Surface Tension: Reflections on Personal and Natural History

by

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"So many things have been shown me on these banks, so much light has illumined me by reflection here where the water comes down, that I can hardly believe that this grace never flags, that the pouring from ever-renewable sources is endless, impartial, and free"—Annie Dillard, *Pilgrim at Tinker Creek* (69)

"I walked in the woods, with boot and stick, hunting that fresh surface of experience, that actual touch and smell of reality without which a philosophy soon becomes metaphysics"—Donald Culross Peattie, *An Almanac for Moderns* (274)

"Everywhere we are surrounded by the ineffable, our familiarity with reality is a myth" –Abraham Joshua Heschel, *Man Is Not Alone* (214)

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Preface

"I went to the woods because I wished to live deliberately, to front only the essential facts of life, and see if I could not learn what it had to teach, and not, when I came to die, discover that I had not lived"—Henry David Thoreau, Walden (343)

In preparation for the thesis, I spent the first two weeks of last summer living the rural life in the Chattahoochee National Forest near Blairsville, Georgia. Quite naively, I felt that this time would hand me a platter of seminal experiences from which to fashion a definitive narrative. I was hoping at some point, Nature would stand in front of me and declare, "I'm here! Know me!" Unsurprisingly, that didn't happen. I did have what may have been the best two weeks of my life, though, and I can recall more incredible brushes with nature than I could feasibly incorporate into a thesis. (For example, I remember awaking one morning after leaving the porch light on only to find the outside of the cabin splatter painted with dozens of species of moths.) Being in that cabin proved a formative experience, and my readings in nature writing and physics coupled with the constant run-ins with wilderness reshaped the way I interacted with my perceptions of the world.

I had initially planned to organize my work around the phylogenetic tree much as Primo Levi did with chemistry in *The Periodic Table*, meaning that in each chapter, a certain clade of organisms would play a pivotal role. When I went through the field notes and reading journal I had been keeping, I realized that I hadn't had enough experiences with a wide enough variety of taxonomic groupings for the plan to work. As I was rereading my notes, I had a (Verlyn

Klinkenborg-assisted) revelation: when we look at an organism, we're not *really seeing* it. Even devoting my entire gaze and undivided attention to, say, a chipmunk only reveals a cross-section of it; I can't see the underlying processes, the nested complex systems, that sustain it. I realized that I would organize my thesis around the limits of human perception and how our ability to conceptualize might be used to overcome those limitations.

I decided that I would pick the natural phenomena that best highlight the limitations of perception and flesh them out into interconnected essays. Remembering the first time I encountered an insect gall, I began thinking about the staggering number of symbiotic interactions that happen around and within us that we don't notice, either because they're invisible to the naked eye or because we don't pay attention to them. And no matter how strong a microscope we use, we can never be privy to that moment of synthesis, that biological point of no return. More than a simple strategy for survival, symbiosis drives evolution in the much the same way as competition. Competition and the adaptive refinements it brings, though, also craft astonishing forms. I knew I couldn't ignore the dynamic specialization that competition produces (especially since specialization manifests itself in impossibly particularized organs, ones that elude our sight), so I decided that it should be considered as distinct from symbiosis. While symbiosis is, in a sense, a kind of specialization, it represents an ontological break with the *concept* of specialization because it relies on union more than mere filiation. The relationship between specialization and symbiosis got me thinking about how processes interact and how, at some point, new

properties (like symbiotic interactions and specialized structures) emerge that are more than the additive sum of their parts. I thought about complexity, the nested, hierarchical organization, of living things, another aspect of nature that our limited perception obscures. I couldn't divorce my thinking about complexity from the concept of scale, of "zooming in" on a structure to reveal its components. I couldn't separate complexity from the related concept of the fractal, a geometrical form in which the parts resemble the whole, and the parts of those parts also do, and so on. In both cases, changing the scale entails resolving finer details. But fractals differed from complexity in that with complexity, those finer details are *interacting systems* made of smaller systems, while with fractals, the details are more singular entities than systems and the dynamic interaction isn't there. The key distinction is that in complexity, we can't possibly perceive all of the infinite *interactions*—the possible movement of every atom and how that affects the cell—and in fractals, we can never perceive all the *details*, the self-sufficient entities.

I view this project as a way of expressing and enhancing my wonder at the natural world, the incomprehensible intricacy and ingenuity of the physical universe. It never ceases to astound me. The improbability of the all parts coming together in something as a common as a gray squirrel bowls me over; I have to pick myself up off the ground and dust myself off every time I take a walk. Furthermore, I'm hoping that this project will help convince its readers that nature writing is still necessary in the contemporary world, that any issue can be articulated in terms of nature just as it can in fiction or poetry. The

landscape of nature (and science) has changed significantly in the past two decades. Just last year, for instance, a team of scientists spearheaded by Craig Venter created "Synthia," a synthetic bacterium in a laboratory, planting a human-constructed genome in the protein body of *Mycoplasma genitalium*. Synthia signals an epistemic break in biology, the point at which humans can *build* life, and nature writing in a post-Synthia world must contend with this.

Moreover, this is my attempt to perceive more clearly. So many people just *miss* aspects of the world that seem impossibly astonishing. I don't think of myself as having any special perceptive capacities—my hearing is certainly no better than most and I have to wear glasses—but I do believe that if we made a stronger effort to understand our surroundings, we would be richly compensated with unabating amazement. In addition to advocating that we pay more attention, I write with something of an agenda. This is, at least implicitly, a conservationist document. The unbelievable complexity and beauty of natural systems stem in part from their dissociation with the human world. If we are not careful, we may end up destroying perhaps our greatest natural resource: the constantly renewing wellspring of wonder. This is my plea to keep that spring flowing.

This project is an attempt at a Grand Unification Theory—not one tying together the four fundamental forces of physics but one weaving together literature, philosophy, biology, physics, chemistry, and personal experience. It splits the difference between science and nature writing, attempting to explain scientific discoveries while incorporating personal musings. In that vein, it is a

unification of writing styles as well. My work is an endeavor to merge the imaginative prose, wide-eyed wonder, and meditative spiritual voracity of Annie Dillard (*Pilgrim at Tinker Creek*), the dense metaphorical nets of Donald Culross Peattie (*An Almanac for Moderns*), the science and speculation of Chet Raymo (The Soul of the Night), the straightforward and elegantly scientific natural histories of Stephen Jay Gould (*Ever Since Darwin*), and the sheer explanatory power and clarifying metaphors that link the quantum to the everyday of Brian Greene (The Elegant Universe). More than just an influence on style, however, two works in particular shaped the way that I think about the natural world, and to them I owe a special debt of gratitude. First, Abraham Joshua Heschel's Man Is Not Alone: A Philosophy of Religion refined my thinking about wonder and the ineffability of the mystery of nature. Heschel reconfigures wonder into a sort of prayer, an acknowledgment of the limitations of human understanding, and peels back the layer of familiarity to transform the mundane into the divine. Most of all, the book that astonished me into a revitalization of the natural world through modern-day mysticism is *Pilgrim at Tinker Creek*. To quote the author, "I had been my whole life a bell, and never knew it until at that moment I was lifted and struck" (Dillard 36); this book was that moment for me.

I also want to acknowledge the influence of several non-print sources that have provided me with a foray into nature that I could never have experienced otherwise. PBS's outstanding *Nature* and *Nova* series afforded a clear view of pertinent topics in nature. David Attenborough's unparalleled BBC nature documentaries (*Blue Planet: Seas of Life, Life in the Undergrowth, Planet Earth*)

have been as decisive in my development as a nature writer as any of the books I've read. Taken together, Attenborough and PBS have made me privy to some of nature's greatest spectacles. The visual clarity and excellent cinematography of their films has allowed me to travel to Borneo and the hydrothermal vents at the bottom of the ocean.

Scientific reason and the creative impulse of literature are not only not incompatible but are best served together—like coffee and cream or peanut butter and jelly. Science does anything but take away wonder; it provides an entry point into it, giving more and more to wonder at. Science furnishes the explanations, the infinite arrays of topics to marvel at, while literature lets us articulate our reactions in the language of wonder. Literature answers the philosophical and poetic questions that scientific study begs. Science and art collide and interact like an electron and positron, annihilating each other and producing a radiant photon glowing in a burst of illumination.

Introduction: A Hike Through Buzzard Swamp

"Wonder is not a state of esthetic enjoyment. Endless wonder is endless tension, a situation in which we are shocked at the inadequacy of our awe, at the weakness of our shock, as well as the state of being asked the ultimate question"—Abraham Joshua Heschel, *Man Is Not Alone* (69)

I've always been more interested in close views than in vistas. But this pond in Buzzard Swamp, a dammed up stream in the Allegheny National Forest, has a panorama so picturesque it could serve as a template for the rehashed, prefabricated paintings that sell at those "1 Day Only! Starving Artist Sales" held in cheap hotel ballrooms. Banks of every hue—orange reeds, dark green pines, purplish trees standing naked and unashamed, white lacy flowers spread like pulled cotton, tan hollow sheaths like the ghosts of dead grass—frame the stream-pond graciously. Bleached dead pines, which must have grown on what used to be the streams' banks in the days before the dam was built, now rise up like bony fingers reaching from the pond's bottom and make perfect perches for a kingfisher. Ripples in the water, almost x-shaped in the way they overlap, cross and blend like chromosomes dancing. Right near the dam, where I'm sitting, the water is brown, catching the sunlight and emanating it in waves, the golden rays forming a sort of undercurrent beneath the rippling layer of the pond's skin. But off in the distance, as the view recedes and the horizon starts dripping into the water and pouring over the surrounding hills, the water is pure blue. Nothing about the name Buzzard Swamp suggests a view this breathtaking, this pond ringed in layers of different colors stretching beyond the limits of my vision;

you'd expect a few muddy marshes, complete with heaps of decaying detritus, but not *this*. I had never realized starting at a static scene could be so dynamic.

But there isn't time to stare. My brother and I are walking a thirteen-mile loop through the viscera of the Allegheny, and we need to be back by sundown. That curfew is entirely nonnegotiable: we didn't bother carrying flashlights because, as we thought, they would only weigh us down. As much as I feel Buzzard Swamp lulling me into a waking dream, I also sense the urgency of finishing the hike nipping at my heels. We slowly raise ourselves from the dam, pass the tubular pipes dealing water to the stream below, and enter into a veil of old growth hemlocks. The instant I reenter the forest I realize how little light is left in the day; Buzzard Swamp lay exposed to the rays of the sun, but the interstices in the leafy hands of the forest trees are pickier about which light they let through. There are still six miles separating us from our campsite.

Plunging into the copse of hemlocks that are so tall that you know they get picked first when trees play basketball, my brother hears a muffled rustling. "Look at that tree!" he gasps. I swivel my eyes to the invisible beam pointing from his fingertip to a naked branch—a distance of at most ten feet—only to see a red-tailed hawk landing. Grabbing a perch with its legs extended like airplane landing gear, the hawk begins to neatly fold its wings. Its huge marble eyes focus on us as we stand as still as possible. At this distance, I can see the hawk with a clarity normally reserved for backyard feeder birds. Its nude, scaly legs look like something out of *Jurassic Park*, and I imagine that if I could pluck all of its feathers off without hurting it, I would have the quivering, pink semblance of a

modern-day dinosaur sitting bare before me. If only I could unwrap this neat, little package of nature, peel away the surface, and get to its essence.

The experience astonished me, and yet, as I reflect on it, I can't help but wag a finger at myself for wanting to see *more*. I saw that hawk with unparalleled acuity, and somehow I had the gall to want to unwrap its feathers to see its phylogenetic history written on its body, to sit in its seat of subjectivity and know its thoughts. Later that day, I had this impulsive wish that I could go back to looking at that red-tailed hawk as I would have when I was a toddler, before I knew what it was, when it was a pure form—nameless and nothing but shape. I wanted again to see the powerful grace of that hawk as an entirely aesthetic impulse, a stimulus without signification. I had this nagging feeling that that's when wonder is the greatest, when a person can appreciate the hawk as a visual phenomenon, an uninterrupted stream of deflected photons striking the retina as the image constantly renews itself at a hundred eighty-six thousand miles per second.

But, again, I wag a finger at myself; I rethink it and realize that if I saw it as a baby does, the hawk would mean nothing. There's no reason that it should excite me more than a chiseled slab of concrete would. The kind of wonder that arises from that experience is entirely dissociated from the thing itself, a purely sensorial breed based only on the neural impulse the hawk's image stimulates. *Knowing* about the hawk, knowing that it *is* a hawk, is the wellspring of an entirely different kind of wonder, an intellective wonder at certain ineffable qualities of the hawk. "Trying to pierce the mystery with our categories," Jewish

theologian Abraham Joshua Heschel philosophizes, "is like trying to bite a wall. Science extends rather than limits the scope of the ineffable, and our radical amazement is enhanced rather than reduced by the advancement of knowledge" (30). Knowing the hawk's remarkable maneuverability, its ability to see ultraviolet light and track prey from miles away, its Herculean strength as it squeezes the life out of a vole like a water color painting dropped in a tub, consumes me with awe. Understanding the underlying mechanism of raptor vision doesn't "disenchant the organism of wonder" (Heschel 30). It raises new questions that only enrich the sense of amazement I feel when looking at the animal, makes me wonder how the hawk's cone cells might be structured and what ultraviolet light actually *looks like* to it. I'm inclined to agree with Heschel: "Scientific research is an entry into the endless, not a blind alley" (30). Science and the intellective wonder it fosters help us to recognize the ineffable in the everyday. Nature's intricacy is infinite; every day, our scientific models bring us arbitrarily closer to infinity. As we near infinity and face its incomprehensibility, Heschel insists, we cannot evade the presence of the divine. The purest expression of Jewish prayer is an "Awareness of the divine that intrudes first as a sense of wonder gleaming through indifference, as a compulsion to be aware of the ineffable..." (Heschel 71). My amazement at the hawk, at its allusion to the ineffable, constitutes both scientific observation and my morning prayer.

* * * * *

"Unfortunately, nature is very a much a now-you-see-it, now-you-don't affair," Annie Dillard bemoans (18). I suppose that's true: a hawk lands before

your eyes, preens for a few seconds, and then jumps and evaporates into the forest. The natural world has no answering machine; if a blue jay calls, you have to be fully present or you'll miss it. Nature is in one sense "now-you-see-it, nowyou-don't," but in a more fundamental way it's "now-you-see-it, now-you-can't." Our eyes can only detect deflected photons within a four hundred-nanometer window, less than half of the sun's radiation and only a tiny sliver of the theoretical electromagnetic spectrum ("Earth's Energy Balance"). Our ears can hear frequencies between 20 and 20,000 hertz. Smell is similarly unreliable, and humans—relative to other mammals—have a very high odor detection threshold. Compared to a dog, the concentrations of, say, ammonia in the air has to be overpowering before we humans can even faintly detect it. Taste works much the same way as smell. Even touch is bounded: textures result from the tiny pits and protuberances of a surface at a microscopic level, and we can only perceive them as finely as the blunt probes of our fingertips allow. It's not just that we miss out on aspects of nature because we're inattentive; nature intentionally obfuscates.

And, *natura abscondita*, elements of nature hide not only from humans but all life. No animal can sense it all, pick up on every detail in its environment. In his pioneering work that marked the beginnings of ethology, *A Foray into the Worlds of Animals and Humans*, Jakob von Uexküll elaborates on the sensory capacities of a tick. Ticks have only three "senses"—a general sensitivity to light in their skin, a sense of "smell" directed solely at the concentration of butyric acid (which mammals give off in their sweat), and a rudimentary sense of touch

that allows them to feel warmth. The sensitivity to light guides the tick on its pilgrimage up a tree; the "smell" of butyric acid signals it to drop from the branch to land on a passing mammal; and the sensation of warmth tells the tick it has landed successfully and helps it locate a prime, hairless spot to drill for blood. That's it for the tick; that's all it gets. It can't feel the imbricate scales of tree bark, see a single color, or a taste the salt in a rich red drop of blood. According to Von Uexüll, "The whole rich world surrounding the tick is constricted and transformed into an impoverished structure that, most importantly of all, consists only in three features" (51). The tick exists in its own "effect space," its space of free movement. Flies see the world as if it were a less colorful impressionist painting, smoothed blobs without edges, objects bleeding into each other. A snail sees an even less focused picture: two-dimensional dark gray striations reflecting the major features of the environment against a uniform slate of light gray. Every organism is encased in a bubble of its own experience, a world unto itself and wholly disconnected from the way that we perceive our environment.

Nature refuses to reveal itself fully to the tick, the fly, the snail, and to us. Though our world is less "impoverished" than the tick's, we are guided by fewer than ten discrete senses (this is counting touch as several distinct senses—such as the ability to detect heat, motion, pain, and texture—and our vestibular sense—the sense of balance and internal positioning). We can't hear the high-pitched whines of wolves or the low rumblings of elephants. We can't perceive the infrared and ultraviolet arcs curved along the top and bottom of a rainbow

streaking the misty eastern sky. When we pet a dog, we can't feel the pulse of blood whipping through its veins, which sit beneath the smooth, stretched envelope of its skin. Our eyes can't "zoom in" like microscopes to see the constant recursion of patterns at smaller and smaller scales. Nature has not vouchsafed any of its creations its full presence. Nature hides behind the curtain of infinity: in the gelatin capsule of bacteria; on the snowcaps of the Himalayas; in the bottom of Mariana's Trench; in the icy, flooded depths of the Son Doong cave; in the black vacuum folded around the edges of the planets; in the hazy cloud of neon dust of the Orion Nebula; at the singularity of a black hole; in the ancient, fiery becoming of the Big Bang and the pure nothingness enveloping it.

Forget omniscient, omnipotent, or omnipresent; I want to be omniperceptive. I want to see every wavelength of light; I want to hear every frequency of sound; I want to smell and taste the tiniest concentrations of substances; I want to feel the minutest inconsistencies each surface has to offer; I want to know every pattern at every level of the world's organization. Naturally, I recognize that this can never happen. I, like everyone else, am trapped in a cage of subjective experience. Nature provides us with something of a makeshift solution for our inability to perceive all the details, though, in our ability to conceive. Even if we can't perceive it when we run our hands along a pine bough, we can know that the pine needles are forever exchanging oxygen and carbon dioxide with the air enveloping them and using light to slam water and carbon dioxide together into sugar and oxygen. Looking at the processes going on underneath the perceptible surface gives an approximation as the limits of

experience approach infinity. Knowing complements the sense of miraculous amazement of pure and all-encompassing sensation; the two weave together to form the kind of wonder I experience when a hawk touches down next to me. This radical amazement is not utterly irrational like the purely sensorial kind or entirely rational like the purely intellective; it is *trans*rational, constantly hovering over the boundary of visceral experience and concept, exchanging gauge bosons between the sensorial and intellective like protons and electrons swapping photons.

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My brother and I have made it back to our campsite. The six miles after Buzzard Swamp passed slowly, ticking and tocking in the pangs of soreness cutting the soles of my feet. We make a campfire by striking the compacted charcoal firestarters and throwing them into a pyramid of wood that blows up in a slow gust of flame. We sit back in foldable lawn chairs and put our feet up on stumps as our spot on the earth turns to face the planet's conical umbra, spinning into the darkness of night—the earth's shadow where light from the sun is blocked. As the sky gradually darkens, continuous like the image of a zoetrope, I reflect on my chance meeting with the hawk (a close encounter of the bird kind), on what I did and didn't perceive. I remember what I've learned about raptor morphology and use it to color in the lines of the hawk. Even if I can't literally see everything going on, I can look at the red-tailed hawk and imagine the tough tendons and muscle that close its talons as a pulley system would. I try to visualize its lungs pumping, its intricate system of air sacs

arranged in a circuit so that it extracts oxygen from the air with each inhalation and exhalation. I saw only the exterior of the hawk, felt the surface tension where the ineffable boils underneath the perceptible envelope of skin that contains it. I stare into the deepening black of the forest air with the hawk's image fixed in my mind. I concentrate on the image and use it like forceps to tease out nature's mystery: The nested scales and interacting systems of complexity, the impeccable patterning of universal fractal architecture, the impossibly fine tinkering of specialization, the cold fusion of symbiosis. There's no easy way to do this; trying to see these mysteries is like a tick trying to hear, "like trying to bite" Heschel's wall. But unlike the tick, the human brain can piece together the unseen and imperceptible, the minutiae that people miss in everyday life, into a conceptual latticework. I set myself to that task and soon become dizzy, spinning like the earth into the cone of night. I see the hawk as an intricate web, a hub of activity and structure that I picture in my head as various cross-sections and angled views. It hits me how tired I am, and I retire into the tent for a night's sleep. When I wake up refreshed by a restful night on the hard, bumpy floor of the wilderness, tomorrow and in the time that follows, I intend to resolve the surface tension, to take a bite out of that wall of mystery that sits beneath the visible surface of nature.

Everything, Wrapped in Strings

"In other words, even on the perfectly ordinary and clearly visible level, creation carries on with an intricacy unfathomable and apparently uncalled for"—Annie Dillard, *Pilgrim at Tinker Creek* (133)

"Walking through the forest near Chan Chich, I was pondering how quantum mechanics can be used in principle to treat individuality, to describe which pieces of fruit will be eaten by parrots or the various ways in which a growing tree can shatter a piece of masonry from a ruined temple"—Murray Gell-Mann, *The Quark and the Jaguar* (6)

My backyard fits neatly into one field of vision. In any absolute sense, it's very small, even though I can't estimate the square footage. There are some birdfeeders set up near the porch. The land slants slightly, bordered by evergreen bushes and anchored by a pine tree. Underneath the visible veneer of a typical suburban backyard, the land is buzzing, glowing with an almost imperceptible radiance lost to all but the most sensitized eye. Past the splotches of dead grass peppered on the pale green lawn lie the rich emotional associations attached to the look, smell, and sound of my minute wildlife refuge. Standing on the edge of the porch, a distance of at most eight feet from my house, I feel like I've broken free from the pressures of modern life, liberated myself from the vise of schedules and planners. For a few minutes, I don't have to worry about where I'll be in five years or what career I'll have; I just exist as a fixed certainty, a somatic coagulation of integument and cytoplasm.

I realized this when I was cleaning out my garage on a brisk November day six years ago, as I uncovered a decrepit hopper feeder buried underneath cobwebs and an abandoned aspiration. My brother had bought this feeder a long

time ago—when he was six or so—to try to attract wild birds to our porch. He only got common, drab, faded brown house sparrows, so he gave up. I figured that with a little work and some know-how, I could entice some fancier birds, so I picked up the stained, cottage-shaped chunk of wood and washed it. I filled it with the first seed I could find (Backyard Bird Buffet from Rollier's Hardware), and hung it from a string tied around a screw eye on the porch. Within a few days, a northern cardinal had accepted my gracious invitation to the backyard banquet. This cardinal's face was slicked with a black curve that bellied out along his face. He popped like a hot streak in the air, a gorgeous, scarlet burst above a patio of gray rock. He blazed brilliantly for a second, landing on the feeder. Taking his fill of safflower and black-oil sunflower seeds, he casually tossed away the swollen red sorghum kernels. Cardinal Wildflower (as I soon started calling him) perched on that feeder was one of those sights that makes you want to cry—not because the beauty is too overwhelming to withstand, but because you need to wet your parched eyes so you can stare that beauty right in the face for a little longer, new and washed and clear. Cardinal Wildflower and I saw each other practically every day, almost as if we'd scheduled appointments ahead of time. Each visit, I'd look out the window to catch a glance of him as his crimson feathers flashed over my reflection.

Cardinal Wildflower initiated a bird-feeding cascade. I became addicted to feeding birds. The compulsion to draw some element of nature arbitrarily closer to my house seized me. There was no stopping me, a true junky, from spending all of my meager earnings on bird-feeding equipment. I bought everything from a

new hopper feeder (made from recycled plastic!) to a heated birdbath. My habit grew to the point that, for my sixteenth birthday, I didn't ask for a car or an iPod; I asked for an elderberry bush. My best investment, though, was a small window feeder. It had the form of any third grader's drawing of a house—a rectangular block with a triangular roof stacked on it—with a small spillover tray on either side. The back was lined with two rows of suction cups—some big, some small. I suctioned the feeder right on my bedroom window, the perfect place for avian visibility. Cleaning the feeder required a tremendous effort and superhuman facility with a wire brush, but the investment was well worth the payout. I got views so close up I felt like I had binoculars screwed into my eye sockets.

