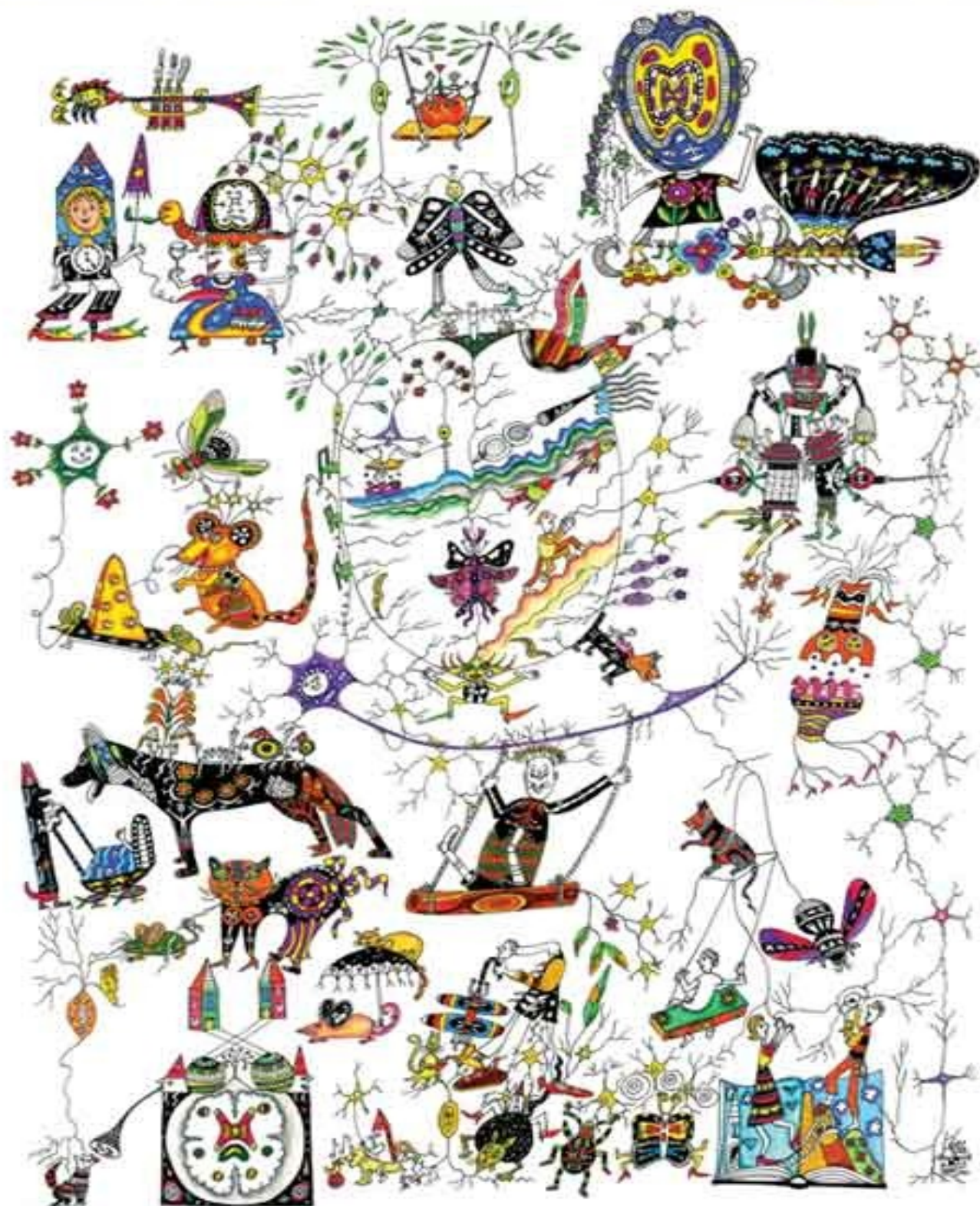


CONSCIOUSNESS

CONFESSIONS OF A ROMANTIC REDUCTIONIST



CHRISTOF KOCH

Consciousness

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Confessions of a Romantic Reductionist

Christof Koch

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To Hannele

Contents

[Preface](#)

[Acknowledgments](#)

[Chapter 1](#): In which I introduce the ancient mind–body problem, explain why I am on a quest to use reason and empirical inquiry to solve it, acquaint you with Francis Crick, explain how he relates to this quest, make a confession, and end on a sad note

[Chapter 2](#): In which I write about the wellsprings of my inner conflict between religion and reason, why I grew up wanting to be a scientist, why I wear a lapel pin of Professor Calculus, and how I acquired a second mentor late in life

[Chapter 3](#): In which I explain why consciousness challenges the scientific view of the world, how consciousness can be investigated empirically with both feet firmly planted on the ground, why animals share consciousness with humans, and why self-consciousness is not as important as many people think it is

[Chapter 4](#): In which you hear tales of scientist-magicians that make you look but not see, how they track the footprints of consciousness by peering into your skull, why you don't see with your eyes, and why attention and consciousness are not the same

[Chapter 5](#): In which you learn from neurologists and neurosurgeons that some neurons care a great deal about celebrities, that cutting the cerebral cortex in two does not reduce consciousness by half, that color is leached from the world by the loss of a small cortical region, and that the destruction of a sugar cube–sized chunk of brain stem or thalamic tissue leaves you undead

[Chapter 6](#): In which I defend two propositions that my younger self found nonsense—you are unaware of most of the things that go on in your head, and zombie agents control much of your life, even though you confidently believe that you are in charge

[Chapter 7](#): In which I throw caution to the wind, bring up free will, *Der Ring des Nibelungen*, and what physics says about determinism, explain the impoverished ability of your mind to choose, show that your will lags behind your brain's decision, and that freedom is just another word for feeling

[Chapter 8](#): In which I argue that consciousness is a fundamental property of complex things, rhapsodize about integrated information theory, how it explains many puzzling facts about consciousness and provides a blueprint for building sentient machines

