INTRODUCTION

What Are Brains for?

In Mark Twain's 1894 novel *Pudd'nhead Wilson*,[1] the title character is a detective who figures out that the eldest son (and heir apparent) of a large Southern plantation is really the child of one of the slaves. The real heir and the slave child, indistinguishable from each other by skin color due to ubiquitous interbreeding between male slave owners and female slaves, had been switched at birth. "Pudd'nhead" was so named because no one ever thought that he could do much, just as children of slaves were assumed to be intellectually inferior. Twain's switched-at-birth scenario was designed to illustrate what we now refer to as the role of "nurture" (as opposed to "nature") in the shaping of a person, and to skewer the prejudice of classifying slaves (and some detectives) as inferior beings. With today's neurobiological perspective, we would cite these as examples of the brain's ability and propensity to adapt itself and its bearer to the world around it. The child raised as the plantation owner's firstborn showed all of the traits and foibles to be expected of his station, whereas the child raised as a slave showed the corresponding characteristics.

So why do we need a brain? It is the only way that we, or any other creature that moves through the world, can deal with the constantly changing panorama of sights, sounds, smells, tastes, and touches, not to mention gravity, and (for some animals) electrical and magnetic fields. Brains allow us to perceive the world, respond to it, move through it, and act on it. The amount of brain we have, measured as the number of nerve cells (neurons), determines how much of a repertoire for perception, response, movement, and behavior we have at our disposal: relatively little for a single-cell protozoan, somewhat more for a jellyfish of 1,000 neurons, a fair amount for a fruit fly of 100,000 neurons, and quite a lot for a human of 100 million neurons. When it comes to brains, size unquestionably matters.

But aside from size, are all brains fundamentally the same? Even identical twins, whose brains are the same size and genotype, do not really have identical brains. And if that is so, then how likely is it that the brain of a human and that of a jellyfish have anything in common? As it turns out, all brains have much in common. Even

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[1] Twain M. 1894. *Pudd'nhead Wilson: A tale*. Chatto & Windus, London.

the single-cell protozoan *Paramecium*, which has been likened to a neuron that swims, has much in common with our own nerve cells. Neurons are for signaling, electrical signaling to be precise, and the nature of those signals appears to have evolved very early—before multicellularity—and to have been well preserved ever since, right down to the molecules that make it happen.

Senses go back a long way as well. Chemical sensing is almost certainly the original sense, given that life arose in the liquid environment of the sea and that even bacteria have a non-neuronal version of it. But with the arrival of multicellular animals, separate sense organs arose and with them the ability to see and hear as well as taste, smell, and touch. The mechanisms that make these sensory detection events possible are also well conserved across distant phylogenies, with some variations. Present-day descendants of these primitive detectors and their molecular machinery are found in simple aquatic organisms such as the barnacle and the horseshoe crab *Limulus*.

But senses by themselves do not require a brain, since plants too can "sense" and respond to light, gravity, and humidity. Movement is the sine qua non of animal life: deliberate, directed, internally generated, often rapid movement. Motor systems depend not only on the electrical signals conducted along neurons, but also on the coordination of activity among sets of neurons and muscles. The rapid communication among cells occurs across synapses, which are the specializations at the ends of neurons for chemical signaling. Just as electrically conducted signals are conserved from *Paramecium* to humans, so the chemically transmitted signals between neurons are conserved through evolution. In the context of the neuronal circuitry of a simple brain, these properties can generate patterns of muscle activation that can propel an animal through its environment. Again, we find present-day examples of what likely were primitive, rhythmically coordinated motor systems in the rhythmic contractions of a jellyfish or the undulations of a swimming leech.

Is that it? Are brains nothing more than glorified sensory input and motor output devices? B.F. Skinner, whose viewpoint (known as "behaviorism") dominated American psychology for most of the 20th century, pretty much believed that. Skinner may have also added to this the ability to make associations, as in the conditioning of Pavlov's dogs (who learned to anticipate mealtime after associating the ringing of a bell with the imminent arrival of lunch). "Associative conditioning" also appears to have a deep, evolutionary ancestry and to be a property of very simple brains. Even a simple animal must adapt to its immediate environment. In fact, the ability to modify its signaling can be a property of any synapse, as seen in the sea snail *Aplysia,* and once again, the molecular machinery necessary for these events shows great similarity in all animals.