One cold winter morning, while a burning flock of scarlet male cardinals (Cardinal Wildflower among them, of course) were picking up any debris that fell on the smooth platform of snow coating my front yard, an especially intrepid black-capped chickadee made a stopover at my window feeder. It was so captivated by the peanuts and hulled sunflower seeds piled inside the feeder that it didn't think twice about continuing its lunch as I pressed my face against the thin glass sheet that separated me from it. Without that crystal membrane holding me back, nothing could have stopped me from endocytosing that glowing, warm chickadee, from merging with it indistinguishably to form a continuous whole. I've never again seen a bird with such precise detail. This chickadee was tiny, but I could make out every nuance of its appearance: its blunt black bill, its black yarmulke and bib that contrasted with its white cheeks, its chestnut underside heaving with the breath of life, the slope of its chest

fluctuating in simple harmonic motion as it drew in fragments of the atmosphere. When it changed position on the feeder, I noticed its reptilian legs grasping on autopilot anytime its toes came into contact with something they could fit around.

Here this chickadee was, the size of a snowball formed in a preschooler's hands, with legs no thicker than toothpicks. Somehow nature had pulled out all the stops and woven with surgical precision every neuron, every tendon, every muscle bound to every honeycombed bone into those legs as fine as 14-gauge copper wire. What needle does evolution use to sew so intricate a pattern? Try making a grabbing claw, the kind a senior citizen might use to pick up cans from the top shelf of the cabinet, the size of a chickadee's leg. Even if you could find a use for such a tiny grabber, you couldn't build it; you couldn't make a simple grasping mechanism with that level of detail. And that wouldn't even need to relay messages back to a central nervous system! Each chickadee egg hatches a pair of these claw tools tuned finely enough to strangle a twig with sufficient force to resist the heaving exhalations of the wind.

I remember seeing an episode of *Good Morning America* with a segment on the world's smallest model railroad. Someone had built a Z-scale model of an N-scale loop, which works out to be something like a 1:35,200 scale. The whole set balances comfortably on a fingertip—about a third the size of a thumbnail—and yet the tiny train manages to go around a circle, even passing through a minuscule mountain. I'm not going to deny that it's pretty impressive. Of course, it's not a typical electrically powered model railroad, where the train rides along

on top of a metal track that conducts electricity. The designer of the microrailroad cheated, cutting the edge of a thin plastic tube to resemble a train and attached the other end of the tube to a geared motor. The tube then rotates around an oval slot cut through a minute background, so the train's not even on a track. Whoever designed the chickadee didn't have to cheat; they rolled together nerves and muscles and wrapped them in a thin sheet of epithelium without having to resort to Z-scale railroading chicanery. That chickadee isn't cut out of a rotating plastic tube to give the appearance of motion; it's fully capable of driving its own movement. The chickadee's leg, unlike the teeny railroad, can conduct an electrical pulse, shooting action potentials along a myelin sheath to the brain in a matter of nanoseconds. Muscle fibers wind around its body, slipping over each other like the tectonic plates of the earth with the push and pull tides of actin and myosin; the whole works is packed into this little archosaurian ball. In the time of a tiny train lap, the chickadee chokes and releases a twig and dissolves into the snow-flecked winter air.

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Coming in from a walk through the Chattahoochee National Forest that I was lucky enough to have as a backyard for as long as my little lease on a backcountry cabin lasted, I experienced, with some perverse delight, my first tick. I had never dealt with any kind of acarid intimately before (excepting dust mites I've unwittingly breathed in), and to see one scrambling across the keratin bramble of hairs on my leg made me regret having gone out that day. As the deer tick hunkered down to take the first bite and rubbed its pyramidal chelicerae in

anticipation, I grabbed it and, much to my (and presumably much more to its) displeasure, incinerated that vampire-in-miniature on a plane of aluminum foil with the flick of a lighter. A second after the flame spread out across the base of the foil, the tick went rigid as if it had a pause button built in, gripped and crushed by the amoebic pseudopodia of ethereal death. I *had* to kill that tick; its metabolic propensities left me no choice. (More accurately, it left me the choice of its life or my getting blood sucked and the possibility of disease, but survival machine that I am, the decision was obvious.) Still, feeling the 4/4 shuffle of its tiny legs on my own leg and seeing its teardrop, proto-spider body made manifest the unceasing complexity of the tiny.

At that instant, I realized that the smallest animals—the ones for whom climbing over an ingrown hair becomes tantamount to scaling Kilamanjaro—often *seem* the most complex. Or, at least, complexity appears more astonishing in them since it seems there's so little room for error or extraneousness.

Everything has to be assembled perfectly to have a tick. We humans are amazed by the intricacy of the tick because we think that it forgets the past faster than, say, a human or an elephant. Sure, when you're a person it doesn't do much harm to carry around an appendix. When you have sufficient attic space, keeping evolutionary tchotchkes around makes more sense. But I want to say that ticks can't hold onto a corporeal reminder of their ancestors, a vestigial family heirloom, in their bodies because space is the limiting resource.

The Z-scale model of an N-scale model railroad strikes me as more impressive than either a Z-scale model or an N-scale model alone. The tick is the

Z-scale model of the N-scale arthropod body plan. Maybe it's no more complex than an elephant, but evolution *must* have used a smaller screwdriver on the tick. Clearly, building a tick would require much more sensitive fine motor adjustments on the part of evolution than constructing a huge elephant. But evolution doesn't exist on a human scale—it's not 5'11" and 170 lbs., and it certainly doesn't have a moustache. Evolution works on every level of every organism simultaneously. Certain cells are selected for; some tissue works more efficiently than others; a given organ bestows an advantage. Tightening the cells of the elephant takes the same-size wrench as it does to adjust the cells of the tick. Complex hierarchical systems make no size distinction, and the elephant and the tick are subject to the same rules of natural selection, are approximately equal in their susceptibility to the stenographic errors of random genetic drift, and conform to the same laws of physics. Gravity doesn't cut the tick a break because of its smaller size; proportionally, gravity works just as hard to keep the tick down as it does for the elephant. (Interestingly, though, because the tick is so much smaller than any mammal, the overall effect of gravity is weaker than that of adhesion, the tendency for unlike molecules to cling together. It's this molecular proclivity that allows ticks and many of their arthropod brethren to climb walls effortlessly.)

The tick and the elephant seem to be the extremes in terms of animal size. In a sense, this is true: the tick is among the smallest animals visible to the naked eye, while the elephant sits alongside the whales (the blue whale, after all, is the most massive organism ever to have existed) as the biggest. These animals are

the fringes not of absolute size but of the *human* size scale, which spans the range of naked eye visibility. Ticks are just about the smallest individuals I've been able to discern when equipped with just my eyes. And an elephant has to be the largest, just because land animals don't come any bigger than that. The human scale serves me nicely for day-to-day life—or maybe day-to-day life serves me nicely for the human scale, since there's really no other way to live. With the naked eye, I can spot everything from a velvet mite (about an eighth of an inch) creeping along a sea-green scale of lichen on the wrinkles of a sugar maple to Brasstown Bald, Georgia's highest peak, rising above the thin oak and pine canopy of the Chattahoochee. Despite its size, Brasstown Bald still fits within the human scale; I can perceive its full extension, its continuity, from the base of the mountain.

The large size differential between ticks and elephants might be the largest possible on the human scale, but it turns out to be smaller than we might expect. The difference in body length between tick and elephant seems a lot smaller when we look at the difference between, say, a myxozoan and a tick (especially if the tick is engorged with a blood meal, after which its swollen abdomen can double in size until you could confuse it with one of those cheap plastic Halloween spider rings with the circular part embedded in the scaly gray skin of a cantaloupe). A deer tick can be almost half an inch in length, while an elephant can grow to be almost thirty feet long. The size difference in terms of body length, then, is a factor of about 720. Myxozoans are tiny endoparasites that look like a translucent cellular oval with nucleus google-eyes that were once

classified as protozoa but are now placed alongside jellyfish and coral in the phylum Cnidaria, and they have only a few cells to their entire being when in their spore form. If a tornado's coming and every organism has to pack up all its cells and run, the myxozoan could prepare to leave momentarily, while the tick would be folding its billion cells and putting them in a suitcase for hours. Myxozoans, in their spore form, are typically ten micrometers (roughly 0.0004 inches) long. A tick is just about 1,280 times the size of a myxozoan, which is to say that the tick is closer in size to the elephant than it is to the myxozoan. In other words, 720 ticks standing nose-to-abdomen would approximately equal the body length of an elephant. But it would take 1,280 myxozoan spores lined up (I can't say nose-to-tail since they're radially, not bilaterally, symmetrical) to equal the length of a tick. (To be fair, though, the second smallest true animal, the placozoan *Trichoplax adherens*, towers over the myxozoan spore, an entire millimeter across, and possesses several thousand cells. Whoever discovered it named placozoa, which means "flat animal," aptly; the smudge of mucus sandwiched between a slide and its cover after sneezing onto the thin glass would look almost identical to *T. adherens*.) When we move beyond the human scale in either direction, sizes and distances, weights and speeds, quickly become irreconcilable with our ability to conceptualize.

On either end of the scale spectrum, like ultraviolet and infrared, we have the macro and the micro, which are colloquially known as the huge and the tiny. Regardless of which end you choose, you're entering the territory of some kind of scope, be it the microscope or the telescope. Our eyes just can't handle

anything beyond the human scale, and our brains, with their ability to sensibly conceptualize quantities, can't go too far beyond our eyes. Something like the ocean is where the macro scale begins. Standing on a beach, you can see a lot of it, but you're definitely not getting the whole picture. No one—no matter how much bigger your eyes are than your stomach—can perceive the full, uninterrupted extension of all the ocean in one field of view. You can only catch sections, and, using many different viewpoints, stitch the sections together to a get a cohesive whole. The macro scale is the scale of the huge—ecosystems, planets, stars, galaxies—and, quite simply, it's ocular overload. And in a myxozoan, we see the beginnings of the micro, something so small that it takes a microscope to see. No matter how hard you strain your eyes, you won't be able to see the myxozoan going about its parasitic business, encysting in the scarlet striations of the muscle tissue of a rainbow trout.

For what seem to me to be obvious reasons, both ends of the scale are insufferably impressive. Imagine we were to build clocks in the style of both macro and micro. The tiniest watch, if only for its fragility, would amaze. That the gears would turn with no end in sight, that the hairline tunings and cranks could be so finely adjusted as to tilt at a few degrees as each second liquefies into the deluge of temporality would astonish anyone. To compete with a deer tick, its face would have to be so small that there's no chance a person could read (let alone *write*) the numbers on it. You'd pop a blood vessel in your eye from squinting whenever you tried to check the time. No, the micro watch makes no practical sense. The macro clock is no more feasible. It would exist on a scale

consummately larger than Big Ben. I envision a macro clock about the size of the moon being constructed and catapulted into earth's orbit so that, like the radiant face of a full moon at night, it could be seen from any point on the planet at some time during a 24-hour day. The gears to support such a fantastical clock would be gargantuan, the size of blocks if not whole cities. The clock's functioning would require unprecedented energy consumption, millions of megawatts pulsating through the clock's wire veins, their heat dissipating in a wake of increasing entropy as it diffuses into space.

Instinctually, I want to say that the micro clock is *more* complex than the gratuitously enormous macro clock. Its parts are so much smaller, so it seems like the micro watch would require so much more precision in the placement of its parts. But the gears of the macro and micro clocks, the cranking cogs and springs, are the same in every way but size. The same mechanical process underlies both of the clocks' functioning. The clocks are, in terms of complexity measured as degrees of hierarchy and nested systems, one and the same. Whether a gear is the width of a hair or a highway, it is equally responsible for turning the cogs next to it, subject to the same mechanized motion. To call one more complex is to commit a fallacy. Brow-furrowing complexity exists at every scale, from the tick to the elephant, from the electron to the galaxy. It is like beauty, an indeterminate quality of a natural object. Does beauty depend on scale? Of course not; the splatter-paint cross-section of plant vascular tissue, bubbles of colors overlapping and blending, and the fractured neon glow of the tapestry of interstellar dust and gas called the Crab Nebula inspire the same

aesthetic appreciation. Complexity works in much the same way. It can't be quantified by the length of an organism's genome—if that were the case, amoebas would be 225 times as complex as any mammal (Mitchell 97). We can't measure complexity; we can only approximate it through constant reductionism, resolving systems into their interacting component subsystems, subsystems into their smaller parts.

Complexity can't depend on scale. Scale is much too arbitrary for that. So, to a certain extent, complexity, like beauty, is in the eye of the beholder. To me, the chickadee's leg appears an impossibly fine suturing of neurons, blood vessels, bones, and muscles. Now you're a velvet mite scurrying around the arms of a serviceberry bush. A massive ball of barbules and integument falls onto the branch like a plummeting bowling ball striking the end of a diving board. The branch wobbles, and you come face-to-face with the cracked-leather foot of a dinosaur, a bird roughly ninety thousand times as heavy as you. From your velvet mite perspective, the chickadee looks gigantic (pretend for a moment that mites have a sense of vision). "Well, that can't possibly be as complex as I am," you scoff. "Of course you can knit a patchwork of tissue in a space as wide as that leg!" Conversely, the intricacy of a tiny human might amaze a blue whale. Humans, after all, could comfortably swim in the whale's blood vessels or sit in the ventricles of its heart. But somehow, the whale might reason, all of its parts are there in that minuscule, bipedal body. A chickadee isn't small or a whale big in absolute terms; their size means something only in relation to an observer.

The closer you look, the more complexity you'll see. Nature is fractal, selfsimilar at every level. It's unlike anything humans have ever created. When you look at a picture from a printer close-up, you see clusters of little dots of ink placed next to each other. No unbroken entity really constitutes the dots. If you zoom in, you don't find smaller dots making up the dots—the dots themselves are already the smallest units a printer can produce. And if you zoom out on the picture, nothing changes; the picture just gets smaller until it fades from sight. Nature doesn't work that way. Every level of magnification reveals new dimensions, ever-smaller dots bunched together to compose a dot that is itself only a component of a bigger dot. Take the savannah ecosystem, the composite web of lions, giraffes, elephants, antelope, and vultures. Zoom in to the level of a single organism, the African elephant. Magnify again to get up close and personal with a patch of its skin, wrinkles overlapping like chunks of slate on the side of a mountain. Suddenly, you'll notice a tick climbing along the ridges. Follow its blood meal into the body of the tick, at the level of the tick's organs. Zoom in until you're in the territory of cells lining the walls of the tick stomach, creases awash in a stinging tide of hydrochloric acid. Magnify the cell another time so that you can see the phospholipids of its cell membrane in the shape of a doublelayer of clothespins bounding the formless cytoplasmic aspic. Watch as the cells, packed as closely together as fans at the Super Bowl, push against each other and absorb and excrete the goods manufactured by their cellular machinery.

Tick or elephant, individual animal cells hardly vary in size. In fact, animal cells, along with those of plants, protists, and fungi, are all more or less the same

size. Bacteria, though, are significantly smaller, on average about one-tenth the size of the eukaryotes. Still, in this tiny space, bacteria have meticulously developed complex structures, organs in miniature that enable them to meet all of life's essential demands. Like the tick to the chickadee, bacteria evidence just how complicated the tiny can get. Certain species of bacteria, called magnetotactic bacteria (which scientists affectionately abbreviate as MTB; one journalist refers to them as "living lodestones" [Faber]), exhibit a behavior known as magnetotaxis. Using specialized organelles called magnetosomes, the capsular MTBs spin like the needle of a compass to direct the bacteria due north; even dead bacteria will rigidly point toward the north. The irregularly shaped magnetosomes, clumped together in chains laid out like Z-scale models of Nscale railroad tracks along the sides of the bacterium, contain the strongly magnetic mineral magnetite. Like the gears of the tiny clock, the magnetosomes produce precisely the right size crystals of magnetite, thirty to ninety nanometers in length, giving them just the magnetic properties they need. Bacterial magnetosomes impeccably optimize the sizes of their magnetite crystals then wrap them in a fatty lipid bilayer, an invaginated inlet of the cell membrane. Sequestering the crystals in a membranous pocket lets the bacteria micromanage every aspect of the vacuole's environment from acidity to the concentration of particular molecules. The crystals within a magnetosome maintain an uncanny order, remaining more regular in shape than if they were found growing inorganically "in the wild." While most bacteria wander aimlessly, gliding in a jagged Brownian course like a parachuted dandelion seed in the

wispy spring air, MTBs slide north along the earth's north-south axis as if on a zip line. The majority of magnetotactic bacteria are anaerobic, meaning that oxygen acts like a poison to them. (Even the ones that aren't entirely anaerobic are microaerobic, indicating that they only thrive in environments with a substantially lower oxygen concentration than that found in the open air.)

Because all of Earth's magnetic field lines have an up-down component as well as right-left and forward-backward axes (everywhere except for the equator, that is), the bacteria can use their intrinsic compass to follow the earth's magnetic field lines downward to the muddy bottom of lakes or the black depths of the ocean, which are areas of low oxygen concentration. Blind and deaf, unable to feel or taste, magnetotactic bacteria migrate unfalteringly, never erring from their downward pilgrimage. Only when exposed to magnets in laboratory settings do the bacteria stray from their virtuous path, wobbling around in what appears to be a hazy electromagnetic stupor.

Magnifying a micron-long bacterium reveals that it's composed of a series of smaller dots printed next to each other to give the illusion of a smooth, even whole—contiguity masquerading as continuity. In reality macromolecular crags jut out of the bacterium, overlapping boulders of proteins intermittently poking out. The name "protein" comes from the Greek *proteos*, meaning "first place," which just about describes the protein's preeminent role in biological systems. Magnifying an MTB lays bare the importance of these magnificent macromolecules, the dots underlying the image of any cell. By weight, proteins contribute about half of the dry bulk of an organism. They are the substance

behind everything we think of as being properly an organism's: skin, nails, hair, hormones, enzymes, DNA decoders, bridges across the cell membrane...there's a protein for every function imaginable. In fact, there are more proteins than imaginable functions; scientists have yet to figure out the functions, having successfully modeled only ten thousand of the estimated hundred thousand or more. My AP Biology textbook (which, I admit, I bought a copy of and sometimes read for entertainment) concludes, "Proteins are the most structurally sophisticated molecules known" (Campbell & Reece 71). A bold claim no doubt, but one with remarkable insight. The largest proteins, called titins and found in the striated muscle tissue of most mammals (the largest of which are, ironically, found in mice), tower over all other molecules with a staggering mass of 3,906 kilodaltons—the equivalent of almost four million atomic mass units (i.e., hydrogen atoms). The mouse titin's chemical formula ($C_{169,723}H_{270,464}$ $N_{45.688}O_{52.243}S_{912}$) is to the world of chemistry what "antidisestablishmentarianism" is to a kid's vocabulary: abundantly larger than anything else.

As with the macro clock, the complexity of proteins arises not because of their size but in spite of it. Titin isn't complex simply because it's huge; it is, quite tautologically, complex because like all proteins its structure is exceedingly intricate. More than "some" assembly is required to build a protein; biochemists have identified four distinct levels of protein structure that constitute the unique three-dimensional shape ("conformation") of a protein. Proteins consist of at least one polypeptide—a fancy name for a chain of amino acids, which are

effectively biological LEGOs. Amino acids are relatively simple organic compounds, a central carbon keystone surrounded by four distinct chemical spokes: an amino group of nitrogen and hydrogen; a carboxyl group of carbon, hydrogen, and oxygen; a single hydrogen atom; and a chemically idiosyncratic variable group called the side chain. It is the side chain that defines an amino acid, giving it its unique properties. Of the twenty amino acids organisms use to construct proteins, no two have the same side chain. Glycine, for example, has a single hydrogen atom as its side chain, while others like tryptophan (the infamous compound with a reputation for causing drowsiness after eating a Thanksgiving turkey) have longer side chains interlinking rings of large heterocyclic compounds. Placing the carboxyl group of one amino acid next to the amino group of another has the same effect as setting the north pole of one magnet beside the south pole of another: the two immediately bind, forming a strong peptide bond that welds the amino acids into a polypeptide. The primary structure of a protein is simply a phonebook-style listing of the amino acids that compose it. It's not entirely accurate to compare the listing to the white pages: although you can have more than one Barney Jones living in Detroit, there can't be two different proteins with the same amino acid sequence. The "simple" protein lysozyme—an enzyme found in tears and sweat that systematically eradicates bacteria by destroying certain molecular signatures on their cellular surfaces—consists of 129 amino acids, strung together to resemble pearls on an unfastened necklace. Precision in protein construction is vital, and order matters. The difference between leucine and isoleucine at position 87 could be

the difference between life and death (at least for the bacterium about to be filleted by lysozyme). Substitute one part for another and the whole collapses.

Secondary structure accounts for the fastidiousness of a protein, since different amino acids result in dramatically disparate shapes. The second level of protein structure describes the general shape of local segments in threedimensional space, as the polypeptide backbone bends and curves as though it had a severe case of scoliosis. Hydrogen bonds, arising from slight differences in electrical charge on the ends of a molecule, connect the marginally positive end of a hydrogen-nitrogen compound to the barely negative end of an oxygen atom elsewhere in the chain. Though these bonds are weak, they're just enough to twist the protein into a helical spiral, or alpha helix, like a bored little girl twirling her auburn hair into curly locks around the axis of her finger as she waits impatiently for class to end. Hydrogen bonds may also reconfigure the ribbon of amino acids into a series of parallel accordion folds, called beta pleated sheets. The string of the protein backbone may bend and turn corners, meandering like a cord of highway along a mountain, in what scientists aptly call "turns." Other interactions are also possible, but alpha helices, beta pleated sheets, and turns are by far the most common. These three "extended structures" define the geometry of polypeptides, curving, coiling, and twirling them so that they end up reminiscent of freshly cooked angel hair pasta spilled on the kitchen floor.

Further levels of structure knit new threads of complexity into the gigantic macromolecular sweaters called proteins. The side chains of the amino

acids, the variable groups that demarcate each as individual, interact with each other, pulled by the slight polarity of hydrogen bonding and other slight charge changes (called van der Waal's forces). Amino acids with sulfur in their side chains link together to construct durable disulfide bridges, sealing a pact with the sharing of electrons. In a watery environment, the polar water molecules align their weakly positive side with the weakly negative side of their neighbors, excluding any molecules that lack these slight charges. The nonpolar (that is, completely uncharged) compounds turn inward toward the center of the protein as the more charged particles move to the outside, blending in with the water. The tertiary structure of a protein defines its shape, as molecules "reach across the aisle" to grab onto the side chains of other amino acids with differing political affiliations. The first three levels of structure determine the form of a polypeptide, a continuous strand of amino acids. The quaternary structure of a protein involves networking, as different polypeptide strands bob and weave together to form a fully functional, whole protein. Collagen, a well-understood structural protein, is a fibrous conglomerate of individual helical strands wound together into a supercoiled triple helix. Braided together like heavy-duty rope, each collagen plait is itself a helix at the secondary and tertiary levels. Hemoglobin packs together four polypeptide chains, intertwining the lobes and molecular outcroppings of each to form a more-or-less solid ball. At the heart of each of the four funnel-cake polypeptide loops sits an iron atom that scoops up free oxygen from its environment (glowing red when the two elements touch) and ferries it along with the molecule.

Within organisms, a protein's specific function "is an emergent property resulting from exquisite molecular order" (Campbell & Reece 74). That is to say, the ultimate function of the protein derives from its structure but constitutes more than the simple adding up of its component atoms; the synergistic interaction of those atoms in the protein's four levels of structure give it its unique function. In the end, how a protein is used is a necessary consequence of the way it's constructed. Proteins have innumerably diverse functions, serving for structure, defense, transport, metabolism, storage, motion, and cellular selfrecognition. Collagen braids together three polypeptide helices to make the cellular equivalent of steel cables; hemoglobin stashes an iron molecule at the heart of each of its four lobes (ventricles and atria?) so that it can scooch along oxygen molecules. Looking just at enzymes, the proteins charged with the responsibility of ripping apart other compounds as if making pulled pork, we see an incomprehensible diversity of functions. An enzyme gets a naturally occurring chemical reaction to happen millions of times faster by lowering the activation energy required. A restriction enzyme, for example, cuts DNA at a specific point, any time it notices a distinct sequence of nucleotides. An entire class of proteins, known as chaperonins, oversees and enables the folding of compatriot proteins. They are, as their name suggests, true chaperones, watching over "younger" proteins to control their environment. Chaperonins arrange themselves in bullet-shaped capsules with flip-tops, letting in other proteins. Inside the bullet, conditions such as pH and temperature are kept ideal to allow the guest proteins to fold and form perfectly. Once folding is complete,

the chaperonin spits out fully-formed proteins of all shapes and sizes. Yet the easiest proteins to understand, I think, are structural proteins; they're effectively bricks and ropes, stacked and woven to create biological barriers. Spider silk may be the best-known example—and deservedly so. Researchers working in Madagascar stumbled upon the strongest biological material yet discovered in the silk of the Darwin's bark spider. Tougher than steel, "C. darwini silk is far higher performing, absorbing about ten times more kinetic energy before fracturing than does Kevlar" (Agnarsson et al.). If you could wrap yourself in a vest of the bark spider's silk, you would have ten times the protection against gunshots as afforded by Kevlar, the material which bulletproof vests are currently made from. A cocoon of C. darwini silk would render a person invulnerable. The strength of silk has its roots in the secondary structure of the protein, a series of pleated sheets stacked together to harness the power of hydrogen bonding.