[Chapter 9](#): In which I outline an electromagnetic gadget to measure consciousness, describe efforts to harness the power of genetic engineering to track consciousness in mice, and find myself building cortical observatories

[Chapter 10](#): In which I muse about final matters considered off-limits to polite scientific discourse: to wit, the relationship between science and religion, the existence of God, whether this God can intervene in the universe, the death of my mentor, and my recent tribulations

[Notes](#)

[References](#)

[Index](#)

Preface

What you're holding in your hand is a slim exposition on the modern science of consciousness. Within the space of a few hours, you can inform yourself about where we natural scientists stand with respect to unraveling one of the central questions of our existence—namely, how do subjective feelings, how does consciousness, enter into the world? “Through your head” is the obvious answer. But that answer is not very helpful. What is it about the brain inside your head that makes you conscious of colors, of pain and pleasure, of the past and of the future, of yourself and of others? Are there any brains that do not suffice? What about the brain of a comatose patient, of a fetus, of a dog, a mouse, or a fly? What about the “brains” of computers? Can they ever be conscious? I'll tackle these questions and then some, including free will, a theory of consciousness, and the *bête noire* of my research: the extent to which quantum mechanics is relevant to understanding consciousness.

This book is not just about science, however. It is also a confession and a memoir. I am not only a dispassionate physicist and biologist but also a human being who enjoys but a few years to make sense of the riddle of existence. I learned over the past years how powerfully my unconscious inclinations, my beliefs, and my personal strengths and failings have influenced my life and the pursuit of my life's work. I experienced what the novelist Haruki Murakami described in a striking interview: “We have rooms in ourselves. Most of them we have not visited yet. Forgotten rooms. From time to time we can find the passage. We find strange things . . . old phonographs, picture books . . . they belong to us, but it is the first time we have found them.” You'll learn about some of these lost chambers as they become relevant to the quest I'm on—to uncover the roots of consciousness.

Pasadena, California

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Acknowledgments

Writing, editing, and publishing a book requires the active cooperation of many people. Books are a testament to the better nature of humankind—taking pleasure in working toward a distant goal, with the primary reward being the feeling of a job well done.

Blair Potter took my prose and edited it. She identified the three distinct strands in my writing, untangled them, and then re-braided them. If the outcome reads like anything close to a monolithic text, it is thanks to her. John Murdzek and Katherine Almeida proofread everything with a fine-tooth comb and Sarah Ball, Amy Chung-Yu Chou, and Kelly Overly provided some more editorial advice.

Volney Gay, professor of psychiatry and of religious studies at Vanderbilt University in Nashville, TN, invited me to give three *Templeton Research Lectures* on “The Problem of Consciousness: Philosophy, Religion, and Science” in spring 2007. It is here that inception for this book took place. I thank the John Templeton Foundation for their generous financial support for these public lectures.

I would like to acknowledge the many students, friends, and colleagues who read installments of the book and identified its many infelicities and inconsistencies—Ralph Adolphs, Ned Block, Bruce Bridgeman, McKell Ronald Carter, Moran Cerf, David Chalmers, Michael Hawrylycz, Constantinos Hippius, Fatma Imamoglu, Michael Koch, Gabriel Kreiman, Uri Maoz, Leonard Mlodinow, Jonathan Padowitz, Anil Seth, Adam Shai, Giulio Tononi, and Gideon Yaffe. Heather Berlin suggested the title. Bruce Bridgeman, McKell Carter, and Giulio Tononi took the time carefully to go through the entire text and emend it. Thanks to their collective efforts, their veiled or direct critiques, the book now reads more smoothly, with fewer knobs that protrude, annoy, or distract.

Thanks to the many institutions that provided me a quiet haven. Foremost the California Institute of Technology, my intellectual home for a quarter of a century. During these past years, the hardest years of my life, Caltech and its people were my one stable rock. They helped me to cope in ways both small and large. Korea University in Seoul provided a refuge in the Far East, with scope to write, think, and reflect upon all the matters discussed in these pages. The Allen Institute for Brain Science in Seattle generously gave me the time to finish this book.

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Chapter 1:

In which I introduce the ancient mind–body problem, explain why I am on a quest to use reason and empirical inquiry to solve it, acquaint you with Francis Crick, explain how he relates to this quest, make a confession, and end on a sad note

I can't tell you what it really is, I can only tell you what it feels like.

—Eminem, “Love the Way You Lie” (2010)

It was an everyday occurrence that set my life on a new path. I had already taken an aspirin, but the toothache persisted. Lying in bed, I couldn't sleep because of the pounding in my lower molar.

Trying to distract myself from this painful sensation, I wondered how it came to hurt so much. I knew that an inflammation of the tooth pulp sends electrical activity up one of the branches of the trigeminal nerve, which ends in the brain stem. After passing through further relays, nerve cells in a part of the neocortical gray matter just beneath the skull become active and discharge their electrical impulses. Such bioelectrical activity in this part of the brain goes hand in hand with the consciousness of pain, including its awful, aching feeling.

But wait. Something profoundly inexplicable just happened. How can activity in the brain trigger feelings? It's just squishy stuff. How can mere meat, as cyberpunk novels dismissively refer to the body, engender sentience? Putting it more generally, how can anything physical give rise to something nonphysical, to subjective states? Whether it is the pain that I experienced on a distant summer day on the Atlantic shore, the joy I feel upon seeing my children, or the taste of a sparkling Vouvray, all have the same problematic origin in agitations of nervous matter.

It is problematic because of the seemingly unbridgeable gap between the nervous system and its interior view, the sensations that it generates. On the one hand is the brain, the most complex object in the known universe, a material thing subject to the laws of physics. On the other hand is the world of awareness, of the sights and sounds of life, of fear and anger, of lust, love, and ennui.

