3.5 Language

The evolution of language in humans is a pinnacle of information processing and learning (Deacon, 1997; Donald, 2001). Language allows people to share knowledge with others and across generations, as well as to negotiate and work cooperatively. In a communicating group, the effective memory and learning capacity can be much greater than for any individual. Language abilities required the evolution of special information processing capabilities in the brain, enhanced perceptual capabilities, and structures in the throat for speaking (Deacon, 1997).

For spoken words, the information medium is sound waves and the symbols are the words. The interpretational infrastructure for spoken words consists of many other layers of information processing, including the receptors for the sense of hearing, as well as the subsequent processing and integration in the brain. Another important component of the interpretational infrastructure is the ability to learn and remember the meaning of words as used in the culture.

Humans are born with a natural capability for language, but must learn the specific language used by a cultural group. The human mind and human culture appear to have co-evolved with the mind creating culture and culture influencing the evolution of mental capabilities (Deacon, 1997; Donald, 2001). As previously noted, the symbols and the interpretational infrastructure must emerge together.

The human brain became extremely plastic in order to adapt to culture (Donald, 2001). The "superplasticity" of the brain allows people to live in diverse and changing environments, but also makes them very dependent on culture for survival. "We are a culturally bound species, and live in symbiosis with our collective creation. We seek culture, as birds seek air. In return, culture shapes our minds, as a sculptor shapes clay" (Donald, 2001, p.300). Human childhood is a period of prolonged dependence on others for survival while learning culture.

Culture is based upon the storage and exchange of information. Donald (2001) argued that the innate seeking of culture results in a natural attraction to belief systems such as myths and religion. Science is a relatively structured learning process for developing symbolic representations that can be used to make predictions, build useful technology, and control nature.

3.6 Imagination and Creativity

The evolutionary trend toward increased information processing has culminated in consciousness with imagination. The media, symbols, and interpretational infrastructure for imagination initially reside within a brain. The symbols represent abstract ideas or concepts that are largely self-generated. Imagination allows manipulation of symbols in a way that can result in greatly enhanced problem solving.

Imagination introduces the ability to create new conditions in the world. Planning based on hypothetical futures is a key result of the evolution of the human mind (Donald, 2001). Problems can be solved by creative brainstorming that generates a list of different hypothetical actions, and then selects an optimal option.

The imagined potential futures can include individual or group activities, or new technology ranging from primitive tools to the complex electronic systems of modern society. Imagination also allows inspirational and entertaining fiction, art, and fantasy.

Creativity such as inventing new technology typically involves developing new symbols and/or meanings that must be incorporated into the interpretational infrastructure. The cultural interpretational infrastructure needs to be sufficiently adaptable to learn and distribute new symbols and meanings.

Creativity and learning are limited more by the properties of the interpretational infrastructure than by the properties of the media and symbols. Consistency of meaning is essential for information, yet the structures that maintain consistency must be balanced against the need for adaptations, learning, and creativity.

Imagination of potential or hypothetical futures is information about possibilities rather than about tangible reality. It is more abstract and creative than the facts, data, and knowledge that are typically the focus of definitions of information. Likewise, imagination and creativity do not fit within the concepts of physical and quantitative information. A broad concept of symbolic information is required.

The ability to learn was a major evolutionary step beyond genetic instincts. Similarly, the ability to imagine was a major evolutionary step beyond associative and observational learning.

3.7 Hierarchies of Symbols

Hierarchies of symbols have an important role in human thought, communication, and learning. Certain characteristics can be identified with one high-level symbol or name. For example, the identification of a particular person or animal has been an important ability for humans. The person or animal is typically identified by name in a unitary manner rather than by listing component features. Learning often involves forming new high-level symbols that make memory and communication more efficient. Similarly, incrementally learned actions such as talking and walking become high-level automatic behaviors with associated high-level information processing.

High-level symbols are particularly important for developing and working with technology. We speak of a TV or computer without itemizing or even knowing all the individual components of the technology. Of course, the various engineers who developed the technology have relevant names for the entire hierarchy of the component parts, which ultimately can extend down to the level of the molecules and atoms for transistors.