Even proteins as strong as silk and as huge as titin originate from something as modest as a single atom. Proteins are, after all, massive molecules, and at heart, a molecule is little more than a combination of atoms. At first glance, an atom looks decisively less impressive than a protein. But titin didn't evolve in a day; it had to start somewhere. Atoms just happen to be the starting point for all of the great proteins we've come to know and love. They're more impressive than their small stature suggests. Atoms are the "uncuttable" of Democritus, the fundamental building blocks of everything we perceive (and of our ability *to* perceive). We know now that atoms can, in a sense, be "cut" since

we have discovered subatomic particles, but an atom still remains "indivisible," the unique bottom-line of all of the elements—everything from hydrogen to gold to uranium. The essential difference between elements is the number of protons they have. Chemists, it seems, just devised a strange and unnecessarily complicated way of counting protons. As Richard Feynman wittily points out, "instead of saying of 'one, two, three, four, five protons,' they say, 'hydrogen, helium, lithium, beryllium, boron'" (113). For whatever reason, numbering the elements lacked the elegance of naming them. Since we discovered many of the elements before even knowing that they had protons in them, gold was known as "gold" long before it could be called "#79." And if you've got gold, silver, lead, iron, carbon, sulfur, etc. already named, why start counting?

No matter how you name the elements, we're often shown a conceptualization of the atom as a solar system shrunken down to submicroscopic proportions. The sun of the atom, the nucleus containing positively-charged protons and electrically-neutral neutrons, accounts for most of the atom's mass, while the orbiting electron planets circle the center with a constant angular momentum. There may be some truth to this understanding, but if quantum mechanics has shown us anything, it's that electrons are supremely unreliable: they never settle into a motion pattern but move scatter-shot through a cloud with only a *probability* that they'll be in a certain location.

Scientists are able to identify electron orbitals, volumes of space where electrons are likely to be contained ninety percent of the time. According to the Pauli

exclusion principle there will *never* be two electrons—a self-loathing particle if ever there was one—in the same location at the same time.

Thanks to the exclusion principle, atoms love to trade electrons and bond with each other. If the exclusion principle were not the case, electrons, protons, and neutrons would all cluster together in a dense nugget. But because electrons despise each other so fervently, as they get pulled toward the proton-rich nucleus by virtue of their opposite charges, electrons repel one another (due to their possessing the same charge), keeping each other on the run around the attractive atomic nucleus. Overall, atoms are the ultimate socialites, constantly networking and making connections. Very few atoms ever seem to be content with the electron configurations they have, so they're constantly sharing or swapping electrons in covalent and ionic bonds, respectively. Covalent bonds are the Communist's choice, an equal sharing with two parties coming together to work for the common good: atoms united in equality and brotherhood. They form when two or more atoms all need the same number of electrons to "fill" their outermost electron orbital, to achieve a stable balance of attractive and repulsive forces. Carbon is the expert, a veritable chemical Lenin. It is capable of forming up to four bonds simultaneously. It is precisely carbon's penchant for multiple bonding that makes the study of organic chemistry so difficult. Nitrogen, oxygen and hydrogen also have propensities for covalent sharing, though less so than carbon. Whenever an oxygen atom, missing two electrons in its outermost orbital, finds hydrogen atoms in its vicinity, a molecular ménage à trois transpires and the atoms make sweet, sweet water. Oxygen is less

egalitarian than carbon, though, so it tugs the hydrogen electrons a little closer to itself, giving it a slight negative charge and the hydrogen atoms a slight positive. As seen in protein conformation, this unequal sharing, called polarity, results in the hydrogen bonds between molecules seen in protein conformation.

Ionic bonds form when two atoms need to gain or lose an easy electron to completely fill their outermost orbitals and achieve a stable balance of the attractive and repulsive forces governing their "orbit." Sodium is strolling by, just itching to give away its last electron. If it can relieve itself of this extra burden, it will be able to eliminate an entire orbital that currently houses only one electron and make itself stable with a full orbital below that one. Chlorine, who just happens to be passing by serendipitously, desperately needs an additional electron; its outer orbital is missing only a single electron. They're the perfect match, sodium and chlorine. Once they're close enough to interact electromagnetically, sodium tosses its extra electron to chlorine. In the process, both atoms become ions, charged atoms. Normally, the number of an electrons and protons in atom is exactly equal, so the negative and positive charges cancel out to make an atom neutral on the whole. After an ionic exchange, though, neither atom remains electrically neutral: Chlorine gains an extra electron, giving it a negative charge overall since negatively-charged electrons outweigh the more optimistic protons. Sodium gives away an electron, meaning that the positive protons outnumber the negative electrons, endowing it with a positive net charge. Since the two ions now have opposite charges and opposites attract, the electromagnetic force brings the two together to form a compound. The

properties of the compound may radically differ from those of the component atoms, a phenomenon known as emergence (or "emergent properties"). Sodium, a temperamental metal that ignites when it comes in contact with water, and chlorine, a noxious gas, form something entirely unexpected when they bond: table salt. Chemical bonding eludes our predictive faculties. If you put a metallic explosive together with nerve gas, the last thing you'd expect would be something edible. But at each new level in nature's organizational hierarchy, new properties emerge that are more than the sum of their parts.

It's tempting to dismiss atoms as a simple system, but that would be unforgivably scalist (my term for discrimination based on scale). The composite of the four fundamental forces, atoms present a system not seen on any other scale. An atom is a complex system, an interaction between a whole host of subatomic particles and forces. Protons and electrons constantly exchange photons, packets of light energy that mediate electrical attraction, to hold each other in check. Photons themselves occasionally dissolve into electrons and their equal-but-opposite, evil twin antiparticles called positrons, which have the exact same mass as an electron but are positively charged. The electron and positron almost instantaneously annihilate each other, releasing energy in the form of photon, the same particle that spawned them. Photons traveling from electron to proton sporadically decide to travel back in time. At this level, it's impossible to tell whether a photon travelled *forward* from a proton to an electron or backward from the electron to the proton, so physicists typically say the particles have exchanged a photon and disregard the order.

Within the atom's nucleus, similar processes are constantly going on. Ouarks, tiny component particles, stick together in triads to make up protons and neutrons. Quark interactions are insufferably complicated, and so far I've only begun to scrape the surface of them. The essence, though, is that just like electrons have a charge, quarks have a flavor of either up or down. (Why Murray Gell-Mann, the scientist who discovered them, chose "up" and "down" as flavors, I'll never understand; if you're going to have the property called flavor, its variants should be chocolate and vanilla or sweet and sour.) Up quarks have an electromagnetic charge of positive two-thirds, while down quarks have a charge of negative one-third. Protons, then, consist of two up quarks and a down quark, giving them an overall charge of positive one (two-thirds plus two-thirds minus one-third). Two down quarks and an up quark comprise a neutron. Quarks are not held together by the electromagnetic force like atoms. Instead, a force called the strong nuclear force holds them together. The strong force lives up to its name: It is by the far most powerful force interaction, a hundred times stronger than electromagnetism. While the electromagnetic force has electric charge as its determinant, the strong force works on color, which can have three possible values: red, green, or blue. Each quark also has a color, but this isn't color in the traditional sense. Provided that we could actually see it, we probably wouldn't observe a "blue" quark to be the color blue. Color is basically like positive or negative, except it has three rather than two possible values. Just as protons and electrons exchange photons to mediate the electromagnetic force, quarks exchange particles called gluons to hold them together as protons and neutrons.

Thus, even if quarks have the same electrical charge, as long as they have different colors, they will attract each other, since the strong force is so much stronger than the electromagnetic force.

Quarks occasionally change color due to a third force, referred to as the weak nuclear force, which results in radioactive decay. The force is "weak" in the sense that it is only one-one hundred billionth (10⁻¹¹) as strong as electromagnetism (and one-ten trillionth [10-13] the strength of the strong force). It is mediated primarily by particles called W bosons. When a W boson interacts with a quark, it changes its color; two quarks of the same color making up a proton then repel each other as like poles on two magnets would, causing the proton to fly apart. The weak force also affects atoms in other ways, but they're not so well understood and require further research. An atom is tiny tiny on a scale that inflates the myxozoan with a tremendous sense of pride—but it isn't simple by any stretch. Three potent forces are at work every nanosecond, constantly reshaping the atomic landscape. Charges reverse as electrons phase in and out of existence, continuously dancing around the nucleus in spur-of-themoment choreography. Continents shift and collide; volcanoes of radioactivity erupt; photonic bolts of lighting strike.

The smaller you get, the less predictable physics becomes. And that's why hardly anybody understands quantum mechanics. The Heisenberg uncertainty principle has turned our understanding of the world into a kind of Proustian physics, where things seem to work more by association than by definitive rules. To know an electron, we need its position and velocity—where it is and at what

speed and in which direction it's going. Heisenberg proved that we can't know both. What it comes down to is the way that we *measure* position and velocity. We have to use a high-energy photon to accurately determine the position of an electron since the accuracy of the positional measurement depends on the size of the photon's wavelength and high-energy photons have shorter wavelengths. If you crash a high-energy photon into an electron, you end up knocking the electron in a different direction at a different speed. And if you want to measure the velocity of an electron, you have to shoot it with a low-energy photon so that you don't mess with its velocity as much. In doing so, you use a photon with a long wavelength, which guarantees that you can't pinpoint the electron's position as accurately. Basically, Heisenberg showed that the universe is inherently turbulent and that it is physically impossible for us to know everything about physics; there's no getting around this fundamental incomprehensibility. Scientists can only predict the likelihood that an electron will be found in a certain place. We can be reasonably sure it's there, but certainty is impossible.

Quantum mechanics operates on probability; every possibility is simultaneously enacted. At the subatomic level, particles can just pass through seemingly solid walls. Richard Feynman believed (as do most physicists today) that an electron takes not the shortest path from point A to point B but every possible one. That is to say, an electron flying from New York to Los Angeles books a direct flight, but it also books a flight with a stopover in Detroit, one that passes through Phoenix, one through Pittsburgh, one that goes from New York to

Boston to Dallas to Chicago to Seattle to Los Angeles—ad infinitum. It's the ultimate frequent flier! To cross a distance the radius of a hydrogen atom, the electron takes a route that leads it past Jupiter, along with an infinite number of other possible routes. But somehow, every route manages to cancel every other one out, resulting in the timely arrival of an electron at its destination. This theory "describes Nature as absurd from the point of view of common sense. And it agrees fully with experiment. So I hope you can accept Nature as She is—absurd" (Feynman 10). It doesn't matter how counterintuitive electron motion is; this is the way it has to happen in order for our observations to be "real." On a quantum level, the universe is unpredictable and illogical. Nature doesn't set itself to be understood by humans; it sets itself to work. If it ain't broke, don't fix it.

Scientists finally have conceptualized a way to make sense of quantum weirdness via string theory. String theory posits that instead of infinitely small, zero-dimensional point particles, the universe, at its most fundamental level, comprises tiny, one-dimensional vibrating "strings." What they're made of, we don't know. The vibrational patterns and arrangements of different strings produce different observed particles just as different strings on a cello produce different notes. So instead of A-flat, you get an electron. D-sharp? Well that's a photon. Physicist Brian Greene calls it "a cosmic symphony," with "notes" from various instruments blending to produce everything we hear (and see and smell...). Superstrings write the rules that particles, atoms, molecules, and, ultimately, organisms like us have to play by. Energy, matter—it all originates

from an irreducible thread vibrating in ten dimensions. Along with the three dimensions we normally see and the time dimension, six spatial dimensions are curled up into a wrinkled-pea shape called a Calabi-Yau space that exists only on subatomic scales. String theory succeeds where quantum mechanics fails because it has a firm lower limit on how small things can get. With quantum mechanics, you keeping zoom infinitely until you reach a level of magnification where space—the "emptiness" between "things"—is no longer a smooth plane but a violent landscape punctuated by crags and holes, gulfs and valleys of "quantum foam." At this magnification, straight-line motion becomes impossible—particles duck and weave around the roiling, jagged crags of quantum irregularities—so nothing is predictable. Strings, though, are large enough that they don't "fit" in the space of the quantum foam; they're one order of magnitude too big to be subject to the caprice of quantum crags and pits.

So you're zooming in and zooming in, and then, suddenly, you hit a brick wall and can't get any smaller. Since strings are one-dimensional, they can't be resolved into a single, infinitely small point. They can't get any smaller than the Planck length, which is, theoretically, the smallest distance possible. Nobel laureate Max Planck discovered the Planck length by combining numbers from the three fundamental physical constants—the only guarantees in a continuously reeling and wobbling universe: the speed of light, the Planck constant (which is used to relate the energy of a wave to its frequency), and the gravitational constant (involved in calculating the gravitational attraction of any two things). It's an intensely laborious process to derive the Planck length, but I

think we can safely trust Planck's calculations, given that he won a Nobel Prize for it. The Planck length ends up being a distance of 16.163×10^{-36} meters (or 53.027×10^{-36} feet, but at this level the difference between feet and meters hardly matters). To put it in perspective, an average bacterium would be about 10^{28} Planck lengths, a number so large we don't have a common English term for it (I suppose you could say "ten octillion," but that doesn't really aid in understanding).

Beyond the Planck length, who knows what can happen? Because strings are the essential components of everything and the smallest physical thing we could use as a probe, there's no way to get past the Planck length. We have no idea what could be lurking below—or if "below" even exists. For all I know, there could be tiny universes contained in a Planck length. Maybe it's the gaps that Annie Dillard mentions, "the spirit's one home, the altitudes and latitudes so dazzlingly spare and clean that spirit can discover itself for the first time like a once-blind man unbound. Squeak into a gap in the soil, turn, and unlock—more than a maple—a universe" (274). The gaps are the places "where you cower to see the back parts of God" (Dillard 274). The divine might be sitting in the quantum recesses of the Planck length. The point is, we can never know.

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Microworlds—cells wobbling drunk on the elixir of life, atoms colliding, the quantum glue holding together the nucleus, the vibrato of superstrings and their constant creation—approach the asymptote of dividing by infinity. This is

complexity, knitting the picture that a grandmother knits in the picture of someone knitting. Each constituent comprises ecosystems of smaller elements, a constant reduction. Not a reduction to absurdity; a reduction to incomprehensibility: The life of the quivering string lived in the life of a down quark in the quantum sandwich of a proton, itself bound to five other protons in the beating heart of a carbon atom, linked and knotted with hydrogen and oxygen to form the ring of a glucose molecule torn apart by the violent oxidation of mitochondria working for the endodermic digestive cell of an exploding blastula, gastrulating into the embryonic blueprint of a blue whale. The intricacy, the impossibly fine detail of the micro, makes it sublime, as every process underlying its existence folds like the amino threads of hemoglobin into such an inconceivably minute space.

With the Transmission Electron Aberration-Corrected Microscope (TEAM), scientists can see atoms clustered together into bubbled sheets (how's that for teamwork?). In my travels through the data mines of science journals, I chanced upon an image of an ultrathin sheet of gold viewed under a TEAM. Tiny circles, just barely visible, aligned themselves side-by-side into rows and columns. Dots and divots, black empty spaces wrapped in a thin, radiant orange membrane, formed a honeycomb hourglass structure. I imagine this is what bees see every morning as they punch the clock for another day in the hive. This is real, though. We can *see* atoms. The proof is in the picture.

But when I wake up at eight o'clock on a winter morning in Connecticut, when the blurry layer of window frost melts into dew, I can't see the atoms. I

don't see the hydrogen bonds pushing and pulling molecules together in a game of electromagnetic tug-of-war. I leave peanuts out on my windowsill, so that I can get a close view of the gray squirrels as they fiddle with the shells, twirling them like batons until they have them at the perfect cracking angle. I watch a squirrel feed a few feet—a decillion or so Planck lengths—from my windowpane. No, I have no way of breaking the surface tension, of knowing what's going on inside that squirrel: how many ions of sodium and potassium are ferried through its neural phospholipid bilayer by transport proteins to carry an electrical pulse along its spine. I have no visceral understanding of the helical keratin fibers wrapped into a single silver hair. I can't measure the wavelengths of the light bounced off of the squirrel's body that strike my retina, which my brain splices and assembles into its image. I strain my eyes, narrow my eyelids like a villain in a silent movie, to try to see the striated muscle sliding the squirrel's jaw up and down, the quintillions of quarks bumping and splitting protons in every one of the squirrel's billions of cells at every moment. I strain but to no avail. I can't see the electrons dancing along its cytochrome, the photons bouncing around inside it, but somehow that squirrel still moves me to awe. That squirrel is the composite of a billion processes that could have turned out any other way. But they didn't. However improbable, they formed a squirrel. By a similar logic of serendipity, I chanced to be there that morning, catching that burning impression of the squirrel, that facsimile of the divine, before he vanished along a hickory path. That squirrel, the world outside my window that

it shelters itself in: it is a gift wrapped in the protein pulp of brown paper, tied with superstrings.

Touching the Infinite

"Wherever there is life, there is twist and mess: the frizz of an arctic lichen, the tangle of brush along a bank, the dogleg of a dog's leg, the way a line has got to curve, split, or knob. The planet is characterized by its very jaggedness, its random heaps of mountains, its frayed fringes of shore"—Annie Dillard, *Pilgrim at Tinker Creek* (140)

I rarely wake up early. It's a habit of mine that I've been trying to correct for the past year or so, but I never seem to have any success in curbing my sleep excesses. If I have somewhere to be, well, then I have no choice but to wake up early. Most of the time, though, I'll set my alarm for some arbitrary time that, before I fall asleep, seems like a reasonable hour to start the day and then, when that time comes, hit the snooze button until I disregard the alarm entirely. Today, for some reason, is different.

My friend and I rented a cabin in northern Georgia at the end of May, giving us two weeks with a national forest at our disposal. I have no trouble waking up on these days, when the late vernal sun, realizing it has only a couple weeks before it has to work overtime after the coming of the summer solstice, rides sidesaddle on a pale cumulus cloud streaming like protoplasm through the Georgia sky. Today I'm up at the obscenely early hour (for me, anyway) of 7:15. I'm lucky enough, for this brief period of time, to have the Chattahoochee National Forest as my backyard. I step out the front door, walking along the front deck past clusters of spiderwebs, still occupied by argiopes busily sewing a zigzag zipper of silk down the central axis of their webs. Off the porch, I head down Papas Mountain Road (I think the intent is "Papa's," but the road sign lacks

an apostrophe—although it is possible that it's named for the Greek surname Papas), a challenging climb for any car. I'm living a scaled-down, economized version of John Winthrop's dream, not quite a "citty" but "a cabbin upon a hill." The hill happens to be extremely steep, which makes for a blur of a descent and a tiring ascent. Still, the climb is well worth it; the one-lane gravel road is flanked with a hefty sampling of nature's abundance. Woods dominated by tall pines unfold on either side of the road. Immediately before the curtain of dampening light that marks the entry to the woods grows a small strip of grass running parallel to Papas Mountain Road. The grass smells sweet, radiating southern hospitality. I crunch patches of it under my foot with each step, but it manages to bounce back, as though pushing up on my foot or helping me lift my leg as I advance to the next step. Guardrails of ferns fence the road. At the bottom of Papas Mountain lies a hollow gully, only a few feet deep by a few feet across. Here the ferns have run wild, unfurling their fronds every which way. Something like this little scene, this fern gully, is what I imagine the first glimpse of land must have looked like to the earliest amphibians when they crawled out of the cold broth of the ocean's womb on new-fangled limbs.

Before my stay in the Chattahoochee National Forest, I had never really given ferns a second thought. I knew they were bold innovators—the first plants to have vascular tissue, tubes of bundled xylem and phloem that seize on the transpirational pull and the capillary action of water to yank nutrients up to their leaves to replace those lost in photosynthesis—that vastly expanded the palette of plant forms. But I hardly recognized their beauty, their mathematical

intricacy until my stay in the cabin. I realized that I wasn't giving ferns the respect they deserved, so I resolved to learn to differentiate them by species because, after all, how can you respect somebody if you don't even know his or her name? I referred to The Audubon Society Field Guide to the Southeastern States to enlighten me. According to the guide, one of the main ways to identify ferns is the shape of their leaves, called fronds. In its infancy, a frond resembles a fiddlehead, curled into a tight spiral, that gradually unfolds to become linear. "Fern leaves," explains the guide, "are commonly compound and may be pinnate (divided into leaflets), bipinnate (subdivided into subleaflets), or even tripinnate (divided again into segments); they are often lacy or feathery in appearance" (Nationaal Audubon Society 88). There are, according to the guide, four main classes of ferns based on "pinnatedness" (regrettably, there is no noun form of the word "pinnate," so bear with me): simple (in which the frond is a single sheath-like leaf), pinnate, bipinnate, and tripinnate. Pinnate fronds have a central stem axis, known as a rachis in technical botanical terminology, with rounded leaflet lobes jutting off. If we were to place a compass (or better yet, magnetotactic bacteria!) at the base of the frond so that north aligned with the stalk, the leaflet lobes would split off to the east and west. In a bipinnate fern, each of these leaflets is its own perpendicular axial stem (called a costa), with subleaflet lobes pointing to the north and south. Bipinnate ferns have a feathery appearance, with each costa as a wing. Tripinnate fronds up the ante so that every subleaflet splits into smaller segments, giving each subleaflet the appearance of a jagged shark's tooth. Regardless of the level of pinnatedness, as

you move from south to north along the rachis, the leaflets shrink in size until they effectively disappear and you're left with only an arrowhead of rachis. Of course, any given fern will have multiple fronds, and each frond, depending on pinnatedness, may have lobed leaflets divided into their own subleaflets further divided into serrated segments.

On that morning when I rose with the sun, I had the good fortune to see all four classes of ferns dotting the margins of Papas Mountain Road. If I hadn't seen all of the major kinds of ferns, I would never have grown to appreciate them. I saw that with each increase in pinnatedness, ferns became more and more compounded, nesting mini-ferns within themselves. One day, I plucked a toothy segment from a fern and examined it under a magnifying glass. Each segment was a leaf! A leaf in miniature, like a Z-scale model of an N-scale fern. The parts of the fern resemble the whole. Without knowing it at the time, I was staring down the magnifying glass at one of nature's most fundamental forms.

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Ferns, as stunning and inimitable as they seem, are not unique in their continually compounding bifurcation. They look chaotic, impossible to reproduce, yet ferns can be modeled almost perfectly by vector mathematics.

Math professor Michael Barnsley created a flawless computer representation of an Asplenium fern, shortly thereafter known as the "Barnsley fern." Barnsley defined a series of matrix transformations (a mathematical concept that I haven't studied in depth, but I'm willing to give Barnsley the benefit of the doubt). Starting with a point, he plugged the coordinates into the system of

functions, got a new set of coordinates as the result, plugged those back into the function, got a newer new result, and continued plugging and solving tens of thousands of times in a process mathematicians call "iteration." The results, when plotted with a computer graphics program called VisSim, are the spitting image of a fern. A curving cord bent through the x-y plane serves as the rachis. As the computer simulation runs, it lays out the skeleton of the fern, fleshing out its costas and adding ever-finer teeth to the subleaflet segments with each successive iteration. When graphed, Barnsley's functions appear nearly identical in form to the bracken ferns lining the road up to my cabin.