These two worlds are closely related—as a stroke or a strong blow to the head demonstrates dramatically. Oscar Wilde expressed it poetically, “It is in the brain that the poppy is red, that the apple is odorous, that the skylark sings.” But exactly how does this transformation happen? How does the brain construct conscious experience? Through its shape, its size, its activity, its complexity?

Consciousness does not appear in the equations that make up the foundations of physics, nor

chemistry's periodic table, nor in the endless ATGC molecular sequences of our genes. Yet both of us—I, the author of these lines, and you, the reader—are sentient. That is the universe in which we find ourselves, a universe in which particular vibrations of highly organized matter trigger conscious feelings. It seems as magical as rubbing a brass lamp and having a djinn emerge who grants three wishes.

I am a nerd. As a kid, I built my own home computer to implement the Boolean laws of logic. I would lie awake in bed, designing elaborate tunnel-boring machines in my mind. So, it was natural for me to wonder during my toothache whether a computer could experience pain. Suppose that I coupled a temperature sensor to my laptop and programmed it in such a manner that if the room became too hot, the word "pain" would appear on its screen in big red letters. But would "pain" feel like anything to my Mac? I'm willing to grant many things to any Apple product, especially its coolness, but not sentience.

But why not? Is it because my laptop operates on different physical principles? Instead of positively and negatively charged sodium, potassium, calcium, and chloride ions sloshing into and out of nerve cells, electrons flow onto the gates of transistors, causing them to switch. Is that the critical difference? I don't think so, for it seems to me that, ultimately, it must be the functional relationships of the different parts of the brain to each other that matter. And those can be mimicked at least in principle, on a computer. Is it because people are organic, made out of bones, muscles, and nerves, whereas computers are synthetic, built out of titanium, copper wire, and silicon? That doesn't appear critical, either. So perhaps it is because humans evolved by chance and necessity, whereas machines were explicitly designed? The evolutionary history of animals is radically different from that of digital machines, a difference that is reflected in their distinct architecture. But I don't see how that affects whether one or the other is conscious. It has got to be the physical state of the system right now that makes a difference, not how it got to be the way it is.

What is the difference that makes a difference?

In philosophy, the difficulty of explaining why somebody can feel anything is often referred to as the *Hard Problem*. The term was coined by the philosopher David Chalmers. He made his reputation in the early 1990s by a closely argued chain of reasoning, leading him to conclude that conscious experience does not follow from the physical laws that rule the universe. These laws are equally compatible with a world without consciousness or with a different form of consciousness. There will never be a reductionist, mechanistic account of how the objective world is linked to the subjective one. The term Hard Problem, with its capital H, as in "Impossibly Hard," subsequently went viral. Nobody disputes that the physical and the phenomenal worlds are closely linked in billions of people every day of their lives, but why this should be so is the puzzle.

Dave taught me an important lesson about philosophers. I had invited him to speak in front of a neurobiological and engineering audience. Afterward, over a bottle of wine, I was astounded when he insisted that no empirical fact, no discovery in biology or conceptual advance in mathematics, could dissuade him of this unbridgeable gap between the two worlds. The Hard Problem was not amenable to any such advances. I was aghast. How could mere words, without the benefit of either

mathematical or a physico-empirical framework, establish anything with that degree of certainty? To me, he had a powerful argument, but certainly no proof.

Since then, I have encountered numerous philosophers who are utterly convinced of the truth of their ideas. Such confidence in one's own ideas—without being fazed by the myriad competing ideas of others, who can't all be right—is rare among natural scientists. Because of our constant experimental confrontation with messy Mother Nature, who forces us to modify our most brilliant and aesthetically pleasing theories, we've learned the hard way to not place too much trust in any one idea until it is established beyond a reasonable doubt.

Still, at some unconscious level, those arguments had an effect on me. They suggested that in seeking to understand the phenomenal world, science had finally met its match, that consciousness was resistant to rational explanation, immune to scientific analysis, beyond the ken of empirical validation. This was the entry point for religion. Religion has an intuitive, plausible explanation for the phenomenon of mind: We are conscious because we have an immaterial soul, our true, inner self. The soul is part and parcel of a transcendental reality, above and beyond the categories of space and time and causality. This soul strives to be united with God at the end of time. These were the traditional answers that I, growing up in a devout Roman Catholic family, was raised to believe in.

Religion and science are two modes of understanding the world, its origin, and its meaning. Historically, they have opposed each other. Ever since the beginning of the Age of Enlightenment, religion in the West has been in retreat, losing one battle after another. One setback was the Copernican revolution, which removed Earth from the center of the universe to the distal reaches of a galaxy containing a hundred billion stars. But the worst blow was delivered by Darwin's theory of evolution by natural selection. It removed humans from their God-given dominion over Earth and replaced the epic story of *Genesis* with a tale stretching across the eons, full of sound and fury signifying nothing. Evolution dethroned humans from their exalted position; we are but one species among innumerable others. In the molecular signature of our genes we can trace our descent from the primate lineage and, in the remoteness of deep time, from pond scum.

As a consequence, much religious doctrine is incompatible with the modern world view. This mismatch should not be surprising, as the myths and doctrines that underpin the great monotheistic religions were formed at a time when little was known about the size, age, and evolution of Earth and the organisms populating it.

Many people believe that science leaches meaning out of human actions, hopes, and dreams, leaving desolation and emptiness in their place. The pioneering molecular biologist Jacques Monod expressed this forlorn sentiment chillingly:

Man must at last wake up out of his millenary dream and discover his total solitude, his fundamental isolation. He must realize that, like a gypsy, he lives on the boundary of an alien world; a world that is deaf to his music, and as indifferent to his hopes as it is to his sufferings and his crimes.

During my college days, this epigram, together with equally icy fragments by Friedrich Nietzsche and others, decorated the walls of my dormitory room. Eventually, I rebelled against this expression of existential, cosmic indifference.

