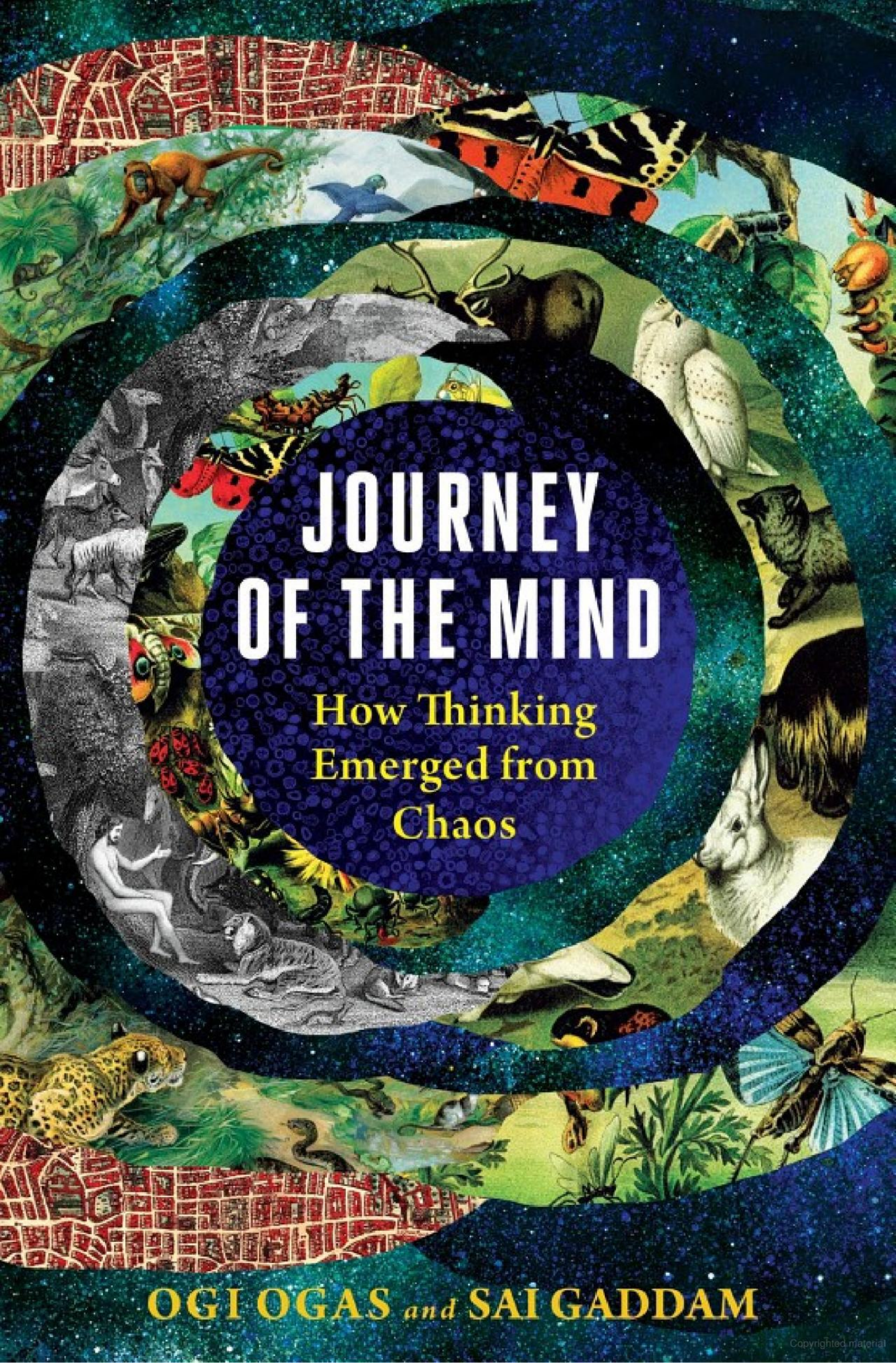

JOURNEY OF THE MIND

How Thinking Emerged from Chaos

OGI OGAS *and* SAI GADDAM

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JOURNEY OF THE MIND

Initial Value Problem

Do not imagine that the Way is short;
Vast seas and deserts lie before His court.
Consider carefully before you start;
The journey asks of you a lion's heart.
—*The Conference of the Birds*, Farid ud-Din Attar

In the beginning, fourteen billion years ago, existence arose from nonexistence and the universe commenced.

Four billion years ago, give or take, life arose from nonlife and the evolution of species commenced.

A billion years after that, purpose arose from purposelessness and the journey of the mind commenced. Eventually, the journey would forge a god out of godlessness, a new breed of mind endowed with the power and disposition to reshape the cosmos as it saw fit.

This book retraces the journey of the mind from the aimless cycling of mud on a dark and barren Earth until the morning a mind woke up and declared to an indifferent universe, "I am aware of *me*!"

The chapters ahead visit seventeen different living minds, ranging from the simplest to the most sophisticated. First up is the tiniest organism on Earth, the humble archaeon, featuring a mind so minuscule that you would be forgiven for questioning whether it's a mind at all. From there, our itinerary will take us forward through a series of increasingly brawny intellects. We will sojourn with amoeba minds, insect minds, tortoise minds, and monkey minds, until we arrive at the mightiest mind to ever grace our solar system . . . one that may be something of a surprise.

Each chapter highlights a new mental challenge thrown down in a mind's path by chaos, the purposeless churn of physical matter, before revealing the mental innovation that surmounted it. This gauntlet of challenges begins with one of the most perplexing of all: *How did a mind emerge from mindlessness?*

You will learn how each new innovation led to an even more daunting challenge that spurred minds to become smarter still. You will see how bacteria make situation-specific decisions without the benefit of a single neuron, let alone a brain. You will discover why the housefly's surprisingly intelligent mind marks nature's boundary between minds that are unquestionably nonconscious and those indisputably conscious. You will come to appreciate how monkeys rely upon hope, rage, and awe to chart a course through life. Each new form of thinking is explained in plain language without any mathematical equations, though curious readers can find additional details and references in the endnotes.

This book is motivated by three goals. First, to help you appreciate the hidden connectedness of all minds. Amoeba minds and human minds are linked through an unbroken continuum that parallels the one linking the ancient Roman town of Londinium with the twenty-first-century London megalopolis.

The second aim of retracing the mind's three-billion-year pilgrimage is to obtain new answers to very old questions. Why do we exist? Where are we all headed? Is there a hidden relationship between chaos and purpose? Is there a cosmic role for love in the universe? For decency?

The third goal is to explain the physical basis of the "Big Three" forms of thinking: consciousness, language, and the Self. How do minds—unlike pebbles and dust and sunspots—boast the ability to *experience* things? You may have heard that mortal consciousness is the greatest locked-room mystery in science, an unsolved puzzle that may never be unriddled. The journey ahead suggests otherwise. By progressing through the sequence of innovations that led to sentience, step-by-step, this narrative offers an incremental account of *why* and *how* consciousness appeared in the universe. You will learn how consciousness works and come to see new strains of consciousness in places you never expected. You will learn, too, how language was constructed atop the architecture of consciousness and why a hairy, hooting biped with a fondness for rocks became the first beast to compose poetry, rather than a soft-feathered flyer with a melodious song. And, finally, you will acquire a deeper understanding of the greatest innovation in biological minds: the human Self.