As the Barnsley fern proves, wild ferns evidence the broken geometry of a fractal. Fractals are strange. Our minds are used to simple, definite shapes and Euclidean geometry: triangles, rectangles, trapezoids, octagons, circles, cubes, pyramids. They have clear boundaries and easy-to-measure properties like perimeter, area, and volume. Fractals don't work that way. They have entirely counterintuitive properties. They look wiggly like a coastline, jagged like the toothy leaf segments of a fern. With a typical shape—say a square or a circle—as you zoom in, you just see a line segment or a curve. So you would think that if you zoomed in far enough on a fractal shape like a coastline, eventually the wiggles iron out and resolve into a smooth segment. Not so; as you magnify the image of a fractal, new details—finer, jagged edges making up the wiggles—become apparent. No matter how much you zoom, you will never be able to smooth out a fractal. Benoit Mandelbrot, the mathematician who discovered the fractal, defines it as "a rough or fragmented geometric shape that can be split

into parts, each of which is (at least approximately) a reduced-size copy of the whole" (Fractal Geomerty of Nature 1). Fractals exhibit the defining feature of "self-similarity," where the structure of each part resembles the whole. This doesn't mean that every part of a fractal is an exact replica of the whole (although this is true in some cases); the self-similarity can be approximate simply in that the smaller parts are just as "wiggly" as the entirety. Take the coastline of Britain. There aren't little Britains making the coastline, minute outlines of the whole country along each mile of coast. Rather, at any magnification, the coastline will look serrated, dented or fragmented. Self-similar is not always self-exact.

Fractals grow weirder when you try to measure their properties. Say, as Mandelbrot did, that you want to measure the length of the coastline of Britain. Now if Britain were an octagon, all you'd have to do is measure the eight sides and add them up (or, if you're a speed-demon, measure one side and multiply it by eight). But we live in reality, not Euclid's dreams, and no coastlines are polygons. So if you want to measure the coastline of Britain, you'll get different answers depending on the size of the ruler you use. If you use a one-mile ruler, you'll only be measuring the major contours of the land. Now, try a yardstick. You'll get more of the finer features, the subtle curves and zigzags missed by the mile ruler. These zags and zigs will add to your total length, and you'll get a larger number than you did with the one-mile ruler. Using a foot-long measuring stick will capture even more of the finer zigzags that the yardstick missed, and you'll get a still larger coastline length. Want to try an inch ruler?

The ultimate effect of this smaller-and-smaller-ruler approach is that as you magnify, you're constantly adding length to the perimeter of the fractal. And since you can never zoom in enough to straighten a fractal out, set it on the right and linear path, the perimeter will increase indefinitely as you move closer and closer. You end up with an infinite perimeter enclosing a finite area. Now, let's say a math teacher has plopped a crazy, multi-sided polygon with sides of irregular lengths in front of me and demands that I calculate the average length of a side. Easy enough; I just measure each side, add up all their lengths, and divide by the total number of sides. The statistical properties of a fractal, however, can be infinite or not exist at all. What if I were asked to determine how many dimensions a polygon has? Intuitively, I would know that it's twodimensional since it has both length and width. Mathematicians, of course, can't rely on intuition. Felix Hausdorff developed a mathematically valid way to measure the dimensionality of an object, which, unfortunately, really can't be explained in any way other than a mathematical formula. The essence, though, is that it requires a new conceptualization of dimension. When we think of dimension, we're undoubtedly talking about topological dimension—the number of coordinates needed to specify the location of a point. The difference between one, two, and three-dimensional objects, then, is that between a number line, a Cartesian graph, and three-dimensional graphing (with an x, y, and z-axis). Hausdorff's conceptualization of dimension, though, is not one of coordinates needed to specify a point; it involves the space-filling properties of an object. Even though fractals have to have the normal, whole-number

topological dimensions we're used to, their Hausdorff dimensions can be fractional since the infinitely fine features can fill up partial amounts of space. The coastline of Britain would appear to be a line, even if jagged, so we would intuitively say its dimension should be one. This is indeed true for its topological dimension. But the line bends and curves, enfolding extra bits of space around it "because the perimeter is so wiggly that it covers more than just a 1-dimensional line" (Liebovitch 64). So it must be two-dimensional! But there are "gaps" not covered because of the bending, lacunae not enclosed by the perimeter. It covers more space than a line but less than the solid block occupied by a square. The Hausdorff dimension of the coastline of Britain is somewhere between one and two; Mandelbrot calculated it to be 1.25-dimensional ("How Long Is the Coastline of Britain?").

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They seem so alien, fractals. If Euclid saw them today, he would want to think that they exist only in the territory of abstract mathematics. "Mandelbrot, you can keep your fractals. I'll take squares and spheres, polygons and Platonic solids any day." Unfortunately for Euclid, fractals are everywhere. Step outside, look around, and, lo and behold!, you'll come across a fractal. "Clouds are not spheres," Mandelbrot writes, "mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line" (Fractal Geometry 1). The billowing edges of a cumulus pillow share the same degree of "wiggliness" as the whole shebang. The face of a mountain is approximately a giant pyramid broken into tiny triangles broken into tinier

triangles ad infinitum. Each diffuse, filamentous saw of ionized plasma in a staccato lightning strike resembles the entire bolt. The same pattern of branching and bifurcation repeats at each split in the lightning bolt, and as you zoom in on its edges, you reveal more smaller-scale wiggles that bend at everfiner magnifications to consume more space than a single dimension. The rachis resembles the whole bracken fern, a cluster of several fronds. Each frond splits laterally into costas with leaflets resembling the frond. The leaves themselves comprise small subleaflets, which radiate perpendicularly like the teeth of a comb and mimic the shape of the larger leaflet. Each subleaflet divides into wavy, toothy segments that imitate the branching subleaflet. With a powerful magnifying glass or dissecting scope, a single segment could almost pass for the bracken plant. The devil's in the details, and the details look a lot like the devil.

I run my fingers across the bracken. Then I squeeze it circularly between my thumb and fingers like I'm making the gesture for money. The waxy green cuticle starts to rub off. The fern is light but not exactly soft, more of a greasy, plush velvet feel. Not expensive velvet; the cheap kind that gets stitched across meretricious old-style chairs. It's a fragmented feel, too. Even though the edges bend and blend together, I can almost distinguish each segment like the barb of a feather. The bracken fern has a certain, indefinable fractal feeling to it—a "fractal sensibility," you might say. I start to imagine what the sense of touch would be like in a Euclidean world, where everything is made of undeviating, straitlaced line segments with a few bowed curvilinear arcs thrown in for good measure. Surfaces would be smooth. Corners would be sharp. That's all. You wouldn't

even need shoes in a completely geometrically regular world; as you long as you didn't walk near the edges of a shape, your feet would never get cut and you'd never stub a toe. Microscopic irregularities arranged fractally on the surface of an object endow it with its unique texture. The fractional dimension gives touch its sensuous vitality: the tiny hooks and barbs on a burr, the minuscule hills and dales and spires of fractured wood in bark. A purely two-dimensional tree trunk would feel no different than a buffed table polished over with Pledge. The slight difference in fractal dimension lets me distinguish the papery birch from the scaly pine. It lets me feel the current twirl around my toes, which sink into satiny banks of silt as I walk barefoot in the Nottely River. I like Euclidean geometry because it's math that's easy enough for me to learn quickly and compute accurately, but it feels empty to the touch: edges and lines can't tantalize the sensory neurons embedded in the tips of my fingers. No, I wouldn't want to live in a world without fractals.

I couldn't live in a world without fractals. Self-similarity cuts to the core of my structure. Those sensory neurons nested in my fingertips are built on a fractal design. Nerve cell structure shares much in shape with the expansive Mississippi River. Dendrites branch in a jumbled mess like the streaming tributaries of the muddy Mississippi. At the point where the streams all flow together and converge to form a single, gigantic and meandering river, a neuron would have the soma, the sinuous cell body. The soma narrows into a long sheath called the axon, bifurcating constantly like the spreading waters of the Mississippi Delta from a bird's eye view, each fork-in-the-cell like the one before

it. A fractal blueprint underlies the neuron "because the pattern of the branching of the large structures is repeated in the branching of the ever smaller structures" (Liebovitch 14). The effectively infinite perimeter of the dendrite branching allows it to pick up a mind-boggling number of stimuli. The nerve cell's strategy seems to be, "Divide and conquer."

A neuron exhibits fractal arrangement not only in space but also through time. Nerve cells pass along information via an electrical pulse that they generate through transporting ions through protein channels. The ion channel protein can change its shape to either allow or block the flow of sodium and potassium ions into the cell, depending on what is needed at the moment. When a dendrite picks up a signal, either passed along by another neuron or excited by some sensory input, the cell activates, opening its ion channels to a massive influx of sodium and potassium ions that changes the electrical charge of the cell to positive. (This is happening continuously as photons strike the neurons in your eyes. Every second, electrical charges are passing through some neuron in your body.) The charge passes along the body of the neuron, from the dendrite to the soma to the axon, as a ripple, each gate handing off a "hot potato" of positive charge to the protein channel next to it. With the change in the cell's polarity, the ion channels close, and the neuron actively pumps the sodium back out. When the signal reaches the many tips of the axon, it initiates the production of neurotransmitters, tiny chemical bubbles that stimulate other neurons, glands, or, in the case of motion, muscles. The waters calm as the neuron returns to its resting state. Amazingly, scientists can actually measure the almostnegligible current produced by the flow of ions through the channel. The current is higher when the channel is open and lower when it is closed. Neuroscientist Larry S. Liebovitch explains a rather remarkable discovery based on the observation of a single ion channel. Instead of zooming in on an image so that an inch looks like a foot, Liebovitch zoomed in on a graph of current over time that so each second looked like a minute. "When a recording of current is played back at low time resolution, the times during which the channel was open and closed can be seen. When one of these open or closed times is played back at higher resolution, it can be seen to consist of many briefer open and closed times" (Liebovitch 18). And one of these open or closed times, played back at a higher resolution—perhaps when a minute is stretched to look like an hour—reveals that it consists of shorter open-closed alternations, and so on and so forth. At every self-similar point on a neuron's branching dendrite or axon terminal, a continuous and self-similar flickering unfurls as seconds liquefy as tributaries into the stream of time. Fractals comfortably nest themselves within fractals.

Anytime an organism needs to cheat the surface area-to-volume ratio, fractals serve beautifully. The amount of surface area relative to volume directly influences an organism's ability to obtain the essential chemicals necessary for life. In general terms, substances move by diffusion, "spreading" out within a medium from areas of high concentration to areas of low concentration. The effect of diffusion can be easily seen with helium balloons. In the first few days after the party, the balloon bouquets, which contain a substantially higher helium concentration than the ambient air, begin pruning into wrinkled knobs.

But once they're small and pruny, the balloons take forever to deflate the rest of the way. When the inside of the balloon and the air outside of it have the same concentration of chemicals—nitrogen, helium, oxygen—the balloon enters a crinkled stasis and diffusion pauses. The latex skin of the balloon serves as a useful model for a living cell membrane. How quickly a substance diffuses from a high concentration outside of a cell past the membrane to its inside depends entirely on the golden ratio of surface-to-volume. The more area exposed to ambient air or water, the more entry points there are for valuable nutrients to make their way inside (or waste products to make their way outside). The total volume—the overall "size" of something—determines the demands of a cell or organism; a huge cell requires more oxygen to support it. But surface area and volume are at odds because volume increases much more rapidly than surface area does. Stephen Jay Gould, a paleontologist at Harvard, explains this biospatial catch-22: "Simply by growing larger, any object will suffer continual decrease in relative surface area when its shape remains unchanged. This decrease occurs because volume increases as the cube of the length (length x length x length), while the surface increases only as the square (length x length): in other words, volume grows more rapidly than surface" (Gould 171). The demands grow faster than the ability to meet them.

I remember an experiment from my high school biology class that solidified this point. We took cubes of gelatin of various sizes and dropped them in a container of red dye for some specified amount of time that I can't remember anymore. Each cube represented a cell. When the time was up, we

took the cubicle cells out of the dye and looked at them. The smallest cubical cell had sides five millimeters long, so its surface area was a hundred and fifty square millimeters, and its volume was twenty-five cubic millimeters. The surface area-to-volume ratio, then, was six. This cell ended up looking beet-red; we sliced it down the middle and saw that the dye had fully permeated it. The larger cube had sides of ten millimeters, with a surface area of six hundred square millimeters and a volume of a thousand cubic millimeters. It had a surface area-to-volume ratio of 0.6, ten times less than the other cube. The outside part of the large cube appeared solidly crimson, but taking a cross-section revealed that the inside had absorbed significantly less dye. A large circle of white stood at the center, ringed peripherally by darkening shades of red. The take-home lesson of the experiment is that the greater the surface area-to-volume ratio of an organism, the more easily it can take up nutrients from its environment.

Now, for a bacterium or a protist, this hardly raises any issues. Its surface area is very high relative to its volume since it's only a single cell swimming around with all sides exposed to the water. Still, to maximize their surface area, bacteria and protists employ a cell membrane based on a fractal blueprint. A cell membrane is not a just a circle of molecules; it is looped and folded, zig-zagging like the toothy segments of a fern to expose as much of itself to the surrounding environment as possible. Paumgartner, Losa, and Weibel, in the Journal of Microscopy, found decisive evidence of this. They photographed a membrane using an electron microscope and calculated the surface area at different

magnifications. As the magnification increased, the membrane seemed to contain more and more wavy undulations, leading to an increase in surface area without a complementary increase in volume. In some cases, increasing the magnification from a measly 18,000X (that is, eighteen thousand times closer than the eye can see) to 172,000X caused the surface to triple. Zooming in more (if the technology were there) would reveal still further membranous undulations. A microscopic bacterium, no more than a millionth of a meter in length, enfolds an infinitesimal volume in a cell membrane of effectively infinite length. Infinity sits on the borders of every living thing.

Multicellularity significantly complicates things for plants, fungi, and animals. Multicellular organisms amount to clustered piles of cells, and most of their cells are buried in the middle of the pileup, completely landlocked. Even though their cell membranes maintain the infinite waviness of their bacterial and protistan forebears, they have no membrane coastlines touching the ambient air or water of their environment. Some, according to Gould, "must alter their entire shape in ways so drastic that plasticity for further evolutionary change is sacrificed to extreme specialization. Thus, a tapeworm may be 20 feet long, but its thickness cannot exceed a fraction of an inch because food and oxygen must penetrate directly from the external surface to all parts of the body" (173). Other multicellular organisms have caught fractal fever in order to circumvent their meager shorelines. In them, fractalmania manifests itself in the form of tissues and internal organs. Organs follow a fractal design, rich in self-similar zigzagging. Ferns, for example, have only a rudimentary internal

transport system compared to flowering plants. Their fronds branch into yetsmaller fronds to increase the amount of leaf surface touching the air. That way, they can take in all the carbon dioxide and give off all the oxygen they need.

* * * * *

The vertebrate body represents a web of interwoven fractals. I take a breath and the air flows through me down a fractal cave. My lungs are intricately and indefatigably fractal. As I breathe in, air rushes down my trachea until it reaches a fork in the road at the center of my chest, two sturdy tubes pointed opposite one another called bronchi. Quite predictably, the left bronchus leads to the left lung, and the right bronchus heads toward the right lung. Or, more accurately, the left and right bronchi constitute the left and right lungs. Because nature is far too extravagant to have a simple line segment splitting at a fortyfive degree angle into two similar line segments, the bronchi are far from the beall-and-end-all of the lungs. The main bronchi diverge into smaller mucouscoated cartilage pipes called lobar bronchi—two on the left and three on the right. Each lobar bronchus splits into thinner tertiary bronchi. The left side contains eight of them, the right ten. A tertiary bronchus marks the boundaries of a bronchopulmonary segment, an independently functioning chamber of the lung partitioned off by a septum of connective tissue. (To remember the names of all the bronchopulmonary segments of each lung, medical students have devised humorous mnemonics like "A PALM Seed Makes Another Little Palm" and "Apoptotic Antlions Stop In, Suddenly Amalgamating Laboratory Posts," which serve the dual purpose of reminding them what the segments of the left

lung are named and explaining why all the good experimental science jobs have been taken [Medical Mnemonics].) Within a segment, the tertiary bronchus again pinches off into primary bronchioles, distinct from the bronchi by the absence of cartilage. The primary bronchioles diverge into several terminal bronchioles, which themselves part to form respiratory bronchioles. They then divide into tiny biological vents called alveolar ducts. Finally, the action of breathing really takes place. The alveolar ducts invaginate like a bunch of grapes to form tiny sacs—lungs in miniature—known as alveoli. Here a layer of epithelium a single cell thick, stretched like Saran Wrap around the mouth of a can, permits oxygen and carbon dioxide molecules to easily flow across. After so much branching, the likelihood that a given molecule of inhaled oxygen will end up in a particular alveolus is (according to my rough mathematics) about one in four hundred thousand.

Fractals determine the structure of the lungs, which are composed of a series of bifurcations—from bronchus to lobar bronchus down to alveolar duct to alveolar sac. Every bifurcation follows the same general pattern, self-similar to the junction before it. Zoom in on a bronchus, and it terminates in lobar bronchi; zoom in on them, and they narrow into tertiary bronchi. Lather, rinse and repeat until you hit a thin boundary of elastic epithelium permeable to air. Each tiny branch winds and meanders, folding in on itself at points and blurring the line between the second and third dimension. A French researcher calculated the space-filling Hausdorff dimension of the lungs to be 2.97, pretty darn close to an authentic 3-D experience (Sapoval). The spindly, attenuated

projection of each alveolar duct increase the surface area of the lungs just enough. Reaching out an elastic finger composed of a single layer of cells vastly raises the surface area of a structure but only marginally contributes to its volume. The ultimate effect is what Gould calls "a richly convoluted bag of surface area for the exchange of gases" (173). Medical images of the lungs reveal a structure resembling the roots of an upturned tree (which, coincidentally, the trees use to increase their absorptive power for nutrients from the soil) or the radiating dendrites and axon tips of a nerve cell. All of this, roosting cozily in your chest. I wish that I could feel my inhalation splitting along the fractal surface of my respiratory system, feel the force of sucking in diminish by half at each tubular juncture. Take a breath; feel the fractal.

Like ice crystals growing on a vine, the lungs are a double fractal. A unique artery supplies blood to each bronchopulmonary segment. Veins and arteries embrace the tiny alveoli. To facilitate diffusion, the blood vessels assume the shape of a fractal. The circulatory river of the pulmonary artery splinters into arterial streams carrying deoxygenated blood from the body along the path of the bronchi, running off into thin capillary brooks, only a cell or two thick, that wrap the alveoli. The deoxygenated blood courses through the capillaries, which are so thin that red blood cells must bend and distort like rubber washers to fit through them, to swoop around the alveolar sacs and refill its oxygen tanks. The re-oxygenated blood runs along as the capillaries condense into veiny rivulets, the branches eventually merging to make up the pulmonary vein. The vein links up to the heart, and the newly oxygenated blood streams through the intricate

branching of the body's arterial network to be rationed among the various somatic tissue clusters. (Of the fifty or so major arteries in the body, only the pulmonary artery—the expressway from the heart to the lungs—carries oxygenpoor blood. Likewise, the only vein that carries oxygen-rich blood is the pulmonary vein.) The circulatory system represents a fractal root system with the purpose of outwitting the surface area-to-volume ratio. As Gould observes, "the circulatory system distributes material to an internal space that cannot be reached by direct diffusion from the external surface of large organisms" (173). Each tiny capillary vessel identically matches the larger artery or vein it descended from and closely resembles the alveolus that it brushes against. The circulatory and respiratory systems must work in tandem to be of any use; the oxygen plucked out of the air by the lungs requires the tributaries of blood vessels to apportion it equally throughout the body. If the air just sat in your lungs without going anywhere, your muscles, nerves, and other organs would atrophy. The breath of life and the lifeblood—entirely codependent—both course along a fractal river.

The fractal river of the circulatory system hits an embankment along the digestive tract, which, like waves breaking against a wiggly coastline, is doubly fractal. Interwoven with the fractal circuitry of the cardiovascular system is the self-similar setup of the intestines. Digestion is the hallmark of animals, so quite understandably it's an involved process. Most of the digestive process in vertebrates occurs in the small intestine, a blushing, vitreous, sixteen foot-long coil of mucosal tissue and sculpted mesoderm enfolding a hollow tubular cavity

known as the lumen. Enzymes from the pancreas and gallbladder flood the lumen of the duodenum, the ecotone between the stomach and the small intestine. Here enzymes thoroughly disintegrate the food by wrapping it in the four levels of their protein structure to speed up its natural breakdown. Entering the jejunum, the longer, middle section of the intestine, the food-and-enzyme soup flows along epithelial folds called plicae circulares that have the rugged, wrinkled appearance of mountainous terrain on a topographic map. Out of the circular folds extend projections, like the rocky outcroppings of fjords. Villi, as they are called, probe into the lumen, as though they were a tightly clustered bunch of Dead Man's Fingers fungus splitting the soil around it. A villus contains a single sheet of epithelial cells gilding a tangle of capillaries and a straight rod of lymphatic vessel called a lacteal. Just as the larger circular folds of the intestine consist of folded fingerlike villi, a patina of finer self-similar cellular membrane protrusions—microvilli—coat the edges of the villi. Anatomists refer to this layer of microvilli as a "brush border," presumably because the fuzzy stubs resemble the bristles of a brush. A microvillus is more or less the size of a single bacterium. The folds along folds along still larger folds achieve a feat far beyond what their size might suggest: they give the small intestine "a huge surface area—300 m2, roughly the size of a tennis court" (Campbell & Reece 865). If we could iron out the pipe of mucosal shag carpeting curled up in our abdomens, we would be able to cover an entire tennis court in a uniform film of cytoplasm. Surface area is of crucial importance here because nutrient absorption depends on the diffusion of valuable chemicals in food, and diffusion depends on the

amount of surface exposed. Each bacterium-sized microvillus yanks nutrients from food down their diffusion gradients into the fractal network of blood vessels circulating at the villus' heart. Neurons that branch, divide, and rejoin to form a honeycombed myenteric plexus sit beneath the flesh of the intestines, opening and closing their ion gates to instruct the muscles there to ripple along in a peristaltic wave.

Fractals regularly make guest appearances in other parts of the body, as well. In the excretory system, the kidneys use a fractally branching structure of tubes to filter out waste from the blood. Annie Dillard tries to describe the functional structure of the kidney, the nephron, in "regular" geometrical terms in Pilgrim at Tinker Creek but concludes, "There is no way to describe a nephron; you might hazard into a fairly good approximation of its structure if you threw about fifteen yards of string on the floor. If half the string fell into a very narrow loop, that would be the Henle's loop" (135). The structure of the kidney turns out to be a looped, confused fractal pattern, which in 1975 (when Dillard was writing) had just recently been thought up by Mandelbrot. Still, Dillard gets the gist of the fractal, hinting at the connection between the winding loop design and surface area-to-volume optimization: "By going from here to there in such a roundabout way, the Henle's loop packs a great deal of filtering tubule into a very narrow space" (135). The brain, too, is modeled on a fractal design. Enfolding and wrapping around itself, it maximizes its storage space, allowing us to cache a lifetime's worth of memories and learning in just about fifteen hundred cubic centimeters. (Perhaps inspired by the brain, the designers of

computer chips use fractal patterns to optimize the amount of data able to be stored.) A complex body plan is so thoroughly fractal that each organ system reveals tiny, self-similar structures which, when magnified, uncover yet smaller features that bear resemblance to the whole. Fractals, it turns out, are the best way to maintain a reasonable surface-to-volume relation since each thinner or flatter branch exposes more of its "outside" to its environment while costing only the most minute bit of volume.

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Bronchi that split into tubes, then tubules, then finally a sponge network of alveolar bulbs; neurons that crack and diverge into a bioelectric lattice; intestines that roll in waves, their involute crests crowned with serous fingers lined with micro-finger bristles; the zigzagging membranous coastline of a cell; the tough fibrous extension of reticulated roots, which explode with microscopic root hairs. Try to draw a diagram of the blood vessels in your body down to the detail of every capillary. Trace every vein through every bifurcation. It's a pattern of such staunch intricacy that the placement of a single cell matters. The human genome has about one hundred thousand genes; fractal structures like the heart and the brain contain between one million and one hundred billion component cells. A hundred thousand genes are responsible for encoding and organizing trillions of cells into complicated structures. The beauty of fractals, though, is that this is only an apparent intricacy. The compounded iteration of a single, relatively simple mathematical formula is all it takes to generate an impossibly complex-looking pattern. The genes save work by coding not for the

structures themselves, but for the simpler mathematical rules that generate the structures. Rather than specific instructions for each constituent part of an organ—"place cell A to the left of cell B, which should sit atop the cuboidal cluster of cells C, D, and E…"—my genes code for a single rule, such as "branch after x microns of tubules have been laid," and repeatedly apply that rule like a computer program plotting a Barnsley fern. A rough biomathematical equivalent of "branch and thin, branch and thin" is really all that's required to generate the seemingly complex patterns of the nervous, respiratory, and circulatory systems.