At this point I have a confession to make. With perfect hindsight, I now realize that what drew me to studying consciousness was a compelling and entirely subterranean desire to justify my instinctive belief that life is meaningful. I thought that science could not explain how feelings came into the world. By giving the study of consciousness my all and failing in this endeavor, I was going to demonstrate to my own satisfaction that science is inadequate to the task of fully understanding the nature of the mind–body divide, that it cannot explain the essential mystery at the heart of phenomenal existence, and that Monod’s desolate sentiments were misguided. In the end, this is not how it turned out. And so my toothache set me on a course to explore the seas of consciousness, with the Hard Problem as my lodestar.

I started studying the mind–body problem with Francis Crick, the physical chemist who, with James Watson, discovered the double-helical structure of DNA, the molecule of heredity, in 1953. This singular event, which ushered in the era of molecular biology, is the best documented and most celebrated example of a revolutionary scientific discovery. It was lauded with a Nobel Prize in 1962.

As recounted in *The Eighth Day of Creation*, Horace Freeland Judson’s brilliant history of molecular biology, Francis subsequently established himself as the field’s chief intellect. It was not only him and his theoretical ideas that others looked for guidance in the exuberant and giddy race toward deciphering the universal code of life. When that goal was achieved, Francis’s interest shifted from molecular biology to neurobiology. In 1976, at the age of sixty, he plunged into this new field while simultaneously moving from Cambridge in the Old World to California in the New World.

Over sixteen years, Francis and I wrote two dozen scientific papers and essays together. All of them focused on the anatomy and physiology of the primate brain and their link to consciousness. When we started this labor of love in the late 1980s, writing about consciousness was taken as a sign of cognitive decline. Retired Nobel laureates could do it, as could mystics and philosophers, but not serious academics in the natural sciences. Betraying an interest in the mind–body problem beyond that of a hobby was ill-advised for a young professor, particularly one who had not yet attained tenure. Consciousness was a fringy subject: graduate students, always finely attuned to the mores and attitudes of their elders, rolled their eyes and smiled indulgently when the subject came up.

But those attitudes changed. Together with a handful of colleagues—Bernie Baars, Ned Block, David Chalmers, Jean-Pierre Changeux, Stanislas Dehaene, Gerald Edelman, Steven Laureys, Geraint Rees, John Searle, Wolf Singer, and Giulio Tononi, to mention a few—we gave birth to a science of consciousness. Though still inchoate, that new science represents a true paradigm shift and a consensus that consciousness is a legitimate topic of scientific investigations.

The midwife attending its birth was the fortuitous development of brain-imaging techniques allowing the human brain to be safely and routinely visualized in action. Those techniques have had an electrifying effect on popular culture: Magnetic resonance imaging (MRI) images of the brain with their telltale hot spots, are iconic. They can be found on the covers of magazines, on T-shirts, and in movies.

Studying the biological basis of awareness has turned into a mainstream, legitimate subject of inquiry.

For the past two-and-a-half decades, I have mentored a group of two dozen students, postdoctoral fellows, and staff at the California Institute of Technology (Caltech) who are focused on such research. I've worked with physicists, biologists, psychologists, psychiatrists, anesthesiologists, neurosurgeons, engineers, and philosophers. I have participated in countless psychology tests. I have had my brain zapped with pulses of strong magnetic fields and with weak electric currents, stuck my head into MRI scanners to see what is inside my cranium, and had my brain waves recorded while I slept.

In this book, I highlight stories from the front lines of modern research into the neurobiology of consciousness. Just as light presupposes its absence, darkness, so consciousness presupposes the unconscious. As Sigmund Freud, Pierre Janet, and others realized in the late nineteenth century, much of what goes on in our head is inaccessible to our mind—is not conscious. Indeed, when we introspect, we routinely deceive ourselves, because we only tap into a minute fraction of what is going on in our head. This deception is why so much of philosophy about the self, the will, and other aspects of our mind has been barren for more than two thousand years. Yet, as I shall describe, the unconscious can profoundly influence our behavior. I also dwell on the related problem of free will, the feeling of having initiated an action, and on how physics, psychology, and neurosurgery are untangling this metaphysical knot. Without much fanfare, discoveries in these fields have solved key aspects of the free will problem.

Finally, I describe a plausible quantitative theory of consciousness that explains why certain types of highly organized matter, in particular brains, can be conscious. The theory of *integrated information*, developed by the neuroscientist and psychiatrist Giulio Tononi, starts with two basic axioms and proceeds to account for the phenomenal in the world. It is not mere speculative philosophy, but leads to concrete neurobiological insights, to the construction of a consciousness meter that can assess the extent of awareness in animals, babies, sleepers, patients, and others who can't talk about their experiences. The theory has profound consequences that bear some resemblance to the prophetic ideas of Pierre Teilhard de Chardin (more of him later).

Discoveries in astronomy and cosmology reveal that the laws of physics are conducive to the formation of stable, heavy elements beyond hydrogen and helium. These laws are amazingly fine-tuned and require a precise balancing of the four fundamental physical forces. Otherwise, our universe would never have gotten to the stage where hydrogen and helium assembled into huge, flaming masses—long-lived stars that provide an endless stream of energy to the rocky planets orbiting them. The stuff out of which these planets and their skin of soil, rock, and air is made—silicon, oxygen, and so on—was created inside the nuclear furnaces of the first generation of stars and dispersed into the surrounding space during their explosive death throes. We are, quite literally, star dust. This dynamic universe is governed by the second law of thermodynamics: The entropy of any closed system never decreases; or, in other words, the universe is unfolding to be maximally disordered and uniform. But this does not preclude the formation of stable islands of order that feed upon the surrounding ocean of free energy. The relentless operation of this law created the statistical certainty that on some such isles in the cosmos, long-chained, complex molecules would eventually arise.

Once this crucial step occurred, the next one was likely to happen as well: genesis—the creation of life in a cave or pond on the primordial Earth and elsewhere, under alien skies. The ever-increasing complexity of organisms, evident in the fossil record, is a consequence of the unrelenting competition for survival that propels evolution.