Such grandiose finales often have modest origins. The journey of the mind begins eons before the first human mew, in a bleak and unthinking void without a trace of purpose in sight. The old fable of Genesis got one thing right, for in this boundless reign of chaos the first mind strove to cleave the light from the darkness . . .

Stage I

Molecule Minds

CHAPTER ONE / **FIRST MIND**

Purpose

> We're building something here, Detective. We're building it from scratch. All the pieces matter.
>
> —Lester Freamon, *The Wire*

1.

A long, long time ago, somewhere in the dark and the deep, volcanic vents blasted through the crust beneath the ocean and spewed out sulfur and minerals in a furious maelstrom of pressure and heat. Out of this infernal brew, the first living organisms began to multiply.

Or maybe they oozed out of asteroid-infused mud. Or seeped from the cracks of sunbaked clay. Or bubbled out of wet pockets of rock galvanized by lightning. Or wriggled out of freshwater pools on volcanic islands. Or—another serious contender—perhaps they hitched a ride across the heavens on a meteor.

The origins of life on Earth remain one of science's most enduring mysteries. Nobody has a particularly persuasive theory regarding the identity or circumstances of the primal chemistry that jump-started metabolism and reproduction, the two fundamental hallmarks of life. Making the task of recombobulating life's firstborn even more knotty is the fact that conditions on primeval Earth were radically different than now.

If you were somehow transported back to the day that the first audacious speck of life xeroxed itself, you would find that the day was a brisk ten hours long, the Earth completing an entire rotation during the length of a modern commuter's workday. A dim chilly red sun barely penetrated a hazy sky the color of brickdust. During the brief night, the moon loomed low and enormous in the sky like some pale fairybook beast. An oxygen-less atmosphere drenched with poison churned over a cold and sludgy ocean.

In this exotic and speculative realm, some combination of molecules interacted with some other combination of molecules and sparked the journey of life—an event whose staggering import scientists dryly mask with the term "abiogenesis." Regarding the identity of this sacred web of chemical permutations, all is contested conjecture. Well, almost all. One hypothesis has risen above the rampant guesswork and attained something close to consensus among scientists. The hypothesis is this:

> *The chemical system of newborn life—whatever it might have been—was swaddled in a tiny ball of fat.*

We should all sing hymns of thanksgiving to this wobbly little globe. It proved to be the cornerstone character in two cosmic narratives: the journey of life and the journey of Mind. (Biologists have a ready term to refer to *all species that ever were*: "life." Neuroscientists lack a corresponding term for *all minds that ever were*, so this book shall employ "Mind" for the task.)

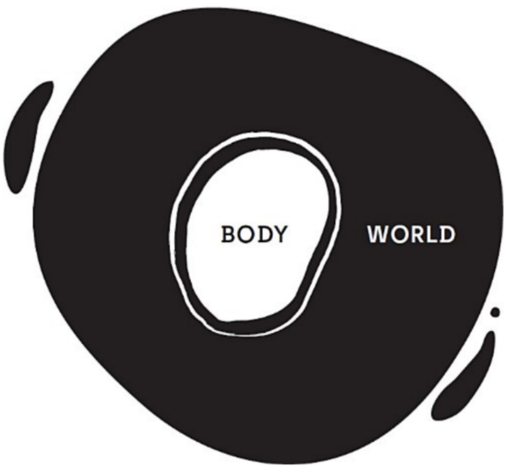
Certain large molecules containing fatty acids—*lipids*, in the language of chemistry—possess a special property. They automatically self-assemble into a membrane. Their physical nature is to link together into an elastic wall that bends back on itself to create a sphere. You've witnessed this process anytime you've noticed a bubble emerge from soapy water. Soap bubbles contain molecules similar to those found in the membranes of living organisms—and similar, perhaps, to those in the primeval membranes that originally cordoned off life from not-life, thereby constructing a private room where the story of biology could unfold in fragile safety.

The establishment of a distinct physical boundary around metabolizing and self-replicating chemical processes inaugurated something marvelous. A *body*. A physical configuration whose constituents were diligently laboring to preserve their configuration's existence.

By separating the stuff performing all the indispensable tasks of self-preservation from all the other stuff in the world—by dividing *me* from *not-me*—an ancient shroud of lipids fulfilled an essential precondition for the emergence of Mind. Every mind needs a border partitioning the physical processes of its *body* from its *environment*, where chaos maintains its indomitable reign.

The inception of a living body introduces the first of four deep principles of Mind that will help us make sense of Mind's ascendance from mindlessness to sentience: the *embodied thinking principle*. According to the embodied thinking principle, it is not possible to separate a mind from its body, any more than we can separate a city from its buildings. In order to understand any particular form of thinking, we must always take into account the configuration of the physical *stuff* that the thinking is incarnated within, even when much of that stuff may not appear to be directly involved with manufacturing thoughts.

THE BIRTH OF BODY



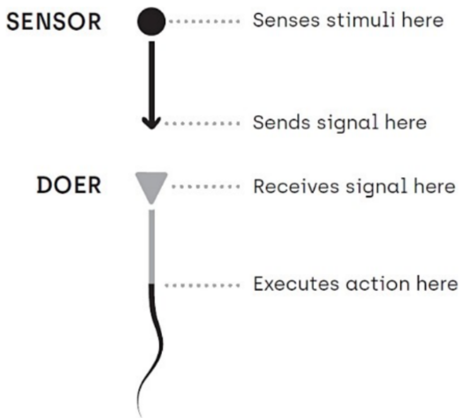
Every mind has a body. Yet, no matter how complex its breathing, feeding, and excreting, a body alone is not a mind. Innumerable generations of membrane-enveloped organisms nursed a vibrant biochemical metabolism and were perfectly alive yet remained totally mindless. That's because these pioneering species lacked something else indispensable for the genesis of thought.

They needed something to think with.

2.

A mind is a physical system that converts sensations into action. A mind takes in a set of inputs from its environment and transforms them into a set of environment-impacting outputs that, crucially, influence the welfare of its body. This process of changing inputs into outputs—of changing sensation into useful behavior—is *thinking*, the defining activity of a mind.

THINKING ELEMENTS



Accordingly, every mind requires a minimum of two *thinking elements*:

- A *sensor* that responds to its environment
- A *doer* that acts upon its environment

Some familiar examples of *sensors* that are part of your own mind include the photon-sensing rods and cones in your retina, the vibration-sensing hair cells in your ears, and the sourness-sensing taste buds on your tongue. A sensor interacts with a *doer*, which *does something.* A doer performs some action that impinges upon the world and thereby influences the body's health and well-being. Common examples of doers include the twitchy muscle cells in your finger, the sweat-producing apocrine cells in your sweat glands, and the liquid-leaking serous cells in your tear ducts.

A mind, then, is defined by what it *does*, rather than what it *is*. "Mind" is an action noun, like "tango," "communication," or "game." A mind responds.

A mind transforms. A mind acts. A mind *adapts* to the ceaseless assault of aimless chaos.