Research on tomato plants has allowed scientists to localize a gene responsible for the expression of a fractal pattern. The gene belongs to a class of genes known as homeotic genes, which dramatically impact the landscape of an organism by controlling what structure a group of cells will become. In many plants, such a gene, identified as KNOTTED-1, influences leaf morphology and the structure of leaflets. When all is well, KNOTTED-1 produces singularly compound leaves. To get an image, imagine something like a once pinnate fern played out with a leaf that resembles something of a cross between an oak and a maple. Each leaflet resembles the general shape of the entire petiole. An overexpression of the KNOTTED-1 gene completely disfigures the tomato plant, causing the petioles to branch into smaller subpetioles, which further split, producing what have been termed "supercompounded" leaves (Campbell & Reece 742). The supercompounded tomato plant hangs from the soil like an inverted lung, more closely resembling parsley than tomato. By tweaking the expression of KNOTTED-1, scientists can create a fractal labyrinth from a

straightforward tomato plant, suggesting that the gene codes for a pattern, a rule to be repeated, rather than the exact layout of a structure. Tomato homeotic genes reveal the timesaving shortcut coding employed by DNA to radically simplify the process of crafting organs. Now, that's not to say that this process is simple. Building, say, the respiratory system with a fractal template is not elementary work. For as much as I've read about fractals, I only understand them conceptually; hand me a sheet of paper with the vector-matrix affine transformations for the Barnsley fern and I'd be as confused as the million chimpanzees, clattering away at their keyboards, that would (so they say) eventually type up Shakespeare's work. But my DNA is a lot smarter than me. It carries out fractal geometry every time it replaces the skin cells killed by stray rays of ultraviolet light. It built my brain, my intestines, my blood vessels, my lungs, my kidneys, and all of my neurons in just about the equivalent of one academic year. Lewis Thomas acknowledges the superiority of our body's automaticity in controlling the enzymatic detoxification processes going on in his liver but laments that he never gets to try consciously to regulate many of the processes going on in his brain: "I have never really been satisfied with the operation of my brain, and it might be fun to try running it myself, just once" (67). I sure don't think so. If my conscious being were in charge of carrying out the instructions of DNA, I would end up like the hero in a bad action movie desperately trying to defuse to a bomb but not knowing whether to cut the green, blue, or red wire. Undoubtedly, I'd cut the wrong wire and overexpress the human equivalent of KNOTTED-1, and—kaboom!—I'd have six kidneys, one

lung, and a densely clumped knot of arteries so clogged up that when blood would attempt to flow through, it would spray wildly like the water from a drinking fountain blocked by a mischievous child's thumb. I'm grateful that my DNA built my body for me; I'll stick with erector sets.

However they manage to do it—perhaps because of the presence of KNOTTED-1—plants seem to delight in fractals even more than my body. Roots invert the bottom-up format of the branches, oozing out to form a sprawling subterranean trellis of primary and secondary roots with delicate root hairs extending in all directions. Leaves are compounded and look like the whole. The trunk of a tree splits into boughs that divide into fat, elephant-leg branches, which fork off repeatedly to form twigs, until eventually a node is hit and the leafy petiole starts. The branching of the aboveground portion of a tree strictly follows a predictable pattern: The combined cross-sectional area of the daughter branches equals the area of the mother limb. The ratios of the lengths and radii of daughter branches remain constant throughout an entire tree. Actually, as Brian Enquist uncovered, they remain more or less constant for all trees throughout the entire plant kingdom (Litton). (The notable exception is the palm tree, which is effectively a single thick, scaly branch with a crown of leaves on the end.) An oak and a maple evince the same basic architecture, and the ratios of mother-to-daughter branch radii and lengths are equivalent. The appearances of the trees, though—their bark, the initial thickness of their trunks, their final heights, their dizzying arrays of the saw-toothed or finger-lobed pouches of

parenchyma we call leaves, even the angles of branching—vary to an almost frightening degree.

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I crunch past the curtain of darkness that seals off the woods a few feet past the fern patches along Papas Mountain Road. By now, the summer is asserting itself, and the temperature hovers around a stickily-humid ninety degrees. An unseen pileated woodpecker finds my presence distasteful, shrieking out the piciform equivalent of "There goes the neighborhood!" While my friend is on the hunt for insect galls, I'm content to squat on a rock staring off into the layered expanse of trees that blend into a hazy collage in the distance. About seven percent of these trees in the copse around me are over a hundred twenty years old. but I'm too much of an amateur to know which ones ("Chattahoochee-Oconee National Forests 2011 Quick Facts"). Pines surround me; sweetgums and stalkier maples, shorter hickories and cedars continually bombard me with the roughly five hundred-nanometer waves of light their chlorophyll refuses to absorb, flooding my eyes with green. The tallest trees look like they're plopped just anywhere by some natural caprice that also happened to sprinkle the shorter ones every which way. I can't discern any semblance of a pattern. The trees might as well have been carried in raindrops that collided with the soil and sprung up from there. To my eyes, it's purely random, intractable chaos.

But I don't have my Mandelbrot glasses on. Brian Enquist, it seems, never leaves home without them. He looks into the forest and notices that trees

position themselves by size. Since trees in a forest compete for the natural resources of sunlight and rainwater, "The result is a fractal-like filling of the forest space, with a few large trees taking up most of the resources and many small trees filling in the cracks" (Litton). Small trees arrange themselves axially around their larger woody brethren as branches would around a trunk. A tall pine uses its roots to stake out its territory. At the edges of its land, stouter maples and oaks stick out their own roots to demarcate the boundaries of their property. And at the edges of the oak-and-maple lot, smaller red cedars and other, diminutive oaks and maples lay claim to their parcels of land. These short trees eventually yield to shrubs until another taller pine asserts itself, and the pattern repeats. Controlling for latitude, forests construct themselves in selfsimilar, fractal, ecological lattices. When you "zoom in" on the edges of the pine's jurisdiction, more details—the little trees inhabiting that area—become apparent. Because of the way forests are set up, which shares much in common with the structure of a given tree, Enquist can take the measurements of a single tree's carbon dioxide absorption and bend that data through some affine transformations to get an estimate for the carbon consumption of the entire forest. He finds order in chaos—with a practical application to boot!

Tiny, toothy segments line the subleaflet of a fern. The subleaflets band together on the pole of a skinny costa to form leaflets, which link to a rachis and assemble into a frond. Inside the frond, a veiny network of bundled xylem and phloem conducts pulses of nutrients. A tangled mess of rhizoids, the fern counterpart to roots, holds the plant in place and brushes up against the

filamentous root hairs of a mountain laurel. The laurel, along with its shrubby compatriots, teeter on the border of a little red cedar, which, along with its compatriots, ring an oak whose roots lightly tap a towering pine. Nature is a single, gigantic fractal. No matter how much you magnify, the wiggly coastline never straightens out. Everything in nature is made out of something. Start with the Milky Way Galaxy, and zoom in on its creamy edges. Rather than a continuous stream, the border is a contiguous bunch of stars. Zoom in on one of the stars, and buried under its wayward glimmer of radial rays, you'll find some gaseous and rocky spheres (to be technical, oblate spheroids) circling it (well, ellipsing, but that's not a word—take your pick if you'd like to be astronomically or grammatically incorrect). Zero in on the pale blue dot, and you'll notice it's wrapped in a cushy atmosphere. Look a little closer, and you'll notice specks walking around on it. And now we're back to the tick and the elephant! Nature is contiguity, molecules slowly and tentatively reaching out a finger to their neighbors like E.T., afraid of discharging the static electricity their constant jittering has built up.

Step back from the Milky Way until it fades into the distance, and a curious pattern emerges. Galaxies clump together like nondairy creamer solids in coffee to constitute clusters, which are separated by immense patches of empty space (since their gravitational "web" is akin to the roots of large trees). These relatively dense groupings of galaxies band together to make superclusters. Superclusters line up and spin a blanched gossamer web of galaxy filaments, the largest structures yet discovered. Many astronomers would

contend that at some point, the universe levels out and homogenizes, ceases to be arranged in this self-similar clustering. "But a small team of physicists," New Scientist reports, "argue that the data shows the opposite: the universe continues to look fractal as far out as our telescopes can see" (Gefter). Whatever level you choose, matter is arranged fractally. Because just about everything is matter, it's all fractal in some hereditary sense.

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I've long since left the Chattahoochee National Forest. And as I walk home in the biting Connecticut winter, I slide on tracts of black ice. The snow banks flanking the sidewalks contain (by my unscientific estimate) billions of self-similar, feathery snowflakes. Examined carefully under a microscope, the jagged icy fingers radiating around the center of a snowflake branch off into smaller "leaflets" and segments, which at higher magnification split off into thinner, bonier icy fingers. As a cloud of my breath rises and splits along the microcurrents of air dancing in front of my face, I remember a PBS documentary I watched ("Fractals: Hunting the Hidden Dimension") that contained a segment about using fractal geometry to analyze EKGs. Apparently, zooming in on a stretch of the serrated, stock-market zigzag of the EKG lays bare further zigs and zags. In true fractal style, this process repeats itself the closer you look. Perhaps the heart doesn't beat in discrete lub-dubs but fractional pulses consisting of minute pumpings, like the sodium and potassium channels of neurons opening and closing. In this weather, I need my blood to circulate quickly and disseminate the five liters of warmth and life that trace the intimate bifurcations

of my cardiovascular system. Enough blood is getting around because I'm moving pretty rapidly, disregarding the hazards of hidden ice patches. I come to a street crossing—the fork in the road is the only visible one among an infinite number of branchings that elude my eyes—and I have to step through the three-foot snow bank. I crunch a million tiny fractals under the heel of my shoe boot, the muffled crack of ice whipping up to my ear at seven hundred sixty eight miles per hour. Microscopic hairs in my ear vibrate and forward the message to my temporal lobes, where my brain reconfigures it into what I perceive as a sound. The neural grid of my brain, more wrinkly than a walnut, opens and closes its ion channels in time with the fractal metronome of my heartbeat.

Through the Eagle's Eyes

"[I]n short, we see beautiful adaptations everywhere and in every part of the organic world"—Charles Darwin, *The Origin of Species* (114-5)

For several years, I've traveled to Hawk Mountain Sanctuary, a little bump along the Kittatinny Ridge in the middle of Pennsylvania, whenever I get the chance. Unfortunately, I rarely get that chance, and so far it has never coincided with a big migration. The first time I went, when I was sixteen, I had unreasonably lofty expectations. As I walked the rugged trails of overlapping rocks to the North Lookout, I kept an ethereal mental specimen in my head, the perfect golden eagle. I imagined it perched, broad-shouldered and upright, in a nearby tree, close enough that I could it him with my cheap 8 X 10 binoculars. Then I envisioned it startled by my approach, jumping in a fury of beating wings until it stabilized itself on a reliable thermal. The eagle in my head hoisted itself up along the column of heated air and, once it reached a comfortable position, stretched out its massive wings like sideways rudders parallel to the ground. Gasping for breath, I would stare it down with binoculars until eventually it would coast out of sight. Now that was how I envisioned my first experience at Hawk Mountain.

Reality never checks with me to see what plans I have in my head, though. It goes along on its merry way ignoring the impotent idling of my will. In actuality, I sat expectantly on the cold, jagged flank of the North Lookout, like a child, face pressed up against a frosty windowpane, waiting for a long-lost parent to come back. Every once in a while, I caught a glimpse of a tiny speck or

two peppering a distant, hunchbacked green ridge; I pulled my binoculars out instantaneously as if by some lightning prestidigitation, but either the speck was irresolvable—too far to focus—or turned out be something that to my sixteen-year-old mind seemed "ordinary" and unexciting, like a turkey vulture or a crow. After a few hours, the pointed spires of rock started irritating my back, fatiguing the old behind and leaving me little recourse but to abandon my search for a golden eagle. I walked back down the mountain cursing July for falling in the fallow period between the spring and fall raptor migrations. I didn't even bother to stop my binoculars from swinging incessantly, beating against my chest with each step.

This summer, while my friend and I were renting a cabin in the woods of Northern Georgia, we drove to the John C. Campbell Folk School to explore the nature trails there before going to a concert by two of the school's students, a rustic-sounding husband-and-wife folk duo. According to *Birding Georgia*, the folk school's trails afforded some prime birdwatching opportunities. By the time my friend and I got to the campus, the sun was approaching its apex. We spent an hour exploring the school's different buildings, ranging from pavilion-style shelters to abandoned farmhouses now leased only by the spiders who inherited them. We followed the Mill House Trail past idle pastures strewn with hay curled into jelly roll-shapes into a snaking copse. Cicadas belted out their summer laments in the old Memphis blues style of the folk school's musicians.

Somehow—I think it had to do with the forest being darker than the surrounding land, almost as if the rest of the world were on Pacific Time while

the forest ticked away on Eastern Standard Time—we managed to follow the wrong path. We ended up in somebody's backyard, which we crossed (in blatant disregard of the "Private Property" sign) to reach a small dirt road no bigger than a bike lane in a city. The sun started sinking as the concert drew near. Wandering without direction, blindly stumbling from dirt road to gravel road to pavement, we desperately searched for Folk School Road.

We ended up finding it, but we were a good few miles from the heart of the folk school where we had started. We walked along in the grassy shoulder, straddling a crude drainage canal filled with half an inch of collected rainwater. I heard the solitary croak of a lone bullfrog, who ostensibly wanted to get a head start on his nightly calling, so I decided to put the search for the concert hall on hold to investigate the stagnant pond where he sat. The sun slid to the west as evening punched its timecard. It wouldn't be long until the moonflowers started unwrapping themselves, switching their pinched pinwheel-galaxy appearance for a more traditional flower mien. I stared at the surface of the pond, engrossed in my search for the frog, when I heard a squealing cry. A huge reflection glided across the water, with the shadow of a six-foot wingspan propped on the pond's thin envelope of surface tension. The solid wing bone broke off into jutting feathered fragments, the primaries spread like a kindergartner's fingers as she traces a hand-turkey to put on the classroom wall for Thanksgiving. The dirty water tinted the feathers a rusty brown (which transformed into a greener hue when the reflection passed over a dense knot of algae). I could tell that this was the golden eagle I had been awaiting for five years. Based on the size of the

reflection, it couldn't have been more than thirty feet above me. I jolted quickly and turned my head to the sky, but the eagle had already passed. I suppose it was all for the better that I only caught the raptor's mirror image. Like looking directly at a solar eclipse, the eagle would have been too much for my eyes to take in directly. Its lucid grandeur would have overwhelmed me. Seeing its reflection slip across the pond as though on a sheet of ice allowed me to stare it down directly, to focus on that eagle without having to look away from its ineffable radiance, without being blinded by the gilded photons deflected from its streamlined wings. I stood by the edge of the pond breathless, my lungs wrung out like a sponge in death grip. I had seen the eagle, and, no doubt, it had seen me even better.

* * * * *

The golden eagle that I saw coasting on a tide of brilliance doesn't have to worry about being seen, for it occupies the niche of top predator in the temperate deciduous forests of most of North America. That is to say, it eats a lot but nothing can eat it. North America's largest raptor with a wingspan of six to seven feet and a weight of up to thirteen pounds, golden eagles mainly eat rabbits and squirrels and their kin, although they're known to hunt a tremendous variety of forest denizens. Prey have included mice, rats, martens, weasels, virtually any bird (from swans to cardinals), foxes, domestic dogs and cats, and even hawks and falcons, black bear cubs, and fully grown deer (Olendorff). Chihuahuas, I'd imagine, would make for an easy, on-the-go snack. After spotting prey, a golden eagle will dive toward it at speeds up to one

hundred twenty miles per hour in a dizzying spiral and grab it with its talons. It might be more accurate to say that an eagle had "knives" rather than "nails" because knives slice into prey but, unlike nails, don't fix them in place. Goldens crush prey with a force of seven hundred fifty pounds per square inch, more than twice the pressure of a typical steam locomotive boiler. More impressive a feat of specialization than how they catch and kill prey, however, is how golden eagles find their prey.

When you stare into an eagle's eye, you're seeing only the iris and pupil; the whites of its eyes are tucked neatly behind its forehead. That gives an approximation of how large an eagle's eyes are: human-sized eyeballs crammed into a skull a little bigger than a golf ball. No mammal even comes close to matching the incredible visual acuity of a golden eagle. In simplified terms, eyes, in all vertebrates, work something like a double-lens pair of glasses. A clear, glassy sheet called the cornea sits at the front of the eye. The cornea is the first lens, slightly changing the direction of light to move it toward the interior of the eye, and it accounts for two-thirds of the eye's optical power. Beneath the cornea sit the pupil, the dark spot in the center of a person's eye responsible for letting light through, and the iris, the band of colored muscle (the part we refer to when we say that someone has blue eyes) that expands or contracts the pupil to let more or less light in. These parts, together with the muscular sclera (the white of the eye), make up the visible part of the eye. If you could jump through the tiny hole of the pupil, you would hit up against another lens, stretched across the pupil like the glass of a window across its frame. This part, for obvious reasons,

is referred to as the lens. The lens has a similar function to the cornea, adjusting the direction of light to focus it on a specific point deeper in the eye. While the cornea doesn't budge, the lens is not so firmly fixed. Another muscular ring, the ciliary muscle, adjusts the curvature of the lens. The curvature of any lens affects where light focuses, so the benefit to adjusting the curve of the lens is that light deflected off both a faraway object and a nearby one can be escorted to a single point in the eye. This point, it turns out, is the retina, a semicircular layer of thin tissue lining the back part of the eye. The tissue of the retina is sensitive to light, containing cells known as cones (which perceive color) and rods (which are more sensitive to motion and night vision). The densest conglomeration of rods and cones occurs at a divot in the retina known as the fovea. The fovea is responsible for sharp central vision, the reason why what's directly in front of you seems clearer than the objects on the fringes of your field of vision. An optic nerve connected to the retina transverse to the lens takes the visual information of the rods and cones and relays it back to the brain, where images are assembled. The optic nerve, though, has no rod or cone cells on it. At the point of its connection to the retina, it prevents light from being perceived. This results in a blind spot. Fortunately, it's only perceptible when you cover one eye; having two eyes compensates for the blind spot pretty nicely. Light energy focused by the cornea and lens strikes the retina, where rods and cones convert it into an electrical pulse that the optical nerve ferries back to the brain. And that's vision explained superficially; on a deeper level, it's substantially more complicated.

Any visit to an ophthalmologist will reveal that "perfect" human vision is 20/20. (Either the doctor will congratulate you on having it or note disapprovingly that your vision is not 20/20). For a golden eagle, 20/20 vision would require heavy-duty corrective lenses; they see with 20/7 vision, able to discern finer details nearly three times as well as humans. The structure of the polished-glass eye of the golden eagle accounts for its tremendously comprehensive vision. Raptors such as the golden eagle manipulate the focus of light more deftly than mammals. While the mammalian cornea is fixed in place, raptors possess an additional muscular ring called Cramption's muscles, that can bend the cornea. They adjust the curvature of both the lens and the cornea to rapidly switch between near- and far-sightedness, focusing perfectly on the close and the distant. I have a rhizioid network of blood vessels diffusing light as it makes its way to the retina; the vessels themselves obscure a portion of the retina and therefore limit light absorption. Golden eagles escape that veiny imperfection; blood vessels are concentrated in the comb structure that scientists denominate the pecten, which sits underneath the retina. The pecten assures that no spiderweb of veins blocks any portion of the retina, contributing to unrivaled visual clarity.

"Even more remarkable," explains a PBS documentary on raptors, "is that raptors have a built-in telephoto lens. A dimple in the retina magnifies part of the image by forty percent" ("Raptor Force"). This has the same effect as having a magnifying glass in the center of your field of vision. The periphery would still look farther away, resulting in concentric warpings in a raptor's vision

somewhat akin to a fisheye lens. Every bird of prey should come with a warning sticker reading, "Objects at the center are farther than they appear." Of course, raptors themselves don't need this instruction; they are able to triangulate the exact position of potential prey using their binocular vision. Golden eagles, along with their hawk, falcon, and owl accomplices, have two foveae, the regions of dense rod and cone concentration. I have one fovea that makes the center of my visual field sharp, but golden eagles have two, making both their center of vision and their periphery crystal-clear. But they don't just have more foveae, they have more effective foveae. My densest concentration of rods and cones is about two hundred thousand per square millimeter; a common buzzard's is closer to a million, granting it eight times the visual acuity I have (Streeter). A golden eagle has a similarly crowded packing of visual cells into its foveae. With five times the number of visual cells as a human—who, I should add, has much better vision than most animals—it's not surprising that raptors see with unparalleled clarity.

The rod and cone cells of birds of prey like the golden eagle work astonishingly well, enabling them to see an extensive array of colors. Humans are trichromatic—that is, we have three distinct types of cone cells receptive to the three primary colors of visible light: red, blue, and green. Every color we perceive is some kind of combination of the three primary colors. Most birds, raptors included, have four different kinds of cone cells, the ones responsible for color perception. Every color that a golden eagle sees is a combination of four primary colors: the three colors we perceive plus ultraviolet light. I suppose we can never know for sure what they see since it's such a subjective experience,

but extrapolating from our own visual capabilities, birds must perceive ultraviolet light as a fourth primary color. In a human, each cone can distinguish a hundred gradations (intensities) of its respective color, which the brain can combine in order to distinguish about a million colors (different "lightnesses" of blue, green, red, purple, etc.) (Roth). Assuming that each cone in a raptor can pick up as many color gradations as a human (one hundred, but it seems reasonable to think that a raptor might perceive even finer gradations), throwing that fourth primary color and its hundred gradations into the equation means that they can see a hundred million colors.

Birds see much more of the electromagnetic force than we think. They perceive not only more wavelengths of light; they can *see* magnetism. A group of German researchers concluded that their "findings strongly support the hypothesis that migratory birds perceive the magnetic field as a visual pattern and that they are thus likely to 'see' the magnetic field" (Heyers et al.). Migratory birds, which include golden eagles, perceive a grid of magnetic field lines; they can *see* north! Various gray bands span the visual field from their left eye; their right eyes, it seems, cannot perceive magnetism. They're able to fly huge distances without getting lost because their left eyes double as compasses.

Golden eagle rods function just as effectively as their cones. They can distinguish motion that to me would be a blur. A person can perceive flickering as a series of distinct movements up until the flickering moves with a frequency of fifty hertz (flickering fifty times in one second), beyond which point our eyes render it a blur. A fluorescent light bulb, for instance, typically flickers at sixty

hertz (sixty times per second). Look at any fluorescent light, though, and you'll see a continuous, uninterrupted glow, not a minor but constant shifting in brightness. A fluorescent light would severely distract a golden eagle, though, with its brightness wavering every sixtieth of a second like a watered-down strobe light. A typical bird has a "blurring threshold" of over one hundred hertz, more than twice that of a human. What to us seems fixed and eternal to them appears sporadic, flickering and finicky. A golden eagle also perceives remarkably slow movements better than I can ever hope to. When I look at the sun, it seems set in place, frozen in time and space until I look away for a few hours and it's magically in another spot in the sky. To an avian viewer, the sun is in perpetual motion, inching along the sky a few seconds of a degree at a time. The stars are in a constant march in the eyes of a golden eagle.

A lot of fine ocular abilities a golden eagle has, but so what? Why should it matter that their eyes concentrate blood vessels into the pecten to prevent them from interfering with an image? Other than an envious ophthalmologist, who cares that raptors see with 20/7 vision? I'm certainly not jealous of their ability to bend the cornea. Surely evolution doesn't value sight per se. It didn't tune the eagle eye to perceive ultraviolet light for the sake of the aesthetic appreciation of new colors. The golden eagle's visual specialization is a direct adaptation to hunting on the wing. In the eagle's ancient history, the individuals with slightly bigger and more acute eyes than the rest caught more prey and thus yielded more offspring. Repeat this process until 2010 and voila: you have the modern

raptor. Every trait of the eagles' eyes increases their ability to find food, which in turn lets them survive and reproduce.