It was accompanied by the emergence of nervous systems and the first inkling of sentience. The continuing *complexification* of brains, to use Teilhard de Chardin's term, enhanced consciousness until self-consciousness emerged: awareness reflecting upon itself. This recursive process started millions of years ago in some of the more highly developed mammals. In *Homo sapiens*, it had achieved its temporary pinnacle.

But complexification does not stop with individual self-awareness. It is ongoing and, indeed, speeding up. In today's technologically sophisticated and intertwined societies, complexification is taking on a supra-individual, continent-spanning character. With the instant, worldwide communication afforded by cell phones, e-mail, and social networking, I foresee a time when humanity's teeming billions and their computers will be interconnected in a vast matrix—a planetary *Übermind*. Provided mankind avoids Nightfall—a thermonuclear Armageddon or a complete environmental meltdown—there is no reason why this web of hypertrophied consciousness cannot spread to the planets and, ultimately, beyond the stellar night to the galaxy at large.

Now you know why the neuropsychologist Marcel Kinsbourne calls me a *romantic reductionist*, because I seek quantitative explanations for consciousness in the ceaseless and ever-varied activity of billions of tiny nerve cells, each with their tens of thousands of synapses; romantic because of my insistence that the universe has contrails of meaning that can be deciphered in the sky above us and deep within us. Meaning in the sweep of its cosmic evolution, not necessarily in the lives of the individual organisms within it. There is a *Music of the Spheres*, and we can hear snatches of it, perhaps even a hint of the whole form of it, if we but listen closely.

The subtitle of this book contains the promissory word “confessions.” In the evolution of the genre, from Saint Augustine, who invented it in the twilight years of the Roman Empire, to today's talk and reality shows, there has always been a whiff, if not a stench, of the exhibitionist, the self-serving, and the mendacious. I intend to stay clear of those malodorous corruptions. I also write the face of a powerful professional edict against bringing in subjective, personal factors. This taboos is why scientific papers are penned in the desiccated third person: “It has been shown that. . . .” Anything to avoid the implication that research is done by flesh-and-blood creatures with less than pristine motivations and desires.

In the following pages, I'll tell you about myself insofar as my life is relevant to the question: Why was I motivated—consciously or otherwise—to pursue certain problems? And, why did I adopt a particular scientific stance? It is, after all, in the choice of what we work on that we reveal much about our inner drives and motives.

In the past few years, as the arc of my life has begun its inevitable decline, I've lost my way. Passions that I could not, or would not, control led to a profound crisis that forced me to confront my beliefs and my inner demons. Dante's opening stanza in his *Inferno* describes it perfectly:

Midway in the journey of our life

I came to myself in a dark wood,

for the straight way was lost.

But before I engage too much in such late-night matters, let me tell you a bit about my early life that is relevant to my science and to the way I view the brain.

Chapter 2:

In which I write about the wellsprings of my inner conflict between religion and reason, why I grew up wanting to be a scientist, why I wear a lapel pin of Professor Calculus, and how I acquired a second mentor late in life

Consider ye the seed from which ye sprang;
Ye were not made to live like unto brutes,
But for pursuit of virtue and of knowledge.
So eager did I render my companions,
With this brief exhortation, for the voyage,
That then I hardly could have held them back.
And having turned our stern unto the morning,
We of the oars made wings for our mad flight,
Evermore gaining on the larboard side.
—Dante Alighieri, *Inferno* (1531)

I grew up happy, obsessed with knowledge, structure, and order. My two brothers and I were raised by our parents in the best liberal Catholic tradition, in which science—including evolution by natural selection—was by and large accepted as explaining the material world. I was an altar boy, reciting prayers in Latin and listening to Gregorian chants and the masses, passions, and requiems of Orlando de Lassus, Bach, Vivaldi, Haydn, Mozart, Brahms, and Bruckner. During summer vacations, our family traveled to sightsee a countless stream of museums, castles, and baroque and rococo churches. My parents and older brother gazed in admiration at ceilings, stained-glass windows, statues, and frescos depicting religious imagery while my mother read aloud, for the benefit of us all, the detailed history of each object. Although I found this forced diet of art excruciatingly boring, and can't quite suppress a shudder even today when I see the three-volume art guide on my mother's bookshelf, I fell in love with the magical intonations of centuries-old Roman prayers and the sacred and profane music of these composers.

Mother Church was an erudite, globe-spanning, culturally fecund, and morally unassailable institution with an unbroken lineage extending across two millennia to Rome and Jerusalem. I

catechism offered a time-honored and reassuring account of life that made sense to me. So strong was the comfort religion provided that I passed it on. My wife and I raised our children in the faith, baptizing them, saying grace before meals, attending church on Sundays, and taking them through the rite of First Communion.

Yet over the years, I began to reject more and more of the church's teachings. The traditional answers I was given were incompatible with a scientific world view. I was taught one set of values by my parents and by my Jesuit and Oblate teachers, but I heard the beat of a different drummer in books, lectures, and the laboratory. This tension left me with a split view of reality. Outside of mass I didn't give much thought to questions of sin, sacrifice, salvation, and the hereafter. I reasoned about the world, the people in it, and myself in entirely natural terms. These two frameworks, one divine and one secular, one for Sunday and one for the rest of the week, did not intersect. The church provided meaning by placing my puny life in the context of the vastness of God's creation and his Son's sacrifice for humankind. Science explained facts about the actual universe I found myself in and how it came to be.

Harboring two distinct accounts, one for the supralunar and one for the sublunar world, to use beautiful Aristotelian imagery, is not a serious intellectual stance. I had to resolve the conflict between these two types of explanations. The resultant clash was my constant companion for decades. Yet I always knew that there is but a single reality out there, and science is getting increasingly better at describing it. Humanity is not condemned to wander forever in an epistemological fog, knowing only the surface appearance of things but never their true nature. We can see something; and the longer we gaze, the better we comprehend.