The identities of the sensors and doers of Earth's first mind are lost in deep time and may never be recoverable. These primal thinking elements may have been simple, perhaps single molecules that changed their shape when they contacted a photon of light. However, it's more likely that the original sensors and doers were ungainly contraptions composed of clumsy chains of free-floating molecules that did not reliably respond to stimuli or consistently exhibit a desired behavior.

Together, this trinity of sensor, doer, and body launched the journey of Mind by solving its first mental challenge: *creating a mind out of mindlessness.* Cast apart, sensors and doers are inanimate matter, flecks of vagrant chemical junk. But when you assemble a sensor, doer, and body so that they interact in a particular way, something interesting happens. To illustrate this physical revolution, it's time for the protagonist of our story to step on stage.

The simplest hypothetical mind is the proud proprietor of a single sensor and a single doer swathed in a membrane. How could a single sensor and doer usefully benefit an organism? If the sensor detects some resource in the environment (light, perhaps) and the sensor activates the doer when it detects the resource and if the doer affords some kind of locomotion (propulsion, perhaps), then this super-simple mind could advance toward the resource.

SIMPLEST POSSIBLE MIND

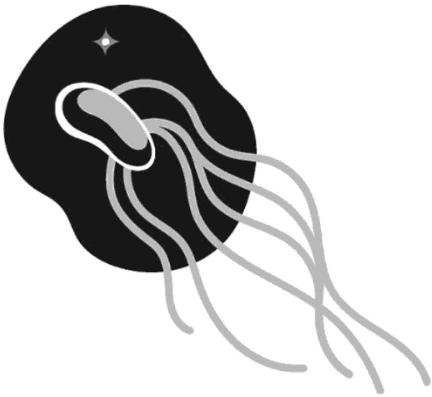
Behold *purpose*, an unprecedented development in the universe!

Purpose is a special class of physical activity, different from all other physical activity that existed before the first mind thought its first thought. A moon orbits a planet because the laws of gravity command it. But a moon with purpose might very well throw off the shackles of its planetary master and soar off into the freedom of open space. Whereas physics obeys rigid laws without aim, a mind pursues an aim without following rigid laws. Physics *ensues*. A mind *adapts*.

Purposeful phenomena are best explained using different mathematics than purposeless phenomena. Imagine predicting the path of an ant as it walks through a forest. It dodges rocks, clambers over twigs, crawls along the side of stumps. Its path is complex and nonlinear, and if physicists attempted to derive an equation that accounted for the ant's trajectory using the same mathematical tools they employ to account for the trajectory of an asteroid, tornado, or electron, they would labor in vain. If they instead recognized that the ant's behavior was *purposeful*—the ant was trying to get home to its anthill—then they could predict the ant's trajectory by assuming that at any given moment, the ant will *choose* the path offering the easiest route home. Predicting the ant's motion requires a different kind of mathematical model than any found in the physical sciences: a model describing the thinking processes responsible for the ant's decision-making. One of the aims of this book is to guide your intuitions about the odd principles of purpose so you can better understand consciousness, language, and the Self.

The first thinking on Earth, whatever it may have been, surely served a specific purpose. And whatever that purpose was, it was surely an advantage in the pitiless contest for survival. Even if the first mind's sensor was feeble and its doer clumsy, such a configuration would move itself closer to food (or away from danger) with a probability better than chance and thereby engage the engine of natural selection. A photosynthesizing organism that could move toward light or away from darkness would outcompete an identical organism that floated about aimlessly like a feather on a pond.

Earth's first mind remains entirely speculative, to be sure, and is the only mind on our journey that we cannot examine directly. Sadly, no organism with one sensor and one doer roams the microscopic wilds of twenty-first-century Earth. So let's visit the next best thing. Let's examine the simplest *living* mind in nature and see how it compares to the simplest *hypothetical* mind.



CHAPTER TWO / **ARCHAEA MIND**

Targeting

We sit in the mud, my friend, and reach for the stars.

—*Fathers and Sons*, Ivan Turgenev

1.

Please take a moment to move yourself one centimeter in the direction of the brightest available source of light.

Done?

Accomplishing this task required the use of your eyes. Your muscles, too. But most important, it required the use of your mind.

You needed to survey the light in your surroundings (an act of perception), determine where it was brightest (an act of judgment), and then will your legs, arms, or hind parts to move there (an act of volition). In a word, you needed to *think*.

Accomplishing this task solves the first challenge that every mind must address. Let's call it the targeting problem: How do you locate a desired objective in your environment and move yourself toward it? On the face of it, the thinking you just engaged in would appear to require a fair bit of mental wiring. Some kind of visual processing circuitry to apprehend the light, you might guess, as well as judgment circuitry that evaluates where the light is brightest, and motor-control circuitry that formulates and executes the plan to move your body toward the light in question. This sounds fairly complicated. And yet, this complex feat of targeting is accomplished by the most rudimentary mind in nature.

Archaea (pronounced "ar-KEY-uh") are wee little beasties. Like bacteria, archaea are single-celled microbes with a cell membrane but no nucleus. Not only do they lack neurons, some archaea are so diminutive that their entire body can squeeze into the nucleus of a human neuron. The smallest known cellular organism is an archaeon: *nanoarchaea* are one-fifth the length of an *E. coli* bacterium.

Archaea form one of the three great domains of earthly life. The other two are bacteria and eukaryotes, the latter of which includes all known species of animals, plants, and fungi. But eukaryotes and bacteria are the youngbloods in the family. Biologists believe that archaea's branch of life extends the furthest back in time.

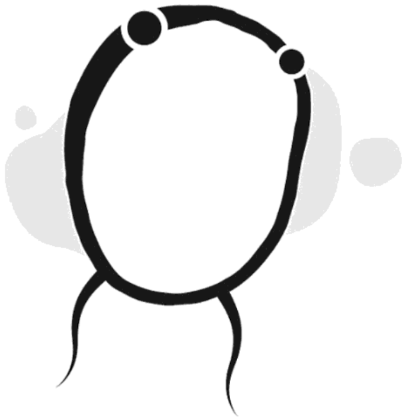
Archaea are found in every habitat on the planet, yet they spent most of the past century hiding in plain sight. Whenever a biologist happened to notice an archaeon on a microscope slide it was misclassified as a bacterium. Science finally recognized that archaea were our long-lost relatives in 1977. That's when an obscure biologist analyzed the RNA of a methane-producing microbe. He discovered that its genetic code diverged from that of every known branch of life. It was a bit like delving into your family tree and discovering that your great-great-great-grandmother didn't emigrate from Germany like everyone thought, but Jupiter.

Though in general archaea look and behave a lot like bacteria, they employ physiological processes unique to their kind that enable them to feed upon sources of nutrition that are indigestible or even lethal to other organisms, including arsenic, ammonia, gypsum, petroleum, and uranium. This allows them to thrive in inhospitable habitats such as volcanic vents, polar ice caps, boiling hot springs, toxic-waste dumps, and subterranean rock a mile beneath the ocean crust.

Haloarchaea, for instance, dwell in water with concentrations of salt so extreme that they are toxic to almost all other life. Haloarchaea derive their energy from the sun. Not through plant-style photosynthesis using green chlorophyll. Instead, haloarchaea conduct their own brand of photosynthesis using a purplish molecule known as bacteriorhodopsin. (The Great Salt Lake in Utah is often tinged with a pinkish-purple hue around its edges from haloarchaea blooms.) Since the sun is its source of "food," the haloarchaeon must ensure it can access a reliable supply of sunlight. That's where the world's simplest living mind comes in.