Seeing ultraviolet light at first feels like an unnecessary adornment, an extra blue swirl on the wing of a butterfly that has no effect on flight. On further examination, it proves an indispensible ability. Raptors primarily eat small to mid-sized mammals: mice, rats, voles, squirrels, and rabbits. These mammals identify themselves by scent, using pheromones contained in their urine to mark territory and communicate mating status, sprinkling a trail of self-declaration behind them wherever they go. Urine just so happens to be a mirror for higherenergy waves of light, reflecting ultraviolet. Because raptors can perceive ultraviolet light, they can see a vole's trail from up in the sky, a radiant glow against a golden brown meadow. Voles can run but they can't hide (unless they consciously regulate their urination, which they seem unable to do). 20/7 vision matters because soaring always puts a raptor far from its prey. With the visual acuity that its densely packed double foveae bestow, a golden eagle can see a rabbit from as far as a mile away. And from that distance, any tiny movement would seem like a flicker if an eagle couldn't distinguish movements with frequencies greater than fifty hertz. Fortunately, it can make out these tiny movements, and from a mile away, can see the rabbit's sides heaving as they expand and fill with the breath of life, pulsate with his fervent and restless vitality laid bare as it inhales and exhales. The golden eagle compensates for its constant motion in the air by finely adjusting its head during flight to keep its crosshairs on the hare. I once ran after a red-tailed hawk with a camera held

loosely in my hand, trying desperately to immortalize that moment in pixels, in a matrix of 0s and 1s to last a lifetime. But I got no results; I couldn't see anything in that mess of a blur the camera recorded. Raptors never have to worry about that; their microscopic neck movements hold the camera of their ocular globes steady, nature's own image stabilization. As it spirals down toward prey at a hundred twenty miles per hour with talons pointed eagerly at the prize, a golden eagle flicks a clear nictitating membrane over its eyes to shield them from dirt and airborne particles, which fly at the eagle like asteroids at that speed. During descent, the eagle never loses focus, bending its lens and cornea to keep the prey in view as it zeroes in. And with the crack of the lemming's spine, natural selection validates the raptor's vision.

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Does a golden eagle perceive things as they really are? I can't help but feel that its reality is somehow more *real* than mine. It can observe firsthand as the Georgia sun creeps across the southern sky. I just have to take it on faith that the sun is moving; as the day progresses while I sit in my cabin, I hear the sound of footsteps, like ghosts stumbling around aimlessly, the creaking of the cabin wood as it expands and contracts in the path of the sun. I have to trust my ears to "see" the solar arc; an eagle can see for itself, watch the baby steps our familiar yellow ball of hydrogen fusion makes along its semicircular path. Golden eagles see the sun move, and they see more of its electromagnetic radiation, catching the bursts of ultraviolet light in as many as ninety-nine million colors unknown to me. I can't even conceptualize a fourth primary color and all the new combinations it

makes possible. Rich hues and nuances open up; birds can perceive shadings and combinations we can't imagine. Using camera technologies, we can "pitch-shift" light from infrared or ultraviolet wavelengths to appear on film as visible light, but this only translates the unseen light into familiar colors. We're not "seeing" ultraviolet light *as itself*, we're seeing it represented in a metaphor of our three primary colors. The golden eagle senses the presence of ultraviolet, views a reality beyond my comprehension with such regularity that it becomes habituated to the sublime.

Every sixtieth of a second, the brightness of a fluorescent light warbles like a common yellowthroat, and I have no clue. I stare; nothing changes—it's a constant pale white, an even, stable sheet of photons. A golden eagle sees the same bulb and notices it flickering like a candle, crest and trough undulating. Brightness pulses with the rise and fall, the curling involute of an ocean wave. That's what's actually happening, unbeknownst to me. A juicy little nugget of reality hides from my eyes. My occipital lobe scrambles to assemble the flickering but all I get is a dull continuity. My brain ignores a facet of the world; it simply can't sense the way things actually are. The golden eagle doesn't see every detail of the world, but it certainly one-ups me. It sees an extended rainbow in a puddle of oil on the side of the road. It looks at a wide variety of new wavelengths of light and sees a series of individual leg movements as a rabbit scratches it head at a hundred hertz, what I perceive as a blur. The eagle sees aspects of the world that escape the human viewer.

What other things might the world be hiding? I have no way of knowing. For all I know, an organism could be seeing the warps and indentions of the spatial grid wrought by gravity. Maybe lying hidden is a gravitational sense, an ability to sense in some way the inconsistencies of the fabric of space. A heavy enough mass puts a dent in the space-time grid like a bowling ball on a sheet of rubber, and I'd be willing to wager that something out in this wide universe can locate objects based on the indentations they make. Any number of things could be hiding beyond my sight. And my hearing—every second a litany of sounds goes on below twenty or above twenty thousand hertz. Just like the wavelengths of light that hide new colors, frequencies of sound waves conceal unheard notes. Seeing (and hearing, for that matter) isn't just believing; it's knowing. Sensing is being able to verify an external reality, transforming the self into a biochemical measuring device.

But I'm not specialized in that way because evolution isn't egalitarian.

One animal gets to see ultraviolet light and another doesn't. One gets to smell even the tiniest concentration of pheromones and other chemical signals, and others don't. Evolution seems to agree with a preschool teacher I once had: "You get what you get and you don't get upset." (In many cases, you get a little extra, too, from random genetic drift or vestigial structures, but those are nonadaptive and therefore beside the point...) You get specialized for what you need to survive, and you run with it. Hawks *need* to see ultraviolet light to trace their prey; they *have to* be able to see a hare from a mile away given the altitude of their flight (as high as twenty thousand feet for some vultures). There are no

luxuries in evolution, and it's anything but prodigal. Everyone gets what they need to survive, and no one has surplus adaptations. Animals are finely tuned to eke out a living in whatever niche they occupy, and that's all she wrote, end of story. You get the skills you need to locate food and mates, but natural selection won't give you a gift of an extra sense if you don't need it to discern between the berries you should be eating and the poisonous ones that kill you. Anyway, I shouldn't complain about my senses—think of how much sensually richer my world is than a jellyfish's. I got what I got, and there's no reason to be upset about it.

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Specialization crafts a staggering number of novel forms. The specificity of a niche determines the details of an organism's intricacy. A survey of animals surviving today shows just how specific niches have gotten. Koalas eat *only* eucalyptus leaves, nothing more, nothing less. They've been wedded permanently to a single plant species, and quite an unaccommodating one at that. Eucalyptus leaves contain very little protein and a lot of indigestible substances toxic to most animals. But at some point, probably when the ancient wombat family began diversifying, a few individuals on the outskirts of the home range were able to eat the leaves without keeling over. Competition for low-protein, high-toxin leaves would have been, understandably, pretty sparse. Whole groves of these plants remained entirely uneaten. The niche of a steady diet of eucalyptus stood wide open, and the koala's ancestors were poised to fill it. Natural selection steps in (well, it's never really *out* of the picture, but...) and a

steady process of specialization to a strictly eucalyptus diet refines the koalas adaptive mechanisms over time (and some genetic drift and random mutations add color to their appearance but don't really do anything functional). Their form adjusts to suit a new function. The koalas with longer cecums, the part of the intestines where plant materials are left to stew in digestive acids, got more of the scant nutrients out of their inhospitable food source. Plants, especially nutrient-poor ones like eucalypts, take a long time to digest and provide little energy, so the entire metabolism of the koala slows down, giving it one of the lowest metabolic rates among mammals. Food is so plentiful that running around becomes unnecessary. They don't even have to avoid predators; the toxins in their diet ensure that no one eats them. Koalas grew sedentary, spending the vast majority of their day sleeping. To save energy, sacrifices had to be made: the brain, perhaps the most costly organ, shrunk significantly. I've seen videos of koalas, and they certainly don't do much. They spend their days chewing indifferently, with a countenance of "Eh, whatever" frozen on their faces. I suppose that the camera crew picked the most exciting moments of a koala's life for the final edit, so that's about as high-octane as that marsupial ever gets.

The koala barely scrapes by, but it's so beautifully and efficiently designed for what it does that it hardly matters. After all, koalas reproduce effectively—why change a winning strategy? Specialization has molded them like a key to fit perfectly into the lock of their niche as eucalypt predators. It has shaped them to survive and pass on their genes, which is life's primary objective.

Survival is the end, and the means are often extravagant, though I suppose any animal, plant, fungus, protist, or bacterium will tell you that the ends justify the means.

The fungal mold *Pilobolus crystallinus* goes to extraordinary (and extraordinarily impressive) lengths to sate its lust for life and reproduction. The evolutionary history of fungi is still largely unknown; in a kingdom with a projected 1.5 million species, we've only formally established seven phyla. (Compare that with animals, of which we've discovered about 1.25 million species split among 36 phyla.) The roots (or more accurately, rhizomorphs) of *Pilobolus* are understood remarkably well for such an unknown kingdom. *P. crystallinus* belongs to the phylum Zygomycota, which has a little over a thousand species. Zygomycetes, the members of the phylum, get their name from the zycosporangium, a mucoid bulb on the tip of a thin, filamentous stalk that produces the fungus' spores. The zycosporangium creates tiny versions of the parent fungi, often numbering high in the millions. Typically spores are dispersed to drift along the jagged, unpredictable Brownian trails of the wind. *Pilobolus* employs a more self-directed strategy.

P. crystallinus, colloquially known as the "dung cannon," shoots for the sky. By this, I don't mean that it has high ambitions; no, this is shooting for the sky in the most literal sense of the phrase. Structurally, a patch of *P. crystallinus* resembles a field of tiny eyeballs attached to descending beads of saliva. The thin, crystalline stalk is composed of hyphae, the fungal equivalent of veins (and tissue—hyphae are the essential building blocks of all parts of a fungus). Hyphae,

single-file cell lines woven into aqueous gossamer, provide the fungus' structure and transport nutrients. At the top of the hyphal stalk, no more than a centimeter from the ground, sits a sticky black cap, the zycosporangium. In *Pilobolus*, a thick adhesive layer coats the sporangium. Mycologists refer to the phallic stalk-and-sporangium combo as the sporangiophore. The clear sporagniophore acts a lens (alas! it has no cornea), focusing light at its base to orient its growth in the direction of the sun. Once the fungus has aimed toward the sun, a transparent vesicle—effectively a cellular reservoir—located between the stalk and the sporangial cap begins filling with water. The plant floods the vesicle until the pressure becomes so great that it bursts, catapulting the coaly sporangium like the cork of a champagne bottle. *Pilobolus* individuals routinely launch their sporangia a distance of close to ten feet. This constitutes about three hundred *Pilobolus* body lengths, the equivalent of a person of 5'10" leaping a third of a mile. *Pilobolus* caps have even been reported to jump over cows at pasture. The sporangium's adhesive layer then grips onto whatever plant it's lucky enough to land on, where it clings until eaten by an unsuspecting grazing mammal. The spores pass unharmed through the mammal's intestinal tract somehow the cap resists digestion—eventually being excreted in the animal's dung. A denizen of the dung, the *Pilobolus* cycle starts anew as the spores develop into their own sporangiophores.

In the world of specialization, form ineluctably follows function. A fungal Super Soaker proves to be a logically adept response to the pressures of the meadow environment. Every aspect of the *Pilobolus* meshes with its

environment and reproductive goals. The sticky mucus of the sporangium glues itself to any target plant. The light-sensitivity of the hyphal stalk guarantees a launch in the right direction; pointing toward the sky in a manner befitting a turret, *P. crystallinus* can't possibly misfire downward to the ground where it currently stands. The vesicle placed midway between the glass-beaded stalk and the tar-black cap collects water and builds pressure until it snaps and sends the cap careening three hundred body lengths away. Because of the immense distance the sporangium flies, spores grow far away from the parent fungus, obviating intrafamilial competition for resources. The powerful, resistant walls of the sporangial cap allow it to pass through the gut of a cow unscathed. And the production of millions of spores hedges the bet that at least a few offspring will survive into adulthood. Every adaptation reveals the meticulousness of specialization, each body part adjusted for a specific function.

Other fungi evolve to even more specialized niches, adapting to fill roles so strange they push the edges of possibility. Countless parasites adapt to an environment so specific that it can be found only in the bodies of members of a single species, unlike the symbiotic tapeworms that plague a variety of target species. *Cordyceps* (Latin for "club head"), a genus of parasitic sac fungi, contains approximately four hundred species adapted to just those sorts of environments. In one of his incomparable natural history documentaries, *Planet Earth*, nature's most excellent spokesman David Attenborough elaborates on one species and its relationship to bullet ants (*Paraponera clavata*) in the South American rainforests. The *Cordyceps* spores infiltrate the ant's body, seizing control of its

nervous system. The parasitized ant stumbles around like a drunkard, exhibiting a host of erratic behaviors: it climbs aimlessly and attempts to devour its own abdomen. Then, like a scene lifted from a B-movie, the fruiting body (ascocarp) of the fungus erupts, splitting the ant's head with a spire of intertwined hyphae. Spores disperse from the tip of the ascocarp, infecting any ants they touch. So, to prevent a *Cordyceps* outbreak from eradicating the entire colony, healthy bullet ants drag infected individuals far away from the group and leave them to die alone. It's an extremely gruesome way to go, slowly being consumed from the inside out by a contagious fungus that controls the victim's behavior. The bad news for class Insecta: ants aren't the only victims of this cold-blooded (or more accurately, no-blooded) killer. Other *Cordyceps* species attack a wide range of insects, each adapted to the specific biological geography of its host. Grasshoppers, caterpillars, butterflies, moths, and walking sticks have all been found lying on their backs, slimy, phallic ascocarp heads bobbing from their bellies, their bodies coated with flakes of fungal growth. A dead insect resembles a forest floor, with curving, clustered sprigs of fungi popping up from its corpse like mushrooms springing from leaf litter. One moth had so many hyphae shooting out from it that it looked like it had fallen asleep on a bed of nails, as though it had been treated with fungal acupuncture. On account of nature's cruelly ironic sense of humor, an insect must die for the fungus to reproduce; death has to precede an act of birth. As sick as it sounds, it's a cycle of rebirth.

Specialization spares no one; it crafts animals for inconceivably hostile and deeply particular environments. *Riftia pachyptila*, a member of the group

known as vestimentiferans (formerly phylum Vestimentifera, but now most commonly classified with earthworms as annelids), inhabits the most inhospitable environment able to support life yet discovered. These five-footlong, tube-dwelling, "garment bearing" (from the Latin vestimentum and ferre) worms—worms only in the sense that they're invertebrates longer than they are wide—live near hydrothermal vents in the deep oceans. Here, the earth splits and lava seeps out, and the pressure's so powerful that it would snap a human spine like a paper-thin wishbone almost instantaneously. Normally, when water heats past its boiling point, its molecules spread out and evaporate into a gas; each molecules finally gets the legroom to stretch out fully. Applying sufficient pressure, though, brings the molecules of water close enough together to render them a supercritical fluid with physical properties somewhere between liquid and gas. At a hydrothermal vent almost two miles down, pressure three hundred times as strong as that experienced on land at sea level compacts water, superheated by the lava erupting from fissures in the earth's crust. This process creates a pool of a semi-liquid mist of foggy, white water—dispersed like a gas but flowing like a liquid. Like a spoonful of oil that refuses to dissolve in water, the fog surrounding the vent has the appearance of an ocean-within-an-ocean rich in noxious sulfides and carbon dioxide. Sunlight never penetrates these depths, as cold and dark as intergalactic space, so no plant or algal life can be found. But still *R. pachyptila* prevails.

The massive worms build their chitinous tubes on rock near the cooling lava by secreting specialized proteins and carbohydrates, forming a structure

akin to an organ pipe. Adults have no mouth, anus, gut, head, or appendages. The worms owe their success to endosymbiotic bacteria, housed in a specialized organ called the trophosome. The trophosome offers the bacteria shelter from predatory mollusks and polychaetes and allows the tubeworms to absorb nutrients directly from the bacteria. The bacteria constitute as much as half the worm's body weight; a single ounce of tubeworm tissue packs over two hundred eighty-five billion bacteria (Stover). They and their worm houses rely primarily on the geochemical energy of the vent, unlike every other ecosystem currently known, which relies directly on the light of the sun for energy. These bacteria latch onto sulfur and through a process known as chemosynthesis, build essential organic compounds. To gather sulfur compounds from their environment, vestimentiferans use their scarlet, filamentous beard of gill-like plumes. Though I say "beard," the apparatus is actually more like a threaded clump of downy feathers folded over itself to make a cylinder. The beard owes its red appearance to the presence of hemoglobin that bonds with sulfur (which shares many chemical properties with oxygen) and transports it to the bacteria in the trophosome. This beard often protrudes from the rigid tube, although *R*. pachyptila can contract it and slip into their tubes like slide whistles. With their beards out, the worms look like giant lipsticks. The plumed beard is simply the first segment of the worm's four-part body. The second part, called the vestimentum, is composed mainly of muscle, though it contains numerous glands, and functions primarily to maintain the beard. The third region, the trunk, makes up the three-quarters of the worm's length. The gonads,

longitudinal blood vessels, and bacterial pouch can be found in the trunk. Many small segments partition the opisthosome, the last region of the worm. Several hooks along this section hold the worm in place and stabilize its periodic jaunts up and down the tube.

Entire communities spring up around the vestimentiferans. Ghostly bleached-white crabs prowl the tops of the organ-pipe tubes in an attempt to pinch off a piece of the worm's flesh. Multiple species of shrimp join the crabs in their efforts. Other organisms, like the scaly-foot gastropod (*Crysomallon* squamiferum), graze on mats of chemosynthetic bacteria excluded from the private housing and chitin-picket fences afforded by vestimentiferans. The scalyfoot gastropod gives the tubeworm a run for its money in pure strangeness. Bearing a resemblance to a pinecone toting a metal snail shell, its muscular foot (the slimy part of a typical snail) is shielded with overlapping plates of iron sulfide and fool's gold. It wins the accolade of the only animal to include iron sulfide, pyrite, and gregite in its skeleton, forming a triple-layered shell from those minerals. Its powerful shell shields it from crab pinches and dissipates heat efficiently, going so far as to incite the envy of the ever armor-lusting military. Even vertebrates join in the fray, with some species of eels frantically scrambling to rip off a piece of vestimentiferan steak. How these eels obtain enough oxygen boggles my mind, and I don't believe there's been (a popularization for nonscientists of) an explanation.

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¹ See "Snail's Iron Armour Eyed by Military," *CBC News,* http://www.cbc.ca/technology/story/2010/01/18/tech-biology-snail-shell.html

The tubeworms and their vent-dwelling ilk have exploited a valuable, if undesirable, niche. They're wonderfully specialized to succeed in an oxygenpoor supercritical liquid medium, to drift through fluid smog by the glow of roiling jets of lava. Regrettably, I'll probably never get the opportunity to see these worms and their neighbors firsthand because I don't have the money or legitimate scientific reputation to rent a submersible. So since I've never really been in the presence of a vestimentiferan (I've only seen them in another of David Attenborough's masterworks, *Blue Planet: Seas of Life*), I have difficulty believing that they *actually* exist. For all I know, it could be an elaborate scientific hoax designed by a handful of zoologists who were bored one day and decided to trick the populace with an extravagant (and wholly gratuitous) lie. I feel like the footage I've seen of vestimentiferans has to be technologically altered, a redhead's beard superimposed on a bumpy, white pipe organ against a green screen of an underwater volcano. Nothing that alien could possibly exist on this earth, on my earth. I'm used to Douglas firs and Canis familiaris fixed to the crust of the earth, the visible surface of the planet, and illuminated by the sun—not human-sized bearded tubeworms living in toxic oases a few kilometer deep in the ocean, completely removed from any trace of sunlight. But I guess these worms have to exist because no one, not even the craftiest biologist, could think up such a wildly outlandish creature as R. pachyptila. It's beyond human imagination. The only way to conceive of such an animal is to behold it, to see it so that you know you have incontrovertible proof of its existence. Seeing is conceiving.

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Even as I reenter the realm of "normal" aquatic life, specialization contrives to transform the seemingly standard into the ineffably well-crafted. Deep-sea eels, impressive as they may be, certainly don't overshadow the more accessible Amazon River-dwelling *Electrophorus electricus*, the common electric eel. "Electric eel" is a misnomer—not because it isn't electric, but because it isn't an eel! The electric eel belongs to the family Gymnotidae, and should therefore properly be called the "electric knifefish." (Of course, that doesn't have the electrifying assonance of "electric eel," despite being truer to taxonomy.) Electric eels grow to a tremendous length of six feet and a hefty weight of forty-five pounds. Specialization, I say, is all but profligate and extraneous—that knifefish *needs* to be that long to house the three organs in abdomen responsible for generating an electric charge. The Main, Hunter's, and Sachs organs consume four-fifths of the fish's body length and contain the electrocytes, cells that produce electronic organ discharge through muscular motion. Looking something like a battery hit by a steamroller, disc-shaped electrocytes carry a slight negative charge on their inside, while outside the confines of the cell membrane, a slight positive charge is created. It sounds far-fetched that eels (technically knifefish, I know!) can generate a charge, but believe it or not, it's happening inside me to a lesser extent right now. My neurons pass along messages by pumping out positively charged sodium and potassium ions through transport proteins embedded in the fractal coastline of neural cell walls. When something in the environment excites my nerves, the protein floodgates

burst open (well, alternate between open and closed on an impossibly small scale), and the positive ions rush in, passing a pulse called an action potential along the fractal highway of the neuron.

Electric eels employ this same biochemical process but to a much greater degree. One cell produces less than a hundred millivolts (0.01 volts), not even enough to fry a shrimp. Of course, electric eels have specialized and developed hundreds of thousands of electrocytes end-to-end, stacked one on top of the other like pancakes in a lumberjack breakfast. When it comes time to shock, the eel's nervous system releases a neurotransmitter dubbed acetylcholine. The chemical opens the cellular floodgates, similar to the neural impulses, but in the electrocytes, the opening occurs on only one side. This has the effect of converting each cell into an organic, flattened battery, with one end positively charged and the other charged negatively. According to Scientific American, "Because the cells are oriented inside the electric organ like a series of batteries piled into a flashlight, the current generated by an activated cell 'shocks' any inactive neighbor into action, setting off an avalanche of activation that runs its course in just two milliseconds or so" (Caputi). The tremendous release of electrical energy generates as much current as a five hundred volt battery, up to a full ampere—enough to kill a grown human. Electric eels can control their discharges, though. They may either use the strong, five hundred-volt shock to kill prey or discharge a smaller voltage (about ten volts) for navigation purposes. The eel sends out the lower discharge like sonar, picking up on any interference with the electric field to locate potential prey or obstacles. Even buried in sheets

of sediment and muck at the bottom of the Amazon, the electric eel can "see" perfectly.

I can actually say I've seen an electric eel, even if I can't claim to have found it in the wild. I saw a large specimen at the PPG Aquarium, coiled like a collagen fiber at the bottom of the aquarium. The water glowed pale green, a combination of turbidity and background coloration (the walls were sea-green). As I stared at the electromagnetically-inclined knifefish, it gradually uncoiled, collagen braids denaturing slowly in the heat of the moment, to gulp a breath of air at the surface of the tepid water. Its body hung down from his head as a cord would from an outlet. Blasting vitality like the sporangial cap of *Pilobolus*, the electric eel struck my eyes with a beam of deflected light. My cornea bent the sheath of photons that had bounced off the eel, narrowing it to fit through my pupil and relaying it to my lens; my lens curved it even more to nest the received light in the center of my fovea, where my optic nerve carried it to my brain to be assembled into an image of the elegant creature before me. My brain continued splicing, and I wondered if the eel could see me, if its electric field, bifurcating like a lightning bolt, could penetrate the glass that pooled in front of him like a supercritical fluid enveloping the base of a hydrothermal vent. For a second, the murky aquarium water peeled back and split like the Sea of Reeds. I saw with the eyes of a golden eagle the bulging, magnified body of an electric eel, glowing in a hundred million colors with devastating clarity. A visceral sensation of awe seized my body like the airborne spore of *Cordyceps* infiltrating the mind of a bullet ant, as though that eel were pulsing just the slightest current through me

so that my spine was buzzing with the embers of fervor that consume a televangelist; and here before me, gulping chunks of air and winding in a fleshy corkscrew, stood nature's Word, the sublime made flesh.