It is only in recent years that I have managed to resolve this conflict. I slowly but surely lost my faith in a personal God. I stopped believing that somebody watches over me, intervenes on my behalf in the world, and will resurrect my soul beyond history, in the eschaton. I lost my childhood faith, yet I've never lost my abiding faith that everything is as it should be! I feel deep in my bones that the universe has meaning that we can realize.

A Carefree Childhood as a Budding Scientist

My father had studied law, joined the German foreign service, and became a diplomat. My mother was a doctor and worked for a few years in a hospital. She gave up her career for the sake of her husband, channeling her considerable ambitions into us children.

I was born in 1956 in Kansas City, Missouri, one year after my brother Michael. Today, you can tell my Midwestern origin, as I retain a fairly strong German accent. We left two years later and started a peripatetic existence, staying four years in Amsterdam, where my younger brother, Andrea, was born. Subsequently, our family lived in Bonn, then the capital of West Germany. After elementary public school and two years at a Jesuit *Gymnasium*, it was time to move back across the Atlantic, to Ottawa. I learned English in a school run by a Catholic religious order. But not for long; for three years later it was to be Rabat, Morocco. I enrolled in the French school in that North

African country, the thoroughly secular *Lycée Descartes* (which may explain my enduring fondness for that particular philosopher). Despite the constant changes of place, school, and friends, and the need to master a third language, I did well, graduating in 1974 with a baccalaureate in mathematics and sciences.

I am fortunate in that I knew from an early age what I wanted to be when I grew up. As a child I dreamt of being a naturalist and zoo director, studying animal behavior on the Serengeti. Around the onset of puberty, my interests shifted to physics and mathematics. I consumed a steady diet of popular books about space travel, quantum mechanics, and cosmology. I loved the paradoxes of relativistic travel, of falling past the time horizon into a black hole, space elevators, and so on. I have fond memories of reading the whimsical *Mr. Tompkins in Wonderland* by George Gamow, in which the hero explores a surreal world where the speed of light can be reached by a cyclist. Or *Mr. Tompkins Explores the Atom*, in which Planck's constant, the number that describes the size of quanta of action, is so large that billiard balls show quantum behavior. These books molded my teenage mind. Each time I bought a science paperback with my weekly allowance, I lovingly inscribed my name in it and cherished it, carrying it around everywhere, reading it whenever I could.

My parents furthered my scientific curiosity by giving Michael and me experimental design sets from the German brand *Kosmos*. These were refined toys, to teach physics, chemistry, electronics, and astronomy via a series of do-it-yourself experiments. One set started with the basic laws of electricity, went from there to the assembly of an electromagnetic relay and an induction motor, and ended with my building an AM and then an FM radio receiver. I spent hours and hours messing around with the electronics, the kind of hardware hacking that today's kids rarely experience. Another set taught the principles of inorganic chemistry. I used my freshly acquired know-how to mix black powder. When I constructed a bazooka, and the metal rod that was supposed to guide the rocket melted (the propellant didn't ignite fast enough), my father intervened, aborting my short-lived career as a weapons designer. In the process, he probably saved my limbs and eyes.

My father bought us a 5-inch reflector telescope, an awesome instrument. I vividly remember one night on the rooftop of our house in Rabat, when Michael and I calculated the position of Uranus on a star map to the background strains of Wagner's *The Flying Dutchman*. What elation I felt when pointing the scope to the estimated azimuth and elevation in the sky, the shimmering planet gently drifted into view. What a terrific confirmation of order in the universe!

During my North African sojourn, I became permanently enchanted by the adventures of Tintin, the Belgian boy whose official job is reporter but who is really an explorer, detective, and all-around hero; his white Fox Terrier, Snowy (Milou in the original French); his boisterous friend Captain Haddock; and the mad scientist, resident genius, brilliant but absent-minded, and nearly deaf Professor Calculus. These were the first cartoon characters I encountered, because my parents frowned upon comics as being either too childish or too crass. I have given every one of the twenty-four Tintin books to my children, who love them too, with no apparent ill effect. Tintin posters even grace the hallway of my house. Professor Calculus is the archetype of the otherworldly scholar who understands the secrets that hold the universe together, yet who is a klutz when dealing with the everyday world. He had such a formative effect on my young mind that I have worn a pin with his

figure on the lapel of my jacket since the day in April 1987 when I gave my inaugural lecture as professor.

Growing up in different countries, attending different schools, and learning different languages allowed me, more so than my less mobile friends, to see beyond the peculiarities and distinctiveness of any one culture and appreciate the underlying universal traits. This was one of many formative reasons that made me, by the time I left home, want to be a physicist.

In 1974, I enrolled at the University of Tübingen, in southwest Germany. Tübingen is a quaint small academic town built around a castle, much like its better-known rival, Heidelberg. At this university I experienced the fellowship of a band of brothers in a fencing fraternity. If you are not steeped in Teutonic academic traditions, think of the Boy Scouts transposed to a romantic, 500-year-old university to get some idea of what I mean. I also became acquainted with and indulged in, sometimes excessively so, the pleasures and perils of alcohol, women, dancing, Friedrich Nietzsche and Richard Wagner. I spent the first Christmas away from home—a friend and I sequestered ourselves in a remote village, enraptured by our readings of *Thus Spoke Zarathustra* and the lyrics and music of *Tristan and Isolde* and *Der Ring des Nibelungen*. I was young, immature, and nerdy, and I needed to take this voyage of self-discovery through the noisy and glorious confusion of life.

In 1979, I graduated from the University of Tübingen with a master's degree in physics. On the way, I had acquired a minor in philosophy, which led me to idealism, the form of monism which teaches that the universe is but a manifestation of the mind.