Introducing Archie, a model of a haloarchaeon:

ARCHIE



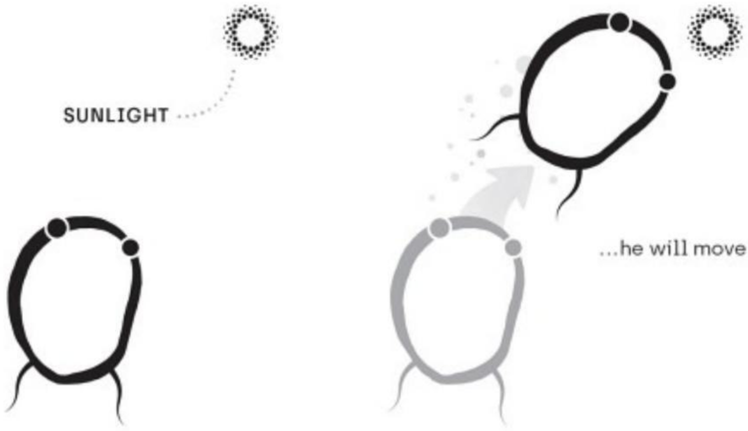
A model is a simplified representation of a complex phenomenon. A useful model allows you to focus on the important stuff and ignore everything else. A map of the Boston subway is a useful model. It allows you to swiftly chart your course from Copley station to South Station, because the map omits distracting real-life details like the bustling crowds of commuters, the twisty, screechy track around Boylston, and the train's broken-down air-conditioning.

All the models in this book are designed to help you focus on the important stuff—namely, the ideas most useful for making sense of the Big Three (consciousness, language, and the Self). In Archie's case, the most important idea is that no matter where you put him, he will always move toward the brightest source of light.

It might not seem like a sun-basking microorganism would require the ability to think to survive. But as you demonstrated a moment ago, to accomplish what a haloarchaeon does, a human being would certainly need to think. Sure, the single-celled haloarchaeon doesn't sport a visual cortex or a motor cortex, let alone a brain. But *some* kind of mental apparatus must survey its environs, judge the direction of the brightest source of light, and command its body to move there.

What constitutes thinking in a creature so piffling that it managed to elude microscope-brandishing scientists for more than three hundred years?

ARCHIE'S MOVEMENT

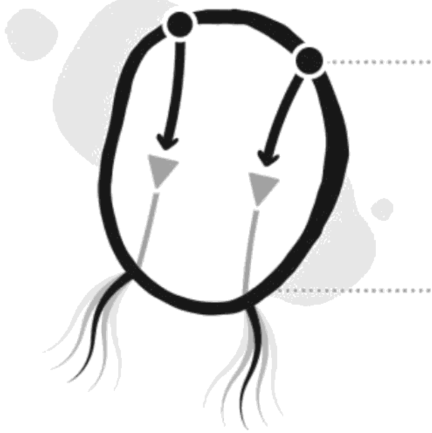


2.

Archie's mind consists of just four thinking elements: two sensors and two doers. Each sensor is connected to one doer, in two parallel sensor-doer pairs.

Archie is an example of a *molecule mind*, the first stage of thinking on our journey. All the thinking elements in molecule minds consist of individually identifiable molecules. The membrane of an actual haloarchaeon is traversed by a shape-shifting molecule known as a sensory rhodopsin. This molecule serves as the haloarchaeon's visual sensor—its "eye." The sensory rhodopsin responds to light (or darkness) by changing its shape, which triggers a cascade of molecular activity that activates the haloarchaeon's doer. Its doer is a *flagellum* that extends from the archaeon's body like a bullwhip.

ARCHIE



Almost all the simplest minds on Earth wield flagella. That suggests that the lash is the primal instrument of earthly intelligence, the ur-tool of the mind that all other anatomical doers (such as claws, teeth, and wings) are functionally descended from. A handful of flagella extend from a haloarchaeon's posterior and thrash like propellers, driving it forward. These flagella (technically known as *archaella* in archaea, because they have a different molecular composition and a different genetic history than bacterial flagella) are made of thousands of molecular filaments. A flagellum is activated by a chemical chain of hundreds of protein molecules triggered by the sensory rhodopsin. That means that the entire sensor-doer pathway in a haloarchaeon consists of fewer than ten thousand molecules. By comparison, scientists have estimated that a single human neuron contains somewhere in the ballpark of fifty billion molecules of protein alone.

When one of Archie's "eyes" detects darkness (much like the night sensor on a streetlamp), it sends a signal to its linked "propeller," which begins to whip Archie forward. The dimmer the light, the stronger the signal. The stronger the signal, the stronger the propulsion, which means that Archie's flagella whip their hardest in total darkness.

Archie is barely more sophisticated than the simplest possible mind, yet despite his austerity he flashes enough intelligence to thrive in his chaotic world, an unpredictable liquid realm buffeted by eddies and shadows where he must obtain sunshine to survive. The four elements of his mind all contribute to a single purpose:

Seek out the light.

ARCHIE'S MOVEMENT EXPLAINED

1.
Initially, the **left-side sensor** detects more darkness because it is farther from the light, so it sends a stronger signal than the right-side sensor, which makes the **left-side doer** whip faster than the right-side doer, which makes Archie move forward and turn to the right …

2.
The **left-side sensory signal** starts to weaken as it gets closer to the light, which makes the two flagella closer in strength, which makes Archie slow down and turn less sharply…

3.
Eventually, the light source is located directly between the two sensors, which makes them send **signals of equal strength**, which makes **the flagella whip with equal strength**, which makes Archie go straight forward. Since the sensory signals continue to weaken, Archie slows down as he nears the light …

4.
Finally, the light is so close and strong that both sensors shut off, which shuts off the flagella, which makes Archie halt.

3.

Imagine you visit a park with a basketball court. Pick out ten strangers at random, invite them onto the court, and toss them a ball. They stand around blinking at you. Is this a basketball game? No. Not even if all ten people, through an uncanny stroke of serendipity, happened to be professional athletes employed by the Boston Celtics.

A game is not defined by the identity of the players. A game is defined by how the players *interact* with one another. If your ten randomly selected strangers formed into two teams of five and began to dribble and pass the ball around the opposing team as they attempted to hurl the ball through the hoop, well then. Now you've got a basketball game.

It's the same with Mind. A mind is not defined by the identity of the physical stuff inside an organism. A mind is not defined by its neurons or, in Archie's case, by its molecules. A mind is defined by how its thinking elements *interact*. A man who has been dead for an hour has the same physical stuff in his brain he had the hour before, but no thinking is going on because his neurons are no longer interacting. A corpse is like ten people standing around a basketball court: no game, no mind.

Both a game and a mind are examples of what mathematicians call a *dynamic system*. A dynamic system is defined by *change*. A given system's dynamics consist of the way the system's activity changes over time. Whenever you read the term "dynamics," you should think of "change," "activity," or "action." The word "mind" is an action noun *because* the mind is a dynamic system. Understanding a mind's dynamics is the key to understanding how it thinks, which is why dynamic systems theory is the most useful branch of mathematics for investigating Mind.