Symbiosis

"Neither stars nor stones, neither atoms nor waves, but their belonging together, their interaction, the relation of all things to one another constitutes the universe. No cell could exist alone, all bodies are interdependent, affect and serve one another"—Abraham Joshua Heschel, *Man Is Not Alone* (121)

Any stretch of woods in the eastern United States is littered with insect galls. They're not necessarily that easy to spot, depending on the texture of the ground, but it's well worth a look. I stumble across more than my fair share of galls as I walk through the Chattahoochee National Forest. It feels like every few feet, I find one of those hollow chestnut-brown bulbs on the ground in the shadow of a pillar of oak bark. Sometimes I'm lucky enough to find one still on a tree. Then it's painfully obvious why these galls are called "oak apples." They form on the bud where a leaf would normally have grown, fattening into a ripe, wooden fruit about two inches in diameter. Once they've been hollowed out and fallen to the ground, they're light—so light they make a handful of acorns seem heavy. They have the shape of an orange, as if some forest trickster had scooped out all the pulp and painted the rind light brown. Squeezing the tiny, foamy skin between my fingers, I hold the gall like an egg about to be cracked. Broken open, they don't seem to have anything inside them. If you could somehow get in the middle, you would feel like you were standing at the center of a balloon: lots of open space with a thin, membranous horizon surrounding on all sides. Of course, once a gall's empty, the action has already happened.

To appreciate a gall, you have to be able to see it from the inside, to see the rips and tears in the plant's cell walls as the meristem—the plant version of human pluripotent stem cells—contorts into a bulbous tumor. Gallflies, the carcinogenic insects that cause these knobby spheres, are rarely flies at all but wasps. Even if it's not accurate, "fly" better suits their size than "wasp": they're only a third of an inch long at their biggest, with most around a quarter of an inch. Wasps are supposed to be big and imposing; flies are smaller and easy to shoo away. Well, gallflies don't play by the rules: they're tiny, shaped with the characteristic wasp waist that anyone who has ever tried wearing a girdle would envy, and they do their reproduction in the most underhanded-but-efficient manner imaginable. That explains their tremendous success. In North America, there are some 800 species of gall wasps, members of the family Cynipidae. When it comes time to lay eggs, the female uses a specialized ovipositor to inject them into a leaf bud. The bud starts to inflate, swelling into a near-perfect sphere speckled with a few flattened nodules here and there, closely resembling a rounded buckyball. Chemicals mimicking plant growth hormones injected by the mother wasp convince the plant to abort the leaf and tell it to start collecting nutrients instead. It transforms the pluripotent meristem tissue into a storehouse of starch and sugars, with the cells dividing as though cancerous. The tree bud balloons into a globular nutrient sink, draining the tree of its carbohydrates and wrapping the wasp eggs in layer upon layer of energy-rich starch. Goaded by the mock-hormones secreted by the gall wasp, the plant encloses each egg in a separate chamber, surrounded on all sides by regenerating, nutrient-loaded tissue. If you were to break open the gall at this stage, it would look like a pomegranate, each seed a wriggling, larval maggot.

The larvae's house is their food, and as they grow, stretching and elongating with each ecdysic wave, they gradually hollow out the tumorous lump of plant food. Finally, the wasps, having molted their way to the adult form from the comfort of their food-home, eat their way to the end of the gall. Each wasp gnaws its way out, chewing a tiny hole through the skin of the gall. The birthing process, then, is just an eat-to-the-finish race. Depending on how many eggs the mother wasp has laid, the gall shell may be peppered with hundreds of tiny exit holes.

Species interactions aren't always a one-on-one affair. By the time the gall is two months old, the original gall wasp larvae make up just ten percent of the gall's population. Inquiline insect larvae of other species, most often from related species of wasps also of the family Cynipidae, bunk with the gall-inducing larvae. Etymologically, the term "inquiline" derives from the Latin for "tenant" or "lodger." Entomologically, it refers to an insect that develops inside a gall built by another. Inquilines avoid the work of having to hormonally persuade a plant to produce a gall by skipping that step entirely. The inquiline mother uses her ovipositor like a hypodermic needle to break into the gall and drop her eggs off inside. The injection phase is dangerous for the gall-inducers already living there. Somewhat akin to the magicians who pierce an assistant crammed inside a box with swords, the inquiline mother's ovipositor lances the wall of the gall. Even though neither the magician nor the wasp can see the contents of the containers they pierce, the gall-inducers aren't always as lucky as the magician's lovely assistant; some larvae end up speared and killed, a hexapod shish kebab on the mother's reproductive skewer. Once the inquiline larvae have made it

inside, it's an unbelievable deal: they get room and board and don't even have to pitch in for rent. These mooching roommates are mainly commensalist, since apart from mom's harpoon ovipositor they don't harm the wasp larvae but benefit themselves. Another wasp, *Torymus nitens*, joins the inquilines in invading an already-built gall, but it isn't so much a mooching roommate as it is a psycho that lives down the hall. The *T. nitens* mother comes equipped with an ovipositing syringe of her own. While the unsuspecting gallfly and inquilines are going about their larval business, she breaks into the apartment and injects her eggs. Part of a class of wasps labeled "parasitoid," *T. nitens* larvae devour the unsuspecting gall-inducers and inquilines, tearing through their waxy, cream-colored cuticles to suck out the larval lipid butter underneath.

Of course, *T. nitens* larvae have to contend with other parasitic wasp larvae. The "Checklist of UK Recorded Cynipoidea" notes that typical galls can contain nineteen insect species, including the original larva, five species of inquilines, and thirteen species of parasitoid wasps (in addition to the host plant). On a normal walk through the woods you can find a microhabitat of some twenty-odd species, a dense ecosystem packed into a fibrous knob the size of a clementine. But that's a *typical* gall. An especially populous oak gall caused by the cynipid wasp *Biorhiza pallida* can cram over seventy-five species into a single gall (Shorthouse & Rohfritsch 238). Imagine the bustling that goes on in there, with the gall-inducer and the forty species of inquiline guests-of-honor battling it out with another thirty parasitoids. In these galls, you find secondary and tertiary parasitoids, eating other parasitoid larvae—a whole food chain

shrunken down to fit inside a space a little larger than a golf ball. Pick up a gall and you've got an entire ecosystem in the palm of your hand, a forest condensed into a single ventricle palpitating with the rushing hemolymph of some two hundred bodies.

Because they're such exceptionally diverse microhabitats, galls have attracted the attention of a number of scientists, termed cecidologists, who specialize in studying them. It makes sense, given the tremendous diversity of gall-inducing insects. "Around 20 families of insects classified in seven orders," writes Pierre Jolivet, "induce galls or occur in close association with galls. About 13,000 cecidigenous insects have been recorded, which represents a small fraction of living insects" (155). For insects, that is a small number, but it's more than all the species of birds, which number about 10,000. Gall-inducing insects come from all kinds of evolutionary lineages, from wasps to aphids to a few moth species; cecidologist M.S. Mani concludes that gall-induction as a reproductive strategy has evolved independently at least seven times. And each species collaborates with a different host plant. The galls they cause are correspondingly diverse. "Some are like exquisitely shaped vases, cups, discs, or fantastic polyps and flower-like growths," comments Mani. "A number of interesting galls look so much like fungi that for years they were misidentified by plant taxonomists" (Shorthouse & Rohfritsch 4). Others bear a striking resemblance to sea urchins or burrs. I remember seeing some leaves along the Appalachian Trail that seemed to be broken out with purple acne, each pustule a tiny gall. The ones induced by cynipid wasps range from geodesic domes to perfect spheres that

hang off a tree like false fruits. A lot of galls could pass for regular plant parts—berries, nuts, crabapples—but at the center they're loaded with plump maggots instead of seeds.

A mother wasp doesn't realize that when she lays her eggs, she's creating an ecosystem within an ecosystem, a tiny cluster of life feeding on a metastasized oak lump. Wasps can't recognize causality. Animals don't think through their symbiotic relationships; they don't sit there and calculate the pros and cons of partnering with this or that plant. Species just can't keep to themselves. At some point, the evolutionary paths of two organisms cross, specialization kicks in to mold them to one another, and then they're wed indefinitely, held together by the sacred bonds of holy coevolutionary matrimony, till extinction do them part. In coevolution, for every action, there is an equal and opposite reaction—or else there's no symbiosis. Believe it or not, a plant gall is a symbiotic relationship. It seems counterintuitive, but a gall is not the result of a plant passively resigning itself to being parasitized. "Galls were once considered to be harmful to the plants," Jolivet explains, "but now the tendency is to consider the gall as advantageous since it protects the plant against possibly even greater damage—complete necrosis of the parasitized tissues" (154). A gall is an active mechanism for harm reduction. The plant shrewdly quarantines the parasite in a small chamber. Sure, it has to sacrifice some sap and starch, but that's a lot better than losing a whole leaf or a branch. Once the plant and gall-inducer were paired up at some point in their history, each species had to respond to a change in the other, like an evolutionary game

of tag. Each successive adaptation changes who's "it." The gallfly tags the plant by laying an egg that mimics plant growth hormones. The plant responds by trapping the insect in a reservoir of starch where its leaf bud would be.

Somehow, the plant is able to react to the hormone-mimic by giving the wasp exactly what it wants—so much of what it wants that it sequesters it in a dome of nutrients to prevent it from parasitizing the rest of the plant. I guess the moral of the story for the gallflies is, "Be careful what you wish for."

Symbiosis can be ugly—at least the way biologists define the term.

Normally, we think symbiosis is a mutually beneficial inter-species relationship and point to clownfish and sea anemones as the typical case. In more formal ecological terms, the word "symbiosis" refers to any intimate ecological relationship between species, whether it's the good, the bad, or the ugly. The clownfish and anemones demonstrate a specific type of symbiosis known as mutualism. Mutualism is a biological contract that benefits both parties involved, nature's true reciprocity. You give me protection from predators and I'll provide you with some nutrients. This is the kind of symbiosis at hand in the vent-dwelling vestimentiferans, who shelter billions of bacteria and receive nourishment in return. Commensalism is the symbiosis of inquilines, the moocher paradigm where one organism benefits itself but neither helps nor harms the other one. Barnacles clamp onto clams; fungi grow out of dead trees.

The barnacles profit but the clams couldn't care less about the hitchhiker—they

just go about foraging like the cirriped protuberances aren't even there. And a dead tree obviously doesn't mind somebody growing on it.

Symbiosis also glues together species that seem to hate each other. This interaction is parasitism, the preferred method of *Torymus* wasps. The parasite par excellence has to be the tapeworm. Not a specific tapeworm; any of the thousand-some species will do. Whoever (or whatever) designed the tapeworm built it to suck. And really well, at that: every vertebrate species can be parasitized by at least one tapeworm. Since there are 58,000 vertebrates out there, some tapeworm species have to work double-duty, parasitizing multiple, related vertebrate species. Their success derives entirely from their structure, which is beautifully (in a grotesque sort of way) suited to the jobs of growing and sucking. The flat ribbon of a tapeworm, called the strobila, divides into neat, square segments termed proglottids. Every proglottid contains its own finely folded digestive system and a branching reproductive tract complete with male and female organs. The densely packed proglottid jelly squares continue reproducing and expanding until they curve and wind like entrails to form a rough equivalent of a *Candyland* board, where each "space" is a proglottid. Take enough turns rolling the dice, and you can follow the proglottid path sometimes as long as a hundred feet—all the way to the head of the tapeworm! There you'll find the head grafted onto the intestinal wall of the vertebrate host. The head doesn't really deserve to be called a head; since it doesn't guide the organism or contain any sense organs, it's properly referred to as the "scolex." I haven't been lucky—or unlucky—enough to see a scolex myself. I've only ever

seen a tapeworm wound around itself bobbing up and down in a jar of formaldehyde, my naked eye rendering the six thousandths of a millimeter-long scolex a blunt dot. But I have chanced upon scanning electron microscope images of it. The scolex is a disfigured caterpillar head with a crown of thorns. On each side of the "face" is a sucker, a crater of ectoderm used to extract nutrients from the host. A circle of involute, crested hooks stab into the intestine of the host and lock the tapeworm in place. Seen from an angle when two suckers are visible on the ventral side, it resembles a cartoon character, topped off with goofy hair in the form of barbed hooks, eyes bulging as though a pretty cartoon lady had just walked by. Bug Out Bob, the pin-shaped, flesh tone, latex Fifties stress relief toy whose red dotted eyes and ears pop out when squeezed, gives a good approximation of a scolex. Bob's a lot more clownish and a lot less imposing, but he has the same general shape, and if you think of each of his eyes and ears as a sucker and the little dot on the crown of his head as a circle of microscopic hooks, you can envision a scolex at a thousand times magnification. Viewed from other angles, the scolex alternately resembles a flying saucer or an old three-bolt diving helmet—the kind actors in a movie version of *Twenty* Thousand Leagues Under the Sea would wear. Cartoon character, Bug Out Bob or diving helmet, the scolex is not to be taken lightly. It, more than any other feature, allows the tapeworm to gorge itself on the digested meals of vertebrates.

And then there are cases when a variety of symbiotic interactions pile on top of each other, in a similar manner to the four levels of protein structure.

Levels of symbiosis compound and weave a tangled web of biological intrigue.

Like a tongue-twister in a Dr. Seuss book, a host may host another host who hosts a host of hosts, giving rise to nested symbiosis. All parties become an integral part of the (inter)action. A gall is a nugget-sized ecosystem, a superconcentrated micro-world, with its very own food chain and habitational hierarchy. Self-contained ecosystems appear all throughout the world, even in human mythology. Lewis Thomas tells of "a Peruvian deity, painted on a clay pot dating from around A.D. 300, believed to be responsible for guarding farms. His hair is made of snakes, entwined in braids, with wings for his headdress. Plants of various kinds are growing out of his sides and back, and a vegetable of some sort seems to be growing from his mouth" (123-4).

The real surprise is that this deity "is, in fact, an imaginary version of a genuine animal" (124). Scientists working in New Guinea in the late 1960s discovered the familiar of the Peruvian god in the form of a mountain weevil of the genus *Gymnopholus*. Moss grows on the beetle's carapace, glazing its elytra deep green and tapping into its flesh. According to an article in *Nature*, *Gymnopholus* "have been reported to carry small gardens on their backs" (Gressitt et al. 765). The saddle-shaped carapace forms a trough for the plants to grow in, turning the curves of its shell into a mountain forested with moss. The filamentous moss rhizoids anchor themselves in every crevice and cleft in *Gymnopholus*' exoskeleton, rendering every crest and valley rich in jagged bryophyte foliage. No matter where it goes, the weevil totes a velvet carpet. This qualifies as mutualism, since both parties protect each other from predators: the moss by virtue of the weevil's movement and the weevil by seamlessly

camouflaging with the mossy forest floor. A study by R.R. Jackson and S.D. Pollard found that jumping spiders that rely primarily on sight couldn't discriminate a beetle from its backdrop. Could you find the one Waldo buried in the crowd of lookalikes? Well, neither can the spiders.

Sprigs and spires from the dense coral of moss on the weevil's back support "phytophagous orabatid mites," "sessile rotifers," "minute nematodes," and "fungi, algae, lichens and liverworts, as well as stray diatoms" (Gressitt et al. 765). Nematodes spiral around the rotifers; mites clamber over tiny towers of fungi; algae and liverworts compete for sunlight. Lichens double up on symbiosis. Already a symbiotic relationship—a wavy spaghetti lattice of fungal hyphae intertwining pockets of algae—these lichens compound complexity and nest a level of symbiosis within a larger symbiotic community. *Gymnopholus* gives us symbiosis squared, exponential interactions radiating outward in the spiral of infinity. Nature even indulged in the creation of a minuscule version of Atlas—around thirty millimeters long—carrying a miniature world on its back.

No *Gymnopholus* is an island, however. The weevil, the glowing sum of so much symbiosis, still needs to eat. It prefers the leaves of woody forest plants, cutting out ovals of parenchyma with its mandibular scissors. As a beetle scurries around a leaf at a speed of two meters per minute, it drags along a habitat with it every step of the way. Whether they like it or not, the mites and rotifers are coming along for the ride, strapped to their algal seats. *Gymnopholus*, a set of compounded biological iterations, makes it possible to have a nematode hunting a rotifer sitting next to a mite and some bark lice on top of a lichen

fastened to a moss gametophyte rooted in the carapace of a weevil eating an oak. The beetle is the rhizome, the intricate root system where nodes and nodules of life intersect and interact, merge and emerge. What happens when the beetle molts? Does the world collapse under the furious weight of ecdysis? To date, no one has reported witnessing a *Gymnopholus* molt—which to my mind is almost a compelling enough reason for me to pack up my life savings and head to New Guinea, video camera in hand.

We're sitting on a lichen on a beetle's back, the rocky carapace of the earth as it sojourns in the emptiness of interplanetary space, carried by the arcing pinwheel arms of the Milky Way galaxy through the endless black nothingness between galaxies. The rotifer has no idea that the mat of algae it's eating is being whipped along at a gait of two meters per minute on the back of a weevil, a worldbug in the truest sense of the (made-up) word; it's only impelled by the urges for food and avoiding predatory nematodes. When I walk on the sediments of the terra firma, I become the rotifer. I'm really only conscious of the nematodes and the algae, the things that exist on my scale. I might be able to see the lichen that is the earth that I stand on, but I can't see past the azure depth of the firmament to the edge of space, the ozone exoskeleton of the voyaging earth. There's no way I can sense the motion of the weevil I'm standing on, the unceasing orbit around the sun at a constant rate of 64,800 miles per hour, a planetary marble rolling down the funnel of the sun's gravitational warping of space. As the earth, dragged along by the sun, rotates on the arc of the Milky Way at 542,000 miles per hour, the galaxy itself hurtles through space with a moreor-less constant velocity of 1.3 million miles per hour. In a single day, the earth is whipped through 31 million miles of intergalactic space, and I have no idea that it's happening. I just go where the beetle goes.

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Symbiosis can get even more personal than it does with *Gymnopholus*. The weevil might have a world *on* it, but a staggering number of organisms have an entire community *in* them. And I'm not just talking about the ones attacked by parasites—that's rarely an entire community. I'm talking about whole populations residing inside a host's cells, a process known as endosymbiosis. Legumes, for example, couldn't even survive without the bacteria they host. Since beans and their relatives can't "fix" atmospheric nitrogen (not that it's broken; fixing entails converting the gaseous nitrogen into ammonia, which can then be used to make proteins and other biochemical goodies) on their own, they enlist the help of a higly-motivated corps of free-living soil bacteria named rhizobia. Sending out the chemical equivalent of smoke signals, legume roots secrete substances called flavinoids to elicit a response signal—nod factors from rhizobia in the surrounding soil. Once the plant gets the nod (pun intended) from the bacteria, it unfurls tiny, single-cell-thick wisps called root hairs from the fractal lattice of its roots in order to entwine the bacteria, wrapping them around several times. The cooperative prokaryotes become an oblong, cytoplastic spool for the stringy root hairs to wind around. (Root hairs, more like the plant equivalent of the microvillus "brush border" than hairs, are not visible to the naked eye, but in my head, I imagine them looking something like the fake

spiderwebs people use for Halloween decorations, pulled so thinly that they are only a hair's width.) Rhizobia commence multiplying once captured, breeding to form a microcolony. The plant then reels in the bacteria via an infection thread that creates a channel for the rhizobia linking the epidermis of the root to the root hairs. Special host cells in the root, known as root nodules, take the bacteria inside them and give them the organelle treatment, incorporating them into the body of the cell as a functioning mini-organ which biologists term a bacterioid. In exchange for the bacteria's loyal service, the plant provides them with room and board, offering them protection from heterotrophic organisms and supplying them with carbohydrates, proteins, and necessary organic acids that they can't make on their own.

The symbionts prove two nuclei (or, in the case of the bacteria, nucleoid regions) are better than one: the legume and rhizobia collaborate to produce an iron-containing protein called leghemoglobin. Remarkably, neither the bacteria nor the plant alone can manufacture that protein; it can only be found in the dynamic synergism of the two organisms. Leghemoglobin and hemoglobin are, as their names imply, very similar; both function as a kind of glue that holds onto oxygen. If hemoglobin is Elmer's Glue, leghemoglobin is construction adhesive, with ten times the oxygen affinity. A bunch of curlicue streamers of amino acids fly around on all sides of a central, crimson porphyrin ring dotted with an iron atom in the middle. This central ring works like a magnet to attract and sequester most of the oxygen molecules in a safe space, where the impertinent element can't interfere with the important business of nitrogen fixation. Since

oxygen molecules have no manners and will just bump into the nitrogen-fixing enzyme nitrogenase without so much as an "Excuse me," free-floating oxygen molecules in the body of the cell disrupt the conversion of nitrogen into ammonia by oxidizing ("rusting") the iron and sulfur-containing keystone of the enzyme. Leghemoglobin performs a difficult and highly precise balancing act, leaving just enough oxygen floating freely for the bacteria to use in respiration (cellular breathing). If the oxygen concentration were a tad higher, the active enzyme of nitrogen fixation would break down; a tad lower and the rhizobia would become "winded," unable to generate the cellular energy they need to get through a hard day of nitrogen conversion. The rhizobia and legume fine-tune their respective contributions to get that Goldilocks concentration of oxygen ("This one is just right...") in every one of the million root nodule cells. I try to remind myself of this whenever I eat lima beans, which due to their taste I have tendency to look at with nothing but scorn.

While most legumes have to lasso their own bacteria, *Psychotria* bacteriophila, a low-growing tree whose binomen means "vivifying bacterialover," lives up to its name and has bacteria with it from the get-go. The seeds of *P. bacteriophila* contain endosymbiotic rhizobia. Think of it as a bacterial godmother who watches over the legume from its youngest days and stays with it as it grows. The bacteria are an inherited trait, so you can get a child with Mom's face and Dad's bacteria. The scientific community still debates how this can happen. Does the parents' DNA encode the entrapment of the bacteria or do they simply relocate some of their own rhizobia for the seed? So far, no one has

provided an answer. (It's questions like these that make me wish I had a degree in biology and access to a lab.) Some process undiscovered as of yet completely embeds the bacteria in the plant embryo like a fly suspended in amber. Slice the seed in half and put it under a microscope and, ta-da!, you've got a bacterial culture! No assembly required.

As remarkable as that sounds, hereditary symbiosis—organism embedded in organism from the start—probably happens in more species than I could count without getting exhausted (since I imagine I'd start getting intolerably sick of counting a little past the five-hundred mark). But I'm not evolution, and presumably it has more than ten fingers to count on, so instead we get thousands of hereditary symbionts. Protists—those little single-celled guys with a nucleus, including algae and protozoa—have a particular fondness for inherited symbiosis. Lynn Margulis describes one such species, *Paramecium* bursaria. I actually have been lucky enough to see this protist glide along a water droplet in the gulley of a depression slide, and I can say that *P. bursaria* is a living wallet, an odd cigar-shaped membranous mass of jelly filled with green Dalmatian spots. Most paramecia are naturally clear, but *P. bursaria* has the color of a lime. That's because it's a school bus for algae. Apart from a perimeter of a membrane that looks like wrinkled skin, the paramecium is crammed with the translucent green dots of *Chlorella* algae. *P. bursaria*, like a unicellular Dalmatian with green spots, almost fooled me into believing that I was seeing a gliding leaf. As the paramecium skimmed along the glass surface, the algae wiggled and bobbed, sliding around in the gooey aspic of the cytoplasm. It

thoroughly amazed me that the protozoan didn't just burst like one of those party poppers and blow out algal confetti everywhere. Packed as densely as a bunch of grapes wrapped in a gelatinous film, the paramecium gets it energy from the algae. *Chlorella* and *Paramecium* have an incredible, amicable, reciprocal relationship; they give and receive equally. The algae produce food for the paramecium. The protozoan offers them protection from voracious unicellular predators and moves them to the best-lit spots. Of course, any predator that could get *P. bursaria* would be in for a hundred-course meal, with ninety-nine helpings of algae and a gummy paramecium for dessert.