By then it had dawned on me that I didn't quite have the mathematical skills necessary to be a world-class cosmologist. Fortunately, around that time I became enthralled by computers. What attracted me was their promise of creating a self-contained virtual world under my complete control. Within their simplified environment, all events follow the rules—the algorithm—laid down by the programmer. Any deviation can always be traced back to faulty reasoning or incomplete assumptions. If a program didn't work, you had nobody to blame but yourself and yourself alone. I wrote programs, initially on punched cards submitted to the university's centralized computer, in Algol and assembler language for astrophysicists and nuclear physicists.

Studying the Biophysics of Nerve Cells

I also became utterly fascinated with the notion that the brain is a kind of computer, processing information. This obsession was triggered by an inspirational book, *On the Texture of Brain: Neuroanatomy for the Cybernetically Minded*, written by the German-Italian anatomist Valentino Braitenberg. Valentino has a larger-than-life personality, living proof that one can be a great scientist, an esthete, a musician, a bon vivant, and a *mensch*, all at the same time.

Valentino was a director at the Max Planck Institute for Biological Cybernetics in Tübingen. Through him, I found a job writing code for the Italian physicist Tomaso Poggio at the institute. Tommy, as everybody calls him, is one of the world's great theoreticians of information processing.

He invented the first functional formula for extracting stereo depth from two disparate views of the same scene. Under his guidance, I did my thesis work, modeling on a computer how the excitatory and inhibitory synapses placed on a single nerve cell interact with each other.

Let me briefly digress to explain a couple of basic concepts that occur throughout this book. Like all organs, the nervous system is made out of billions of networked cells, the most important of which are neurons. Just like there are kidney cells that are quite distinct from blood or heart cells, there are different types of neurons, maybe as many as a thousand. The most important distinction between them is whether they excite or inhibit the neurons they are connected to. Neurons are highly diverse and sophisticated processors that collect, process, and broadcast data via synapses, or contact points with other nerve cells. They receive input via their finely branched dendrites, which are studded with thousands of synapses. Each synapse briefly increases or decreases the electrical conductance of the membrane. The resultant electrical activity is translated, via sophisticated membrane-bound machinery in the dendrites and the cell body, into one or more all-or-none pulses—the fabled action potentials, or spikes. Each of these pulses is about one-tenth of a volt in amplitude and lasts less than one-thousandth of a second. These pulses are sent along the neuron's output wire—the axon, which connects to other neurons via synapses. (Some specialized neurons send their output to muscles.) Thus, the circle closes. Neurons talk to other neurons via synapses. This is the habitat of consciousness.

The power of the nervous system is found not in the snail-like speed of its components, but in its massive parallel communication and computation capabilities: its ability to link very large and highly heterogeneous coalitions of neurons over large distances in very specific synaptic patterns. As I would demonstrate thirty years later, it is out of these patterns that our thoughts arise. Synapses are analogous to transistors. Our nervous system has perhaps 1,000 trillion synapses linking about 80 billion neurons.

Under Tommy's guidance, I solved the differential equations that describe how the electric charge inside and outside of the membrane surrounding a nerve cell is transformed by the branching pattern of its dendrites and the architecture of its synapses. Today, such modeling is routine and well-respected, but back then biologists were baffled by the use of physics to describe events in the brain. At the first national meeting where I presented my research in the form of a poster to other scientists, I was quarantined to the back of the conference hall. Only two visitors came by, one of whom was looking for the bathroom but was polite enough to stay and talk to me. I got drunk that night wondering whether I had chosen the right field. Despite such setbacks, I graduated in 1982 with a Ph.D. in biophysics.

During my years as a doctoral candidate, I fell in love with and married Edith Herbst. Edith is a nurse, born and raised in Tübingen. While pregnant with our son, Alexander, she typed my thesis into the institute's mainframe (with a 128-kilobyte core memory!). When my thesis advisor, my *Doktorvater* as we say endearingly in German, became a professor at the Massachusetts Institute of Technology (MIT), we followed him to Cambridge. Twenty-five years old, I was starting off in a foreign country as a postdoctoral fellow.

MIT was an intellectual blast. I stayed for four years in the Department of Psychology and the Artificial Intelligence Laboratory. I was free to pursue science, pure and simple. Remaining so long with the same advisor is irregular, but it worked out well for my career. Tommy and I continue to interact today, a testament to the longevity of the link between doctor-father and son.

Caltech, Teaching, Research, and the Brain Viewed by a Physicist

In fall 1986, I moved farther west with my family—enlarged by a daughter Gabriele—arriving at the California Institute of Technology as an assistant professor of biology and engineering. Caltech, one of America's most selective, hard-core science and engineering universities, lies in Pasadena, a suburb of Los Angeles. It is crisscrossed by broad avenues lined with palm, orange, and oak trees, nestled at the foot of the San Gabriel Mountains. I was immensely proud of joining Caltech's faculty.

Caltech is a nimble, private university—about 280 professors and 2,000 undergraduate and graduate students—dedicated to educating the best and brightest in logic, mathematics, and how to reason about the natural world. Caltech and its people embody everything that is great and noble about universities—institutions that have been in existence for eight hundred years. It is an ivory tower in the best sense of the term, affording ample freedom and resources to pursue the nature of consciousness and the brain.

The first thing anybody asks when they find out that I'm a professor is, "What do you teach?" In the eye of the public, a professor is fully defined by his or her traditional role as a teacher. I enjoy "professing" and teach a variety of classes. Instructing brilliant and motivated students who have no hesitation in pointing out errors or inconsistencies is an intellectual challenge of the highest order and emotionally rewarding. Time and again I've had insights while preparing my lectures or answering questions in class that illuminated a well-worn problem from an unexpected angle.

Yet the members of my tribe derive their self-esteem and sense of worth principally from their research. Where we are in the tribal hierarchy is determined by how successful our investigations are. Research is what drives us and is our greatest source of pleasure. The yardstick used to gauge success is the number and quality of our publications in high-profile, peer-reviewed, and hypercompetitive scientific journals.