Though the size of a mind's sensors and doers, their location in the body, and their chemical identity undoubtedly influence a mind's dynamics—this is what the embodied thinking principle advises us—these features by themselves don't constitute a mind any more than the height of the players, their position on the court, and the color of their jerseys constitute a basketball game. A game consists of jump shots and blocks and free throws and fouls—that is to say, the *action*. A mind consists of the activity of its thinking elements as they move around, change their shape, send out signals, and react to other thinking elements. We'll call this activitydictated conception of the mind the *basketball game principle*, the second key principle in the journey of Mind.

The basketball game principle holds a very important lesson for how we should think about thinking. If you were watching an actual basketball game, you'd probably focus on the ball. After all, the ball drives all the action and accounts for all the scoring. This seems to suggest that if you simply traced out the trajectory of the ball over the course of a game, you'd acquire a pretty good understanding of the game. Not so. A basketball game consists of the activity of *all* ten players, even the ones who aren't touching the ball.

As every coach knows, if you want to understand how a particular player scored, you need to know what all the other players were doing. During a given play, a player might be cutting toward the basket, blocking out an opponent, setting a screen for a teammate, or performing many other actions that influence the flow of the game. All these individual actions are happening simultaneously in real time and each player's activity influences every other player's activity. If one player leaps up to block an anticipated shot, her opponent might react by passing the ball to someone else, or faking a shot before taking the real shot, or leaning into the blocker in an attempt to draw a foul. Meanwhile, one of the blocker's teammates might sprint down the court in the opposite direction in the hope of a fast break. In a basketball game, everything is happening everywhere all at once. According to the basketball game principle, then, if we wish to understand the dynamics of a game—or a mind—we must learn to think *holistically.*

There is no isolated or compartmentalized thinking activity within Archie's mind. Thinking occurs everywhere at the same time. Archie's mind is nothing like a computer program, which is the opposite of a dynamic system. Archie does not follow a functional sequence of: perception *then* judgment *then* action. In fact, Archie has no distinct "perception circuit" that creates a representation of the light. Nor does he possess a "navigation circuit" that judges which direction to go. There's not even a "motor-control circuit" that executes his navigational plan. It's simply not possible to say, "*Here* and *now* is where Archie's mind forms an image of the light" or "*Here* and *now* is when his mind makes the decision to move." Instead, Archie's "eyes" and "propellers" all interact continuously and simultaneously in real time to move him toward his desired target through ceaseless loops of blurred causality.

You might imagine that even though archaea's thinking is simple and holistic, that eventually the journey of Mind must cross some decisive bridge separating primitive forms of thought (like Archie's sun-seeking) from magical forms of thought (like consciousness, language, and the Self). Not so. The basketball game principle proclaims: *the magic was already there from the very start.*

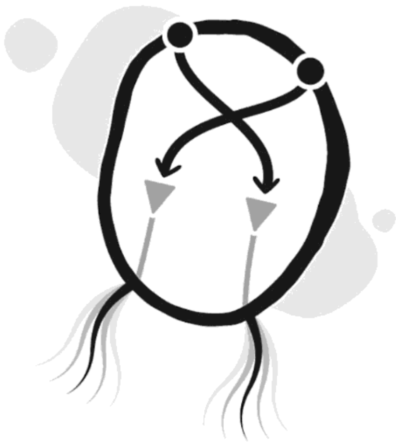
In physical matter's transition from purposelessness to purpose, it wasn't the *elements* of mind that were enchanted. It was their *arrangement*. The holistic mental dynamics solving the archaea's targeting problem are generated by a special configuration of ordinary molecules. A more complex configuration of the same ordinary molecules generates the holistic mental dynamics responsible for the Big Three.

The relevance of a mind's configuration becomes apparent if we make a single tiny change to Archie's wiring and thereby transform him from a creature of light into a creature of darkness.

4.

Here is Cross-Wired Archie:

CROSS-WIRED ARCHIE



Cross-Wired Archie has the exact same thinking elements as his predecessor, in the exact same locations. The *only* thing that has changed is that all of his sensor-doer connections are now wired *across* his body, instead of running parallel to one another. There's been no change at all in the substance of Archie's mind. No new thinking elements, no shuffling around existing elements, no new wires. The only change we've made is swapping the *ends* of the wires.

Let's place Cross-Wired Archie in the same spot as before. How does he behave now?

CROSS-WIRED ARCHIE'S MOVEMENT EXPLAINED

1.
Initially, the **left-side sensor** detects more darkness because it is farther from the light, so it sends a stronger signal than the right-side sensor, which makes the **right-side doer** whip faster than the left-side doer, which makes Archie move forward and turn to the left …

2.
As Archie turns, **both sensors** move away from the light, which makes both send stronger signals, which makes **both flagella** whip harder, which makes Archie swim faster and continue to turn to the left …

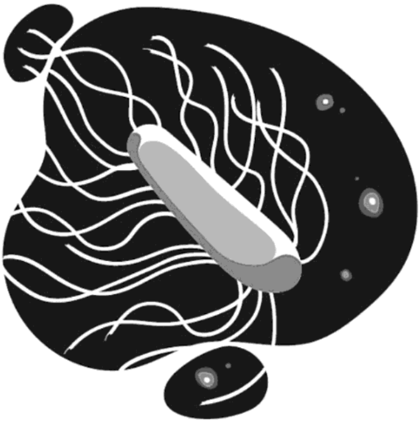
3.
As Archie continues to turn away from the light, **both sensors** eventually send signals of equal strength, which makes Archie stop turning as he continues to swim faster and faster …

4.
Finally, Archie reaches his maximum velocity as he swims directly away from the light, deeper and deeper into the darkness.

If you alter a mind's dynamics, you alter its purpose. Cross-Wired Archie's behavior—avoiding light and seeking darkness—is the exact opposite of Parallel-Wired Archie's. Parallel-Wired Archie was a Light-*Seeker*. But Cross-Wired Archie has become a Light-*Shirker*.

The divergent behaviors of Parallel-Wired Archie and Cross-Wired Archie illustrate how the evolution of the earliest minds likely unfolded. Slight changes in the location or activity of a single molecular thinking element can lead to dramatic transformations in a molecule mind's behavior. (Similarly, replacing a short player with a tall player or a great shooter with a great defender can lead to dramatic changes in a basketball game.) During the molecule mind stage of the journey of Mind, minor tweaks to molecular thinking elements produce major innovations that empower molecule minds to better adapt to their world.

Calculus, comedy, and kitesurfing might seem impossibly remote destinations from the unassuming archaeon, but even the lengthiest of journeys begins with a single purposeful step—or twitch of the flagellum.



CHAPTER THREE / **BACTERIA MIND I**

Decision-Making

Exploration is in our nature. We began as wanderers, and we are wanderers still.

—*Cosmos*, Carl Sagan

1.