As with *Psychotria*, *P. bursaria* inherits the algae from birth. It is almost entirely dependent on its birthright for its survival, too. Margulis explains one experiment when the algae were separated from the paramecium: "When the host is deprived of its guests, it will survive only if extra nutrients are added to its medium" (Margulis 50). The reunion of the long-lost symbionts demonstrates how hereditary the symbiosis truly is. Once the algae are reintroduced, they "multiply, but only until the normal, genetically regulated number of algae per paramecium is obtained" (Margulis 50). Evolution resembles an airline, placing a strict limit on the amount of luggage before it begins to get costly. There's less standardization than with airlines, though. The size of the individual paramecium determines the number of carry-on bags. A larger paramecium can hold more algae. Once the limit is reached, the protist starts getting rid of any extra baggage; if it encounters a *Chlorella* in the environment, it envelopes and then digests it instead of storing it undigested in its cytoplasm. *P. bursaria* will

also eat any algae species other than its specific type of *Chlorella*. The hitchhiking *Chlorella* have been granted some kind of immunity to digestion. Margulis doesn't speculate on how this happens, but I have my own ideas. Either the host, like a chipmunk carrying seeds back to its den, "knows" not to swallow what's already in its cheeks, or the *Chlorella* endosymbionts carry a chemical marker that prevents their digestion. Maybe the paramecium is a perfectly calibrated machine with DNA programming that explicitly prevents it from digesting the *Chlorella* it's born with. The DNA could contain an elaborate "if-else" style code, much like sophisticated computer programming does, something to the effect of "If chemicals detected on algal cell wall, then do not digest them. Else, eat them." Who knows though? I can't get inside the mind of a paramecium for a whole host of reasons, the foremost being that they almost certainly don't have a mind—at least not in the way we would conceive of one.

Nature always manages to up the ante. Always. You thought one endosymbiotic species was enough? Evolution doesn't agree with you. One is never enough, so Nature threw in *Myxotricha paradoxa* to add new, nested levels of symbiosis. *M. paradoxa* is not so much a paradox as a study in iteration, symbiosis brought to a climactic culmination. *M. paradoxa* belongs to a group of protozoa called flagellates, coated in hair-like cilia that beat like paddles and a few, long whip-like flagella that lash back and forth to keep the organism on the lam from the laws of parsimony. Cilia and flagella are not so unique—all the flagellates have them. In fact, *M. paradoxa* is one of the only ones that doesn't have its own cilia. *M. paradoxa*'s cilia turn out to be a wig. Each cilium is a rotini-

shaped bacterium pasted into the folds and fissures of the protist's infinitely long cell membrane like feathers in the pores of a bird's skin. Ostensibly, Nature was involved in a game of darts, hurling spirochete bacteria onto a protozoan board. And they all managed to stick. Her opponent (perhaps Evolution?) had less luck; only a few of his shots with another species of spirochete actually stuck, nested in the fractal lagoons along the protozoan's membranous coastline that weren't already occupied. The only spot the players didn't hit was the oral groove, the protozoan analog of a mouth—which is a good thing for *M. paradoxa*. Otherwise, how could it have scooped up a third species of symbiotic bacteria that buoy along with the crests of translucent waves of cytosol coursing through the host cell?

To top it all off grandly, to reach the very apogee of symbiosis, *M.* paradoxa lives inside the gut of termites. Itself an endosymbiont, this protist's hard work and ingenuity enable termites to digest wood. It is a study in self-similarity: zoom in on the termite, you'll find a protozoan; magnify the protozoan to see that it's ringed with two species of spirochete bacteria, speckled with a third species inside its cytoplasm, ekes out its living as an endosymbiont of a termite. The spirochetes maneuver the flagellate around and let it gather particles of wood in its mouth, and the bacteria living indoors aid in the digestion of it. Any stray compounds stripped from the wood nourish the termite. Finally lignin, indigestible in any form, is excreted by the termite and used to build mounds. Without *M. paradoxa*, there would be no termite mounds,

substantially less food for anteaters, and no reason for chimps to use their crude stick-tools as insect fishing rods.

When you have this many levels of symbiosis, interacting like the quarks of a proton, you have to wonder where it began. Which was the relationship that started the symbiotic cascade? Perhaps M. paradoxa started out with one species of spirillum implanting itself onto the membrane. Given that the relationship increased motility, it stuck. Now that *M. paradoxa* is zipping along at a brisk clip, it's easy to imagine it serendipitously colliding (over several generations, of course!) with another spirochete, who boosted motility even more. M. paradoxa then becomes a top-of-the-line cellular predator. It eats plenty of bacteria, but one species just doesn't seem to go down; it has some chemical force field around it that prevents it from being digested. There's a tradeoff: though the bacterium can't be digested for nutrition, it facilitates *Myxotricha*'s breakdown of wood. A hapless termite wanders along and gets ahold of the myxotrichan conglomerate. Since it gets the leftovers from wood digestion, the termite decides to run with it. Throw in a few million years, and this strategy has become so successful it's firmly entrenched and unlikely to change. Symbiosis is life's Energizer Bunny: it just keeps going and going.

* * * * *

As it goes and goes, symbiosis produces not just relationships but radically new forms of life. Many biologists, following Lynn Margulis' lead, now think that symbiosis created the adaptation that gave rise to eukaryotes—the larger, more complex cells that archive their DNA in a membranous nucleus

found in protists, plants, fungi, and animals. Endosymbiotic theory proposes that all the specialized parts of a eukaryotic cell descended from bacteria living symbiotically inside the body of a host bacterial cell. My high school biology book (the one that I read for fun) concludes that "the evidence is now overwhelming that the eukaryotic cell originated from a symbiotic coalition of multiple prokaryotic ancestors, not just one" (Campbell & Reece 549). A coalition of the willing—spirochetes, cyanobacteria, proteobacteria—pooled together like the atoms of a protein to increase their chance of survival. And the evidence is indeed overwhelming: chloroplasts (the sites of photosynthesis) and mitochondria (where food products are oxidized to get energy) have their own DNA and the RNA equipment necessary for making their own proteins. They actually produce some of the proteins they need without any help from the host cell, although they do know when to ask for assistance in the trying times of manufacturing complex enzymes. Along with chloroplasts and mitochondria, nuclei have two membranes: one from the endosymbiotic bacteria they descended from and another from the host cells that swallowed them whole. These membranes contain uncanny biochemical similarities to those of contemporary species of bacteria, the smoking gun left at the scene of the crime.

According to endosymbiotic theory, cells didn't just compete with each other, resulting in small morphological modifications that over time collected and produced new structures. Lynn Margulis, perhaps the biggest proponent of endosymbiotic theory, explains, "Cells without nuclei were the first to evolve.

Cells with nuclei, however, are not merely mutant descendents of the older kind

of cell. They are the product of a different evolutionary process: a symbiotic union of several cells without nuclei" (Margulis 49). They combined, synthesized, fused to form something entirely new: complex organelles that couldn't arise from little adaptations building as time passed. The fusion of mitochondria and the host cell is something unprecedented and qualitatively different. The term "symbiosis" doesn't do this level of biological intimacy justice; it's symbiogenesis, the merging of two distinct organisms to form a new, single organism. This isn't painting the walls blue *and* yellow; this is mixing blue and yellow to paint the room green.

Even though we're blending colors for the first time, it's only a small evolutoionary jump from *Myxotricha paradoxa* to the interdependent organelles of mitochondria, chloroplasts, and cilia. *M. paradoxa* hosts a wide variety of symbionts wedged into the infinite creases of membrane or bobbing around in its cytoplasm. Conceptually, it's not difficult to see *M. paradoxa* as a missing (well, present) link between prokaryotic and eukaryotic life, but ontologically, it's a lot more complicated. When the spirochetes lodged in the cell's border wiggle, they're moving as unique organisms. Equate the two, subject them somehow to same cellular volition, and *then* you have symbiogenesis. But at what point do the independent cells become one entity? When do they form an "atom" in the Greek sense of being "uncuttable?" My intuition is that once one symbiont can no longer be separated from the other without instant lysis—when the contents of the cell burst out like custard from a cream puff that gets

squeezed just a little too tightly—the two formerly independent organisms have tied the endosymbiotic knot and enacted the holy sacrament of symbiogenesis.

With symbiogenesis, you can't remove a part without the whole collapsing. My biology textbook boldly proclaims, "The eukaryotic cell is a chimera of prokaryotic ancestors" (Campbell & Reece 550). Instead of the body of a lion, there's the cytoplasm of a large bacterium. The head of the goat is replaced by the ingestion of a proteobacterium for the mitochondrion, and the tail of the snake is the flagellum whip made of spirochetes. When Bellerophon, levitating on the wings of Pegasus, lodged a block of lead in the lion head of the chimera, the whole creature suffocated and died (and this is historical fact, I should add). If you take out the nucleus, the cilia, the flagella, the centrioles, the mitochondria, and the chloroplasts out of a eukaryotic cell, what you have left isn't a eukaryote; it's a big old bacterium that can't even reproduce, a cell membrane wrapped feebly around a ball of translucent cytosol. And that's the distinction between symbiogenesis and the other forms of endosymbiosis. If you remove the algae from *P. bursaria*, you still have a paramecium. A hungry paramecium that struggles to feed itself, but a paramecium nonetheless.

If *M. paradoxa* enjoys all the benefits of symbiosis without being so closely entwined with its symbionts that it risks lysis on separation, why should endosymbionts become so good at reading each other that they meld into one organism that does have to face that risk? Isn't it easier to be ontologically distinct organisms? Not quite; having a rich repertoire of new organelles at the cell's disposal opens up a world of possibility. The nucleus provides the perfect

example. DNA is rarely used; only when cells need to produce something new, divide into more cells or pinch themselves off to form reproductive half-cells does DNA do serious work. The nucleus serves as a shed to store the seasonal DNA, reducing clutter in the cytoplasmic house for the low, low price of endosymbiosis! Packing DNA into the nuclear envelope freed cytoplasmic space for more specialized parts and allowed radically more DNA to be stored. In turn, genomes got more complex, and organisms could make finer adjustments to their environments and expand their metabolic capabilities. All of a sudden, the orchestra of life went from a single cellist to an entire symphony, producing new, exquisite, and more intricate melodies and harmonies. Life became immensely more complex as the new organisms started doing things that prokaryotes never even dreamed of—crazy exploits like cellular respiration, multicellularity, and sexual reproduction. The floodgates broke open two billion years ago, and nothing could stop the vital outpouring of biodiversity. If you accept endosymbiotic theory, every eukaryotic species—amoebas, algae, plants, fungi, and animals—has origins in that breaking of the floodgates and would be hereditarily symbiotic, a number totaling over 3 million, which is way more than I'd ever care to count.

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Symbiogenesis makes it difficult to "know thyself." Mitochondria are in my cells, but really, they're just doing their own thing when it comes to replication. They can Xerox themselves without the consent of the nucleus. Lewis Thomas points out, "My centrioles, basal bodies, and probably a good many

other more obscure tiny beings at work inside my cells, each with its own special genome, are as foreign, and as essential, as aphids in anthills" (Thomas 4). Suddenly, it becomes apparent why he named his book *The Lives of a Cell*: each cell is living a double (or triple or quadruple...) life, each part living in its own manner. My cells carry on their own lives, trillions frolicking about and doing what I need them to do. Every day, there are millions of deaths and births in me. Luckily, mutiny never crosses a cell's mind (unless it becomes carcinogenic through some mutation). Ralph Waldo Emerson draws the distinction between the soul or self (the "Me") and nature (the "Not-Me"), but biology is starting to blur that division beyond recognition. Assuming that energy is required for consciousness and that brain activity reflects thought, I need those mitochondria to think! So the not-me is me. Or at least, the not-me is powering me. Adenosine triphosphate (ATP) drives the economy of my body. It's the fundamental energetic currency of all living things, and it's produced in the mitochondria, the modified bacteria lounging in my cells. They're "as foreign as aphids in anthills," and yet they're the generators pumping their membranous pistons day in and day out to make all my precious ATP. The myosin and actin that push and pull my muscles, sliding their fibers like tectonic plates, would be locked in place without the ATP my houseguests are cooking up for me. And a lot of me is notme. Thomas writes, "My mitochondria comprise a very large proportion of me. I cannot do the calculation, but I suppose there is almost as much of them in sheer dry bulk as there is the rest of me" (Thomas 72).

I have this indefinable feeling of tension between the me and not-me, nesting itself below the surface of my cells. I'm fine with expropriating the fruits of mitochondrial labor; what causes me anxiety is that the most intimate corners of my being are inhabited by trillions of not-me's. Centrioles, the chromosomal lassos that line genes up for cell division, tubules bunched together to look like licorice bites, are descended from bacteria. Even the organelles that touch my chromosomal DNA—basically the biochemical ego—are foreign hands. With each mitotic division, centrioles swing my DNA do-si-do and put it back in its place. The not-me is ordering around the very essence of me!

The cilia-based senses of sight and smell have their origins in an endosymbiont and are effectively bacterially-mediated. All of my impressions have to pass through a bacterial board of censors. If they don't see it, I don't see it. If they don't want to pick up the light reflected off an object, they don't transmit the signal to my brain. Annie Dillard laments the cruel irony that only relatively simple organisms are able to perceive the universe as it really is, without the interference of neural networks, but lack the cognitive capacity to appreciate it. Seeing the universe as it is must not be all it's cracked up to be since the bacteria surrendered that perception in order to work for the network; their descendents now are the first stage of the neural screening. I can't move a muscle, blink an eye, or think a thought without the endosymbiotic seal of approval. I need the energy of the mitochondria to pump the sodium and potassium ions that give my neurons an electrical charge and transmit a pulse along my nerves to my brain. I'm the house that endosymbiosis built. My very

consciousness is mediated by someone else. Saying "I," thinking of my body as housing a singular subjectivity, comes into question. Perhaps instead of "I," I should say "we." To be honest, I don't even know if I have the authority to speak for all my endosymbionts. I just have to hope that in exchange for the housing and safety I provide them, they'll let me make all the big decisions. So far, that's been working out just fine.

I'm not distinct from nature; I'm my own habitat. I am a gall, a small protuberance from the face of the earth sequestering organisms in chambers inside myself. Inquilines are constantly buzzing through me and replicating themselves within the space bounded by my skin. Billions of bacteria swim along the fractal boundaries of the lumen of my intestines. It's almost as if I have the trophosome of the vestimentiferan to help me break apart the food I eat, which then gets passed to the not-me mitochondria nested in my cells for cellular respiration refinement. The intertwined symbiotic braids of symbiont within symbiont within symbiont, wrapped like collagen fibers, course through me like the *T. nitens* larva injected into a gall populated with a gall-inducer and thirteen inquiline species. Centrioles round up my DNA like the nematodes chasing the rotifers on the back of the world-beetle *Gymnopholus*. Even if I can never perceive it, symbiosis nests itself in every living crevice of the infinite border of my being, taps into the root nodules, the self-similar network of veins that transmits the pulse of life. My heart pumps with the parenchymal waves of a gall, which slowly balloons on the creamy green axil of an oak and fattens into a chestnut of pure being.

Epilogue: Gravity

"What is extraordinary appears to us as habit, the dawn a daily routine of nature. But time and again we awake"—Abraham Joshua Heschel, *Man Is Not Alone* (34)

There are four fundamental forces at the roots of the universe: the strong nuclear force, electromagnetism, the weak nuclear force, and gravity. Gravity is always the odd one out, and the fundamental challenge of physics today is working out a unified field theory, a Grand Unified Theory that can be bring all four forces together in a single equation. So far, scientists have gotten a Grand Unified Theory to bring together all but gravity. At extremely high energy, the strong, weak, and electromagnetic forces all merge to form a unified force. A few roadblocks stand between gravity and complete unification. For example, the other three forces have been known to exchange particles that mediate them: Electrons and protons, with electromagnetic charges, exchange photons in their interactions; quarks, the constituents of protons and neutrons, trade gluons; W and Z bosons interfere with quarks to trigger the nuclear decay of the weak force. No one has ever observed the theoretical particles that may mediate gravity, called gravitons. Compared to the other three interactions, gravity is pitifully weak, so even at extraordinarily high energy, it lags behind the other forces. Even the weak force, the second weakest after gravitation, could beat gravity senseless; it's a staggering 10^{25} times as strong as gravity.

What's more, all the forces except gravity carry charges. Electrons are negative, protons positive. Having equal-but-opposite charges allows the weak

and strong interactions and electromagnetism to cancel out; one object can repel as much as the other attracts, leading to an overall net influence of zero. Gravity only carries one possible "charge;" it's positive and it must under all circumstances attract. The force of gravity is always mutual, and if the objects are of comparable size—say Earth and Mars—they'll meet each other halfway. Gravity can never repel, and it can never cancel out. The gravitational force exerted by an object on others cannot be zero; it can be *effectively* zero, approach it so closely that the force hardly registers, but it can never fully disappear. The strength of the three unified forces is proportional to the charge a particle carries. The charge is a unique property of the particle; putting an electron next to a proton will not change either's charge. Because of their dependence on charge, the strong and weak interactions occur at the subatomic distance scale and electromagnetism exerts its force primarily over the orbit of an atom. Mass, rather than charge, determines the strength of gravity. As more and more particles grow closer together, gravity strengthens and pulls in other objects that are farther away. When as many particles as constitute, say, the Andromeda Galaxy gather together, their massive gravitational influence extends for lightyears. Gravity works on an incomprehensibly large scale—effectively infinite and never cancels out. Every object in the universe is in some way, no matter how small, interacting gravitationally with every other one.

Einstein's big bombshell was his discovery that gravity was not a projectile force between objects but a warping of the coordinate grid of space in which all things are suspended. The presence of matter distorts and ripples

space, painting it with x-shaped waves like I saw on the surface of Buzzard Swamp. Gravitational attraction owes to these warpings, which slope space-time. Imagine your mattress as the fabric of space-time and your body as a massive object placed on it; notice how the foam padding of space-time dents and curves under the weight of your body, how it draws in objects like a marble rolling down the divots of compressed foam.

It is precisely these dents in the grid of space that allow matter to coalesce at large scales. Gravity funnels particles together: an atom creates the tiniest ripple, slightly sloping space-time so that other particles will slide to it as if rolling down the smallest-grade ramp imaginable. Once the particles reach each other, they band together in particulate symbiosis to enlarge the grade of the ramp and draw more particles in. They continue pulling and consuming, creating larger and larger masses, strengthening and compacting into an object like sediments forming sheets of sandstone. Eventually so much matter collects that a planet forms, and if it's lucky enough to have a good location near enough to other matter, it can continue to enlarge. At a certain critical mass—larger than Jupiter, for sure—the strength of compacting gravity becomes so great that it overpowers the electromagnetic force. Like charges will repel, so two protons will never sit next to each other unless some other force has its say. In massive objects, gravity becomes so strong that it brings protons close enough together that their quarks begin exchanging gluons, sealing them together with the strong nuclear force—a process called nuclear fusion that releases enormous amounts

of energy. Suddenly, gravity ignites a wave of fusion, turning a matte ball of matter into a radiant, roiling star.

The fusion of atoms releases enough energy to keep gravity from further compacting them since heat is molecular motion. Once the star runs out of fusible atoms, though, gravity returns to condensing it, eventually collapsing the star under its own weight. Whether a star collapses to form a black hole, a neutron star, or a white dwarf, its center creates so much gravitational potential energy that it casts off the material further from the center in an awesome explosion known as a supernova. If gravity had its way, all the matter in the universe would be collected into a single supermassive point, like the Big Bang in reverse.

I can already feel gravity trying to have its way, its minute tugs and yanks. The Andromeda Galaxy, nestled like a creamy nougat dot in the sky 2.5 million light-years away, is sloping space and gently funneling our Milky Way Galaxy toward it. It is lightly pulling on my arm, pulling the strings hooked up to my hands and giving them the tiniest jittery movements even when I try to hold them perfectly still. The fly that walks along the brambly hairs of my right arm needs to reach a certain escape velocity to decrease my gravitational influence to a hardly noticeable level just as a spaceship leaving the earth must. I am the hub of a wheel with infinite spokes extending in every direction, each one linked to another hub. As I walk along Foss Hill in Connecticut, some piece of me rolls down the imperceptible incline created by the weight of the red-tailed hawk at

the Allegheny National Forest. It and I are forever interacting, attracting each other by virtue of our masses, longing to be unified.

The sun holds our earth in check, whipping it around in an egg-shaped orbit and carrying the eagle and me along for the ride. Our sun is a third generation star. All of the material in our solar system came from the blown-out shells of the sun's predecessors during their last gasps in supernovae, which catapulted elements into the interstellar space where they eventually resettled and continued pulling each other gravitationally to form planets. Those planets, and everything on them, are made of far-flung pieces of stars. The RNA and proteins that assembled themselves into the first proto-bacterium had their origin in the stellar core of the sun's grandmother. We are built from the remnants of blown-out stars. And one day, in approximately five billion years, when the sun runs out of atoms to fuse, it will explode in silence in the vacuum of space and sow elements in the field of interstellar space, starting a new cycle of creation.

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At the end of October, I traveled to Acadia National Park in Maine. When I woke up at 5:45 to watch the sun rise over a jagged, fractal promontory, the star seemed so solid and everlasting as it pulled its way across the sky. I sat in almost complete silence, the only sound vibrations around being the pulsing of the ocean against the cliff I sat on and the hee-haw calls of the herring gulls. The disc of the sun came up perpendicular to the horizon and cast a golden path like glitter glue along the rippling surface of the water, gilding the wave crests,

illuminating the surface so it flickered like a flame on the wick of a candle. If you traced the path of the column of light, it would lead directly to the sun. The image was burned into my retina, and as I walked back to my tent I saw a band of red where the path of sunlight had been in my eyes. My field of vision caught fire. The sun was a spindle reeling out rose gossamer on the crystalline palette of the firmament, illuminating the horizon pink and dying the clouds salmon. And this beauty is vouchsafed us every morning, as the earth turns out of the cone of night and spins the sun across its curved sky without fail. Never in the earth's history has the sun not risen.

I keep this in mind when I wake up, that every morning, the sun's rays touch the earth, and that that is cause to rejoice in hymn. In Jewish morning prayer, the suppliant celebrates the reappearance of the sun by wrapping himself in phylacteries, small cubes that contain parchment scrolls with verses from the Torah and attach to leather straps. As he prays, he wraps himself in the words of Jacob and Moses, binding the *tefillin* (as they're called in Hebrew) to his arm and his forehead. Gravity is my *tefillin*; I am constantly bound in prayer and wonder. The filaments of gravity bind my arm and my forehead, my heart and my mind, to the natural world, to the straight gelatinous arrows of magnetotactic bacteria buried in the mud of a lake bottom, to the bracken fern dotting the cusps of Papas Mountain Road, to the gigantic tubeworms sewing up the lavaleaking stitches of the ocean floor, to *Myxotricha paradoxa* and all its endosymbionts lumberjacking away in the gut of a termite. All of them pull on me, tilt me slightly as though I were trying to balance on one leg, with the net of

their gravity. Me and them, we're not so different. All of us are formed of the same wet clay, and to dust we shall all return.

As the sun skitters across the dawn sky, I bind myself in gravity's *tefillin* for my morning prayer, which is nothing more than an exercise in presence. The chickadee, the golden eagle, the electric eel, the tick, the magnetotactic bacteria, and everything else sculpted from the blown-out bits of that ancient supernova wear the same phylacteries, the ties of gravitation with the Word of nature written in the center. I turn my eyes to the ineffable, the phenomenal improbability of existence. I ignore Abraham Joshua Heschel for a moment and take as big a bite out of the wall of mystery as I can. I bite past the exterior wall of the gall and expose its fleshy, larval innards. I bite through the glass at the PPG Aguarium and touch the electric eel in front of me. I bite open the frosty windowpane and hear the scurrying of the squirrel and chickadee a decillion Planck lengths away. I bite the gunk off my hands and feel the fractal jaggedness of a bracken fern, resolving new textures with each increase in magnification. I bite away the gauze over my eyes and focus them like a Transmission Electron Aberrance-Correcting Microscope to see gold atoms stacked upon each other like chips on a crowded Plinko board. I bite through the hydrogen bonds that create the thin skin of surface tension sealing away the ineffable, and for a moment I break through the perceptible exterior. I bite away at the wall that separates me from the mystery of nature, and suddenly I'm entrained into the hollow warpings of space-time and whipping along the gravitational current until

everything I've experienced coalesces into an infinitely dense phantasmagoric nugget of matter and energy, being and becoming.

As the day unfolds, I learn to wonder. I find God hiding in the gaps, hiding beneath the perceptible surface of the world. In Jewish practice, we cover our eyes when we say the *shema*, the affirmation of monotheism, because God walks in front of us. We can never see His presence directly because nature obscures itself. We can't see His presence directly, but folded into the extradimensional Calabi-Yau spaces, tucked securely under the Planck length, God walks before us. My morning prayer, bound in gravity: I am here, I am awake.

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