The greater the impact our discoveries have in this rarefied world, the bigger our reputation. Teaching plays only a minor role in the field's collective self-image. We professors spend the bulk of our time on investigations—thinking, reasoning and theorizing, computing and programming, talking thru ideas with colleagues and co-workers, reading the commodious literature, contributing ourselves to it, speaking at seminars and conferences, generating the countless grant proposals that feed the research machinery and keep it lubricated, and, of course, supervising and mentoring students and postdoctoral fellows who design, fabricate, measure, shake, stir, image, scan, record, analyze, program, debug, and compute. I'm the chieftain of a band of about two dozen such researchers.

Besides characterizing selective visual attention and visual consciousness—more on that later—we continue to investigate the biophysics of neurons. The brain is a highly evolved organ, yet it also a physical system that obeys ironclad laws of conservation of energy and of electrical charge. Gauss's and Ohm's laws regulate the distribution of charges inside and outside of nerve cells and their associated electric fields. All the synaptic and spiking processes described above contribute to the electrical potential that is picked up by electrodes stuck into the brain's gray matter. If tens of thousands of neurons and their millions of synapses are active, their contributions add up to something called the local field potential. The distant echo of this electrical activity is visible in the never-ceasing peaks and troughs recorded outside the skull by an electroencephalograph (EEG). The local field potential, in turn, feeds back onto individual neurons. We are now learning that this feedback forces neurons to synchronize their activity.

This reciprocal interaction between the local action of neurons and the global field they collectively produce and are enveloped by is very different from electronic silicon circuits, whose designers lay out wires, transistors, and capacitances to avoid interference with each other, keeping "parasitic" cross-talk at a minimum. I'm very interested in the brain's electrical field, how much information is carried by this field, and its possible role in consciousness.

What is striking to a physicist studying the brain and the mind is the absence of any conservation laws: Synapses, action potentials, neurons, attention, memory, and consciousness are not conserved in any meaningful sense. Instead, what biology and psychology do have in exuberant abundance are empirical observations—facts. There is no unifying theory, with the singular exception of Darwin's theory of evolution by natural selection—and although it is an exceedingly powerful explanatory framework, evolutionary theory is open-ended, and not predictive. Instead, the life sciences have lots of heuristics, semi-exact rules, that capture and quantify phenomena at one particular organismic scale—such as the biophysical modeling that I worked on for my thesis—without aspiring to universality. That makes research in these fields quite different from physics.

Once More unto the Breach of Consciousness

When I started off in California, I became reacquainted with Francis Crick. I first encountered him lying under an apple tree in an orchard outside of Tübingen in the summer of 1980. Francis had come to town to talk—his favorite activity—with Tommy about our ongoing dendritic and synaptic modeling work.

Four years later and on another continent, Francis had invited me and Shimon Ullman, a computer scientist at MIT's Artificial Intelligence Laboratory, to the Salk Institute for five days. Francis wanted to know everything about a model of selective visual attention that Shimon and I had just published. Why this particular wiring scheme? How many neurons were involved? What was the average firing rate? How many synapses did they form? What was their time constant? To what part of the thalamus did their axons project? Could that account for the celerity of the behavioral response? This went on and on from breakfast until late afternoon. A break was followed by dinner

and more conversations focused on the brain. No idle chatter for Francis. It left me breathless. I admired how his wife, Odile, dealt with this intensity for decades.

A couple of years later, Francis and I started to collaborate, with daily phone calls, letters, e-mail, and monthly extended stays at his hillside home in La Jolla, a two-hour drive south of Caltech. The focus of our work was consciousness. Although generations of philosophers and scholars had tried in vain to solve the mind–body problem, we believed that a fresh perspective from the vantage point of the neurosciences might help unravel this Gordian knot. As a theoretician, Francis’s methods of inquiry were quiet thinking, daily reading of the relevant literature—he could absorb prodigious amounts of it—and the Socratic dialogue. He had an unquenchable thirst for details, numbers, and facts. He would ceaselessly put hypotheses together to explain something, then reject most of them himself. In the morning, he usually bombarded me with some bold new hypothesis that had come to him in the middle of the night, when he couldn’t sleep. I slept much more soundly and, therefore, lacked such nocturnal insights.

In a lifetime of teaching, working, and debating with some of the smartest people on the planet, I’ve encountered brilliance and high achievement, but rarely true genius. Francis was an intellectual giant, with the clearest and deepest mind I have ever met. He could take the same information as anybody else, read the same papers, yet come up with a totally novel question or inference. The neurologist and author Oliver Sacks, a good friend of us both, recalls that the experience of meeting Francis was “a little like sitting next to an intellectual nuclear reactor I never had the feeling of such *incandescence*.” It has been said that Arnold Schwarzenegger, in his heyday as Mr. Universe, had muscles in places where other people didn’t even have places. This *bon mo* was transcribed to the rational mind, applied to Francis.

Equally remarkable was how approachable Francis was. No celebrity attitude for him. Like James Watson, I, too, have never seen Francis in a modest mood. But neither have I seen him in an arrogant mood. He was willing to talk to anybody, from lowly undergraduate student to fellow Nobel laureate, provided that the interlocutor brought him interesting facts and observations, a startling proposal, or some question he had never previously considered. It is true that he would quickly lose patience with people who spouted nonsense or didn’t understand why their reasoning was wrong, but he was one of the most open-minded savants I have ever known.

Francis was a reductionist writ large. He fiercely opposed any explanation that smacked even remotely of religion or woolly-headed thinking, an expression he was fond of using. Yet neither metaphysical sentiments nor our forty-year age difference prevented us from developing a deep and abiding mentor–student relationship. He relished the opportunity to endlessly bounce ideas off the younger man with plenty of energy, domain-specific knowledge, a love of speculation, and the temerity to sometimes disagree vigorously with him. I was very fortunate that he took a liking to me, essentially adopting me as his intellectual son.

Let me now define the problem of consciousness and describe the approach Francis and I took to explore its nature.

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