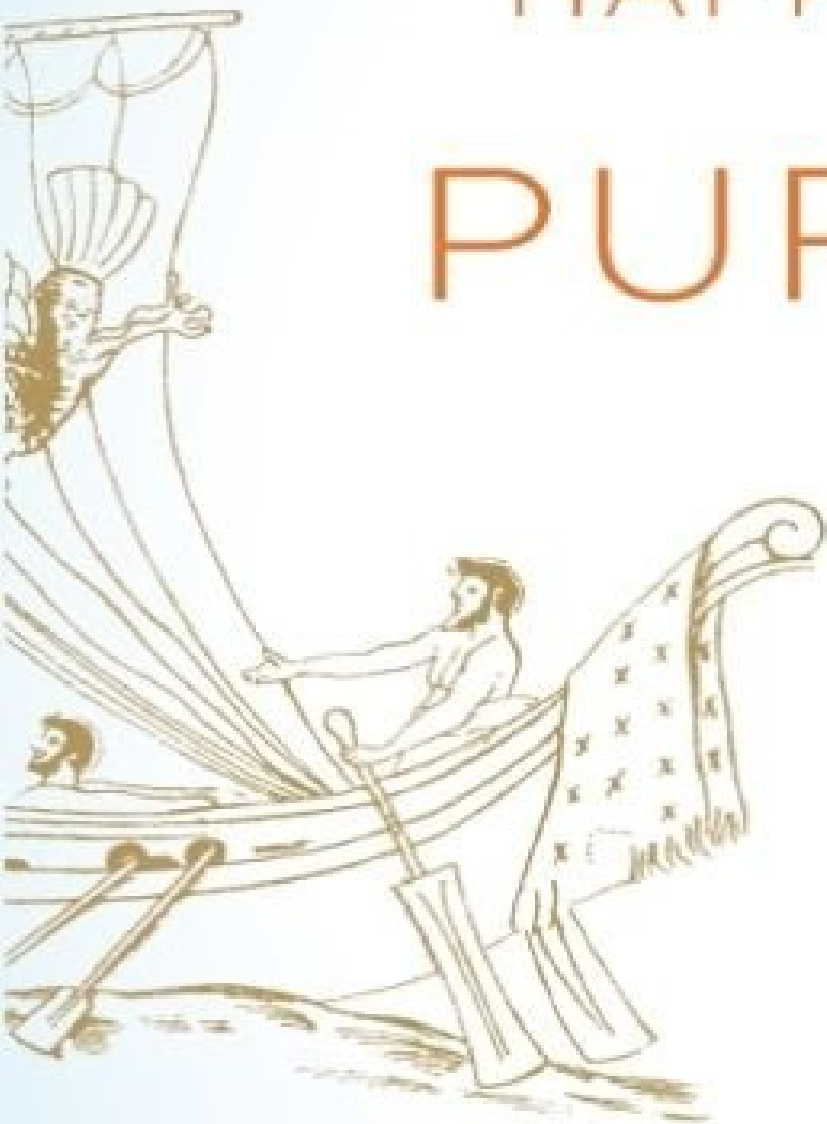