3.8 The Origin of Life

The origin of life remains a profound mystery because the DNA medium, the genetic code for the symbols, and the complex interpretational infrastructure all must have originated together. It is difficult to imagine how the complex interdependent information processing systems that are the foundation of life could have spontaneously appeared. The usual scientific speculations about the origin of life assume that evolutionary adaptations somehow spontaneously occurred in nonliving material—even though such processes have never been observed.

However, others argue that evolution is a result of life, not the initial cause of life. Symbolic information processing with genes is required for evolution (Pattee, 2007). The principles of evolution cannot account for the origin of life because genetics and evolution as currently understood cannot occur without all the information processing components functioning in an integrated manner. Evolution is applicable once the genetic information processing is in place in living organisms that behave as if they have a motivation to survive and reproduce. Without the genetic information processing and underlying motivation, evolutionary processes as currently understood are not applicable. After a career of research and teaching in biochemistry and molecular biology, Harold commented that “The origin of life appears to me as incomprehensible as ever, a matter for wonder but not for explication” and suggested that “there is much more to this mystery than is dreamt of in molecular philosophy” (Harold, 2001, p. 251).

There is increasing recognition that living organisms have synergistic, emergent properties that cannot be predicted or understood by applying scientific determinism and reductionism to the component parts. “From the chemistry of macromolecules and the reactions that they catalyze, little can be inferred regarding their articulation into physiological functions at the cellular level, and nothing whatever can be said regarding the form or development of those cells” (Harold, 2001, p. 5). “The belief of mechanist-reductionists that the chemical processes in living matter do not differ in principle from those in dead matter is incorrect. … If genetic processes were just complicated biochemistry, the laws of mass action and thermodynamics [rather than DNA] would govern the placement of amino acids in protein sequences” (Yockey, 2005, p. 5). Kauffman (2008) provides many examples and arguments from chemistry, biology, and physics that reductionism is not an appropriate strategy for many key areas of science.

The origin of symbolic information processing systems appears to be outside of the usual scientific strategy of deterministic reductionism. The arbitrary assignment of meaning to symbols, the co-evolved interpretational infrastructure, the disproportionate influences on the distribution and flow of matter and energy, and the capability for creativity all contribute to effects that cannot be predicted or understood with pure determinism and reductionism. “Therefore, the interpretation or function of any such semiotic or informational sequence is literally metaphysical (beyond physics)” (Pattee, 2007, p. 126). The currently established principles of physics can be used to describe and design information-processing systems, but offer no forces that would cause such systems to be initially created in the absence of living systems.

3.9 Conclusions about Information and Living Systems

Livings systems have layer upon layer of interacting symbolic information processing, including within and among genetics, communication between cells, perception, behavior, memory, learning, communication between organisms, imagination, creativity, and culture. The purposeful nature of living creatures is based on information processing. The interpretational infrastructure actually consists of other layers of symbolic information processing. The information processing is parallel as well as sequential, and often with hierarchical integration.

Symbolic information processing is a defining property of life and provides the capability for creative adaptations.

Conceptually distinguishing symbols, media, and interpretational infrastructure may clarify the dilemma that our self-aware consciousness feels like it is separate from matter, yet appears to emerge from and depend on the matter in the brain. This dilemma is the source of much debate and controversy in science and philosophy. The media for information is matter and energy, but the symbols and meaning are separate from the media.

The physical brain serves as media for symbols, but the symbols have meaning beyond the media function of the physical brain. The basic nature and value of information is that it provides meaning beyond the physical properties of the media. The many layers of awareness and information processing in humans amplify this effect. A type of dualism between meaning and media is implied. This is true for information in general, and for imagination in particular. The impression that our thoughts are more than the matter in the brain and are beyond matter is correct. At the same time, if the media are damaged, information processing is also damaged.

The ability to symbolically represent hypothetical possibilities as well as to represent manifest reality is pivotal. Ultimately, most information of interest to living beings pertains to manifest reality. However, the ability to think about abstract possibilities provides the power to cause or create the actual manifestation of hypothetical possibilities. This ability emerges from many layers of information processing.

Generating the ability for creativity in living systems is clearly a major result of symbolic information. One could reasonably argue that generating creativity is the primary purpose of symbolic information.

The origin of life remains a profound mystery that becomes more mysterious with increasing understanding of symbolic information. This mystery may indicate that important scientific principles remain to be discovered.

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Next Section: 4. The Nature and Meaning of Information in Quantum Physics
Previous Section: 2. What is Information?

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