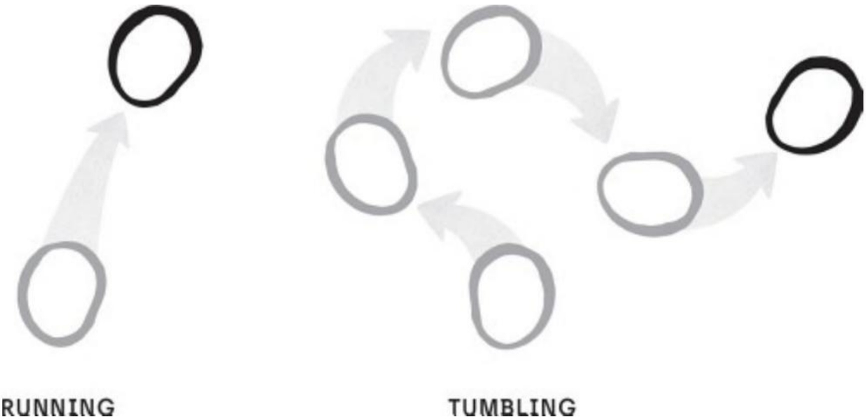
Bill Belichick is widely regarded as the most talented American football coach alive. He's won the most playoff games in the history of the sport. He's been to twelve Super Bowls, the World Cup of American football, winning eight of them. One of the main tactics powering his winning ways is what Belichick calls "situational football"—the notion that you need to select the right play for the specific situation that you are faced with at any given moment. Some scenarios demand a passing play, where the quarterback hurls the ball through the air to a receiver. Other scenarios demand a running play, where the quarterback hands the football to a running back who tries to bulldoze his way through the defense. The challenge, of course, is correctly deciding which action the circumstances call for. Coach Belichick has mastered this challenge so well that he is considered a football genius.

Nobody would consider bestowing the epithet of "genius" upon a lowly bacterium. Despite this snub, bacteria have mastered what we might call "situational food-ball."

In 1972, biologists noticed that bacteria exhibited two distinct types of locomotion. The first consists of rapid darts straight ahead. They dubbed this type of movement *running.* The second consists of haphazard, erratic jostling. This was dubbed *tumbling.*

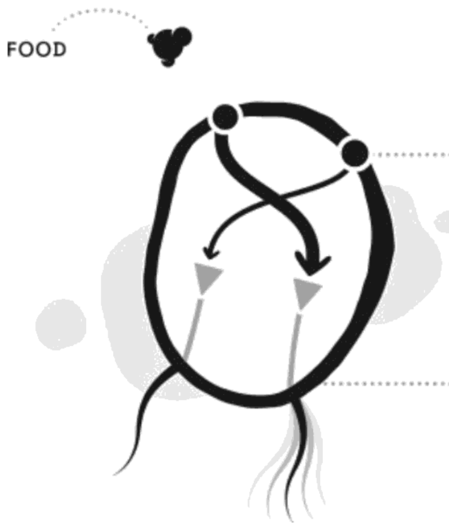
After further investigation, it became apparent that bacteria run toward food and tumble about when they arrive at the food. They were somehow *deciding* to switch from running to tumbling or back again according to the conditions they encountered. But how can a microscopic molecule mind make context-dependent decisions?

RUNNING VS. TUMBLING



As it turns out, it's possible to transform Cross-Wired Archie into a situational decision-maker without adding any new thinking elements or modifying any of his connections. To see how, please make the acquaintance of Sally the salmonella:

SALLY



Salmonella enterica is a bacterium. It is one of the most common causes of food poisoning in humans and is the pathogen responsible for typhoid fever. About 155,000 people die every year from salmonella-related disease. Like archaea, a salmonella bacterium has sensory molecules on its membrane that detect a variety of stimuli in its environment, including particles of food. Its food sensors send signals to its flagella, which whip the bacterium forward. When a salmonella notices food, it *runs* toward it until it gets close, then erratically *tumbles* near the food as it slurps it up.

Sally steers toward a food particle using the same dynamic that Cross-Wired Archie used to steer toward darkness. If food is toward the left, Sally's right-side flagellum whips harder, turning her left. If food is to the right, the left-side flagellum whips harder, turning Sally right. If food is straight ahead, both flagella whip hard, causing Sally to *run*.

Sally has not added a new decision-making thinking element. Her configuration of sensors and doers is identical to that of Cross-Wired Archie, who does not choose whether to run or tumble. So how is Sally able to decide when her circumstances call for running and when they call for tumbling—and how does she switch between the two?

The answer lies within an upgrade to Archie's doers.

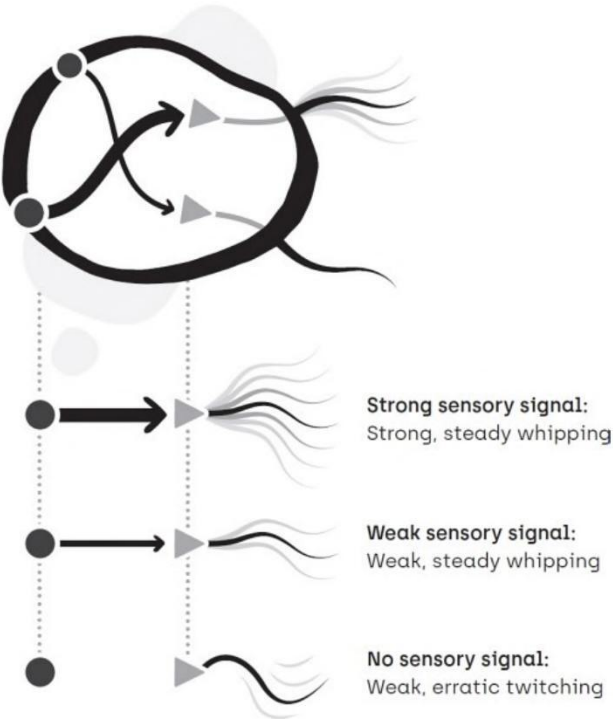
2.

Sally's flagella operate slightly differently than Archie's. Archie's flagella, recall, always whipped with an intensity proportional to the signal received from their sensors. Stronger sensory signal = stronger whipping. No sensory signal = no whipping. But Sally's enhanced flagella can perform two distinct actions: *whipping* and *twitching.*

When one of Sally's flagella receives a signal from a sensor, it behaves the same way as Archie's flagella, namely, it *whips* with a strength proportional to the intensity of the signal. But let's see what happens when no signal is arriving at a flagellum. Without any incoming stimulation, Sally's flagellum *twitches* intermittently at an irregular pace. It's as if Sally's doers have a low and random "idling rate."

But how does a twitching flagellum furnish Sally's mind with the power of "situational food-ball"? Whenever Sally detects a distant food particle, she reacts in the same manner as Archie, with her "eyes" activating her "propellers," prompting Sally to run toward the food.

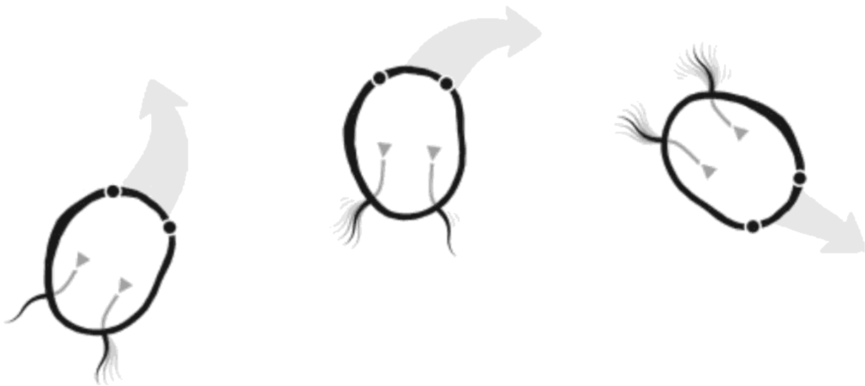
SALLY'S DOER



But when there is no food nearby, something unusual happens. Her flagella go into "idling mode." They start to twitch randomly. Since each flagellum is now quivering at its own independent and irregular interval, Sally jounces about unpredictably. She begins to *tumble*.