Skinner theorized that these simple capabilities, associative conditioning in particular, account for all of our behavior, including our mental experience. This represents the most radical, antideterminist view of human nature. Its counterpart was originally proposed by two of the founders of modern genetics and eugenics in the late 19th and early 20th centuries, Francis Galton in England and Charles Davenport in America. Their opposing viewpoint states that human nature and behavior are biologically determined through and through. Mark Twain would certainly have more sympathy for Skinner than for Galton and Davenport, as the story of Pudd'nhead Wilson and the slave versus master upbringing shows. But he was too shrewd an observer of the human condition to go along with Skinner's complete denial of an intrinsic human nature. In fact, Twain states, "With all respect for those ancient Israelites, I can not overlook the fact that they were not always virtuous enough to withstand the seductions of a golden calf. Human nature has not changed much since then."[2]

Whether brains are determined or changeable, they are essential for the richness and diversity of behavior that animals display. How the brain organizes a repertoire of behaviors has been explored in the fruit fly *Drosophila melanogaster*, champion of genetic studies in the 20th century. The range of biological problems that can be answered by studying *Drosophila* is continually expanding. These little flies have shown us not only how similar the genes of all animals are to one another, but also how similar many overt animal behaviors are. The similarities are not just skin- or cuticle-deep, as the case may be, but extend to the underlying mechanisms as well. Circadian rhythms and associative conditioning are prime examples, with findings on sleep and arousal, the sequencing of motor patterns, and perceptual events catching up quickly. And they do this with a relatively modest brain of roughly 100,000 neurons. If one looks to the honeybee, a cousin of *Drosophila* with roughly 1 million neurons, one finds a highly sophisticated ability to make abstract discriminations (e.g., to recognize asymmetry per se) and to find their place in a region as if referring to a map (see Chapter 8).

These postcards from natural history tell us that brains are more than just input–output devices and more than just associatively conditionable, Skinnerian machines. They are complex organ systems, capable of arousal, perception, context-appropriate reactions, anticipation, and sophisticated discriminations; all elements that, in the more complex, neuron-rich environment of the human brain, go together to produce consciousness, feelings, and ideas. We know a lot about the molecular parts that comprise this organ system, a lot about the physiology of its cells, and something about the neuronal circuitry for certain tasks. We have general outlines about how some of the more sophisticated feats are achieved, but few of the steps are known, especially in understanding links among the levels of molecules, cells, and circuits. There remains much that is mysterious. As a prominent neuroscientist has said, "The kidneys just make piss but brains make epistemology."[3] Understanding the brain and the way it performs its functions stretches the limits of our scientific and linguistic abilities.

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[2] Twain M. 1869. *The innocents abroad: or, The new Pilgrims' progress*, Chapter XLVI, p. 480. American Publishing Co., Hartford, Connecticut.

[3] *BioEssays* **26:** 326–335.

Aside from the intellectual challenge of understanding brains in general, we have some more immediate concerns that relate to understanding brains. Much of our time as human beings is spent trying to understand one another: What did she say? What did he mean by that? Why did they do that? How can we get them to change? These are the grist for our daily conversations and are often of more than idle importance to us. The underlying plot of these conversations is the effect that the goings-on in one person's brain has on those in another person's brain. So in a sense, we spend much of our lives trying to understand one anothers' brains. Granted, we do not always do such a good job of it, but we try nonetheless. This is one justification for trying to understand how brains give rise to behavior in animals. And because none of us wants to submit to being experimented upon, beyond maybe earning $20 to play a video game for a psychology experiment as students, we study animals.

Why study invertebrate brains, as opposed to those of other mammals, if we want to understand our own brains? Evolution has produced a wide range of variations in how animals accomplish tasks and solve problems. Invertebrates include a much greater share of this variation than vertebrates and much more than mammals. As a result, there are some experiments that are only possible to do in certain invertebrates. The examples in this book are drawn from such experiments. At the same time, for all of evolution's variety, there are common threads that run through the workings of brains in all animals. Often, these are more easily revealed in the experimental setups possible with invertebrates and later confirmed in mammals.

There is also a broader reason for wanting to understand the range of possibilities open to brains. Evolution may be seen as one vast experiment in how many ways there are for living things to get by on this earth. No single one of them is necessarily "the best," and all are only as good as their ability to hang on and avoid extinction. Yet the range is not infinite. Not only are all organisms limited in what they can do, but there may be limits to how behavior can evolve based on the limits to what brains can do. Being made of cells that communicate with one another by means of electrical and chemical signals may carry its own inherent limitations. By exploring the boundaries of these limitations in the living world, we may arrive at a deeper understanding of the principles that govern the architecture and workings of nervous systems.