SALLY RUNS

SALLY TUMBLES



How does Sally benefit by tumbling when there's no food around? It allows Sally to aim her food sensors in different directions until she detects a new particle of food. Since she has no idea which direction might be most fruitful, a random search works just fine. As soon as she notices a distant whit of nutrition, her sensors light up, her flagella whip in harmony, and she scurries for her supper.

By making a small change to Archie's doers, while keeping everything else the same, Sally gained a powerful new skill: situational decision-making, a talent that enables salmonella to track down our intestinal cells and slip inside, triggering a nasty case of gastroenteritis.

3.

One of the chief problems that every organism must address is how to get the resources it needs to stay alive. Every living thing, no matter how enormous or tiny, must find *food*. Before the first minds came on the scene, the earliest microscopic critters probably dwelled in a nutritional Garden of Eden where food was abundant and easy to access. Perhaps they harvested minerals or electrons from the rocks they clung to, perhaps they floated around pools or oceans soaking up compounds dissolved in the water, perhaps they simply luxuriated in the sun's rays and converted solar energy into metabolic energy. For a long time, life would have been passive and uncompetitive.

As the food supply eventually began to shrink from endless generations of feeding or competition from ever-growing numbers of rivals, the first sensors and doers likely appeared, making it possible to *search* for food. The first mental revolution in the journey of Mind was probably a transformation from the sedentary lifestyle of tiny mindless organisms to a hunting-and-gathering lifestyle of tiny thinking organisms.

Once the first mind was able to discriminate between light and darkness, or food and toxins, the lazy days of Eden were over. The hunting-and-gathering lifestyle introduced new challenges for the fragile young minds, none bigger than the problem of choice. The capacity for targeted movement introduced a dilemma that all minds must constantly grapple with. *Should I keep exploring for more promising opportunities—or exploit what I've already found?*

This is the exploration dilemma.

A dilemma is a mental challenge where a perfect solution is not possible because there's an unavoidable trade-off. An organism confronting the exploration dilemma must decide whether to enjoy the resources previously obtained or spend resources on a quest for new resources—and risk finding none.

Our own species has come up with a variety of maxims that capture the uncertainty inherent to the exploration dilemma. "Fish or cut bait" is a common admonition in business, giving voice to the question of whether you should continue to invest money and time in an opportunity that hasn't paid off yet and may never pay off (that is, continue fishing)—or cut your losses and move on (that is, cut the bait off your line so you can pack up your fishing rod and go fish somewhere else). "A bird in the hand is worth two in the bush" provides concrete guidance for managing the exploration dilemma by suggesting one should consume a single serving of food rather than go hunting for two servings of food that you may not be able to acquire. The exploration dilemma is expressed in its most naked form in the ultimatum "Take it or leave it."

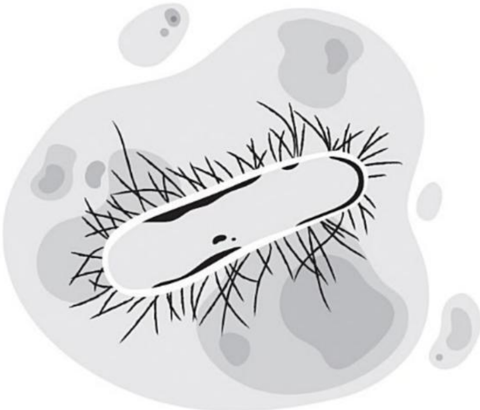
Archie's implicit solution to the exploration dilemma is to whip in the direction of the brightest source of light—that is, to *explore*—then stop whipping once he gets close enough to the light to soak up its nourishing rays—switching over to *exploiting.* Sally, in contrast, handles the exploration dilemma by shifting between two modes of behavior: *running* for exploration (moving toward a place where there might be food) and *tumbling* for exploitation (staying put upon reaching food so she can eat it).

The mind's solution to the exploration dilemma embodies a dynamic that distinguishes minds from other physical systems: decision-making. A mind makes choices. The ability to *choose* one course of action over another is the ultimate source of agency in the universe: unlike protons, rivers, or black holes, a mind can *decide* to explore rather than exploit—or to exploit rather than explore.

Sally illustrates the simplest biological dynamic of situational decision-making, and it's somewhat counterintuitive. Sally does not possess a "Coach Belichick molecule" that issues an authoritative command to run or tumble. There is no explicit site in Sally's mind where she "recognizes" there is no food nearby. We cannot identify a specific place in her mind where she "decides" to switch from running to tumbling nor a precise moment when such a decision occurs. This is not a matter of our having incomplete information about Sally's mind. We can identify *absolutely everything* happening inside Sally. There is simply no answer to the question "What part of Sally's mind is responsible for situational decisions?" because her decision-making process is holistic, involving all her thinking elements working together in unison.

As we continue onward, the environments of more advanced organisms will steadily expand in size, scope, and complexity, goading their minds to develop increasingly sophisticated tactics for contending with the exploration dilemma, not just in the pursuit of food, but in the pursuit of sexual partners, nesting spots, and entertainment, and in the avoidance of toxins, predators, and stress. At its heart, the exploration dilemma presents a profound philosophical quandary that speaks not only to the essence of the human condition but to the condition of all thinking beings.

Should we settle for *this*? Or risk it all in the hope for something better?



CHAPTER FOUR / **BACTERIA MIND II**

Memory

I’ve got a more graceful solution to the memory problem. .
. . I use habit and routine to make my life possible.
—Leonard Shelby, *Memento*

1.

When we ponder the nature of remembrance, our mind may gravitate toward fond memories, like a romantic trip with an amorous partner, a hard-fought victory, or a sweet moment with our child. Or we may contemplate *Jeopardy!*-style facts, like the name of the sixteenth American president or the capital of Bahrain. Or we might marvel at celebrated feats of recollection like those of Kim Peek, the inspiration for *Rain Man*, who could recall the exact contents of twelve thousand books and the location of every ZIP code in the United States.

These examples can make us instinctively conceive of memory as a kind of hard drive filled with files that we retrieve and store, somewhat like the Pixar film *Inside Out*. In it, a girl’s memories are visualized as glowing orbs stacked tidily upon enormously long shelves. The blue orbs are sad memories. Yellow orbs are happy memories. Green orbs are disgusting memories. The widespread impression of human memory as a kind of cloud-based file storage from which we upload and download facts and experiences is undoubtedly influenced by our immersion in the Internet Age. But memory does not work like this in any living creature.

Like all the mental innovations in the journey of Mind, memory first arose to solve a specific challenge. We might call this challenge the gradient problem. On the face of it, the gradient problem doesn’t seem to have anything to do with memory. In fact, it naturally presents itself as a navigation problem.

When we examined Sally and her reaction to food, we presumed that the stimuli her sensors detected were singular and discrete—that is to say, we presumed Sally's mind treated her environment as if it contained *one* particle of food at a time. In reality, bacteria are usually immersed within hazy clouds of food particles of ever-shifting densities.

VARIABLE CONCENTRATION OF FOOD

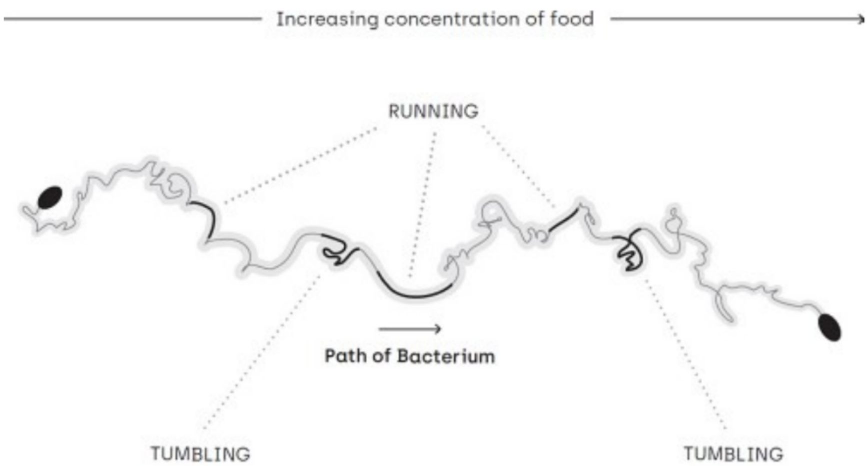
Piloting through such a nebulous environment presents a novel stumbling block. If Sally attempted to navigate through a fog of food particles, she would end up twisting and careening about in an inefficient manner as each new movement of her body brought a different morsel near her sensors and triggered another reorientation. She would spend more time twirling and jiggling than eating.

One strategy for solving this navigational challenge would be to ignore the individual crumbs and instead attempt to determine where the greatest *concentration* of crumbs lies. This requires a major mental shift from thinking in terms of discrete points to thinking in terms of continuous gradations. Instead of searching for the nearest *particle*, in other words, search for the nearest *region* with a high density of particles. This is exactly what *E. coli* does.

Like salmonella, *Escherichia coli* is a rod-shaped bacterium important to both scientists and our intestines. Many strains of *E. coli* live symbiotically inside our guts, aiding with digestion and protecting our digestive tract from malicious bacteria. Regrettably, several strains of *E. coli* are pathogenic, which is why it occasionally moonlights as the villain in a national food recall. *E. coli* has long served as a kind of guinea pig for microbiologists. The bacterium can be cultured easily and inexpensively in a laboratory setting and is consequently one of the most studied organisms in science. Running and tumbling were first discovered and fully described in *Escherichia coli*.

Like salmonella, *E. coli* has sensor molecules that detect a variety of stimuli, including sugar, salinity, acidity, temperature, amino acids, and toxins. *E. coli* runs toward high densities of food, then tumbles when it arrives. To illustrate this, here is an actual path taken by an *E. coli* bacterium in a petri dish where the concentration of food steadily increases to the right. Though the bacterium's herky-jerky path is far from optimal—it is so minuscule that its body is constantly jostled by molecules, like bicycling in a blizzard—it reliably moves itself into the region with the highest available concentration of food.

E. COLI LOCOMOTION IN FOOD GRADIENT



Adapted from Waite et al.

So how does a bacterium manage to steer itself through an ever-morphing cloud of nutrition? One method might be to compare the density of edibles at two different locations on *E. coli*'s body. That's what larger single-celled organisms such as amoebas do. They compare what their sensors detect at one end of their body to what their sensors detect at the other end and calculate which side senses the higher concentration.

But *E. coli* are too small to perform this trick. Amoebas are one thousand times larger than *E. coli*. There's simply not enough distance between the front and rear tips of *E. coli* to effectively assess the relative density of food. Fortunately, another approach is available to the bacterium, one that makes use of an indirect source of information.

E. coli can harness time.

Instead of comparing food concentrations at two different *locations* on its body at the *same* moment in time, a bacterium compares concentrations at the *same* location on its body at two different *moments* in time. Thus, a spatial problem becomes a temporal problem. If a bacterium detects more food nearby than it did previously, that means it's moving into a higher concentration. Great! Keep going! If it detects less food than previously, that means it's moving into a lower concentration. Oops! Better stop!

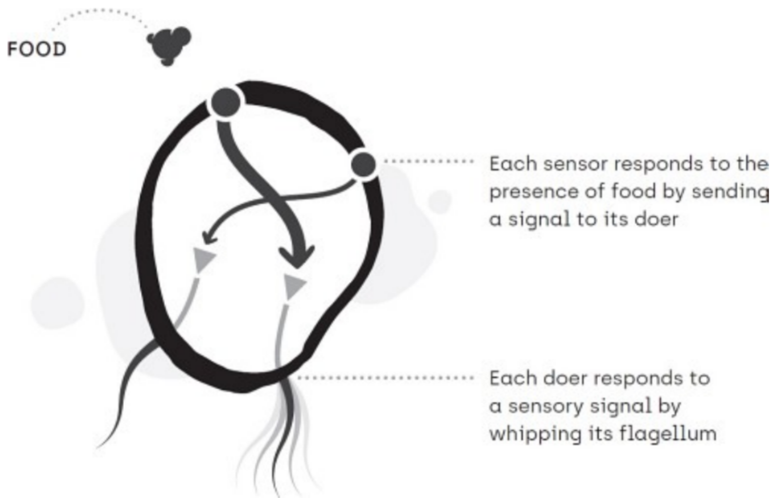
To evaluate food gradients using this time-based approach, an *E. coli* mind must somehow store information about the amount of food it detected in the recent past.

In other words, it must form a memory.

2.

Please exchange greetings with Eska the *E. coli*:

ESKA



Eska has the same four-element configuration as Sally. Her two sensors respond to food. Her two doers *whip* when activated by a sensor signal and *twitch* with no signal. Thus, Eska *runs* toward food and *tumbles* when no food's nearby. So far, so familiar.

But Eska trots out her own upgrade, another molecular tweak. Until now, all the sensors we've encountered exhibit a response proportional to the strength of the stimulus. Strong light evokes a strong signal, weak light evokes a weak signal. But this is not how Eska's sensors behave. After they encounter a stimulus—like food—they steadily lose their responsiveness. They send a weaker and weaker signal to their doer like the fading light from a dying ember. This is known as *habituation.*

When Eska's sensors detect food, they react the same way that Archie's and Sally's sensors did. They fire off a signal to their flagellum proportional to the strength of the stimulus. Lots of food = strong signal. But here's where the difference lies. The moment Eska's sensor fires, it starts reducing its responsiveness to food.

ESKA'S SENSOR

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Production manager: Anna Oler

Library of Congress Cataloging-in-Publication Data is available

ISBN 978-1-324-00657-2

ISBN 978-1-324-00658-9 (ebk.)

W. W. Norton & Company, Inc., 500 Fifth Avenue, New York, N.Y. 10110
www.wwnorton.com

W. W. Norton & Company Ltd., 15 Carlisle Street, London W1D 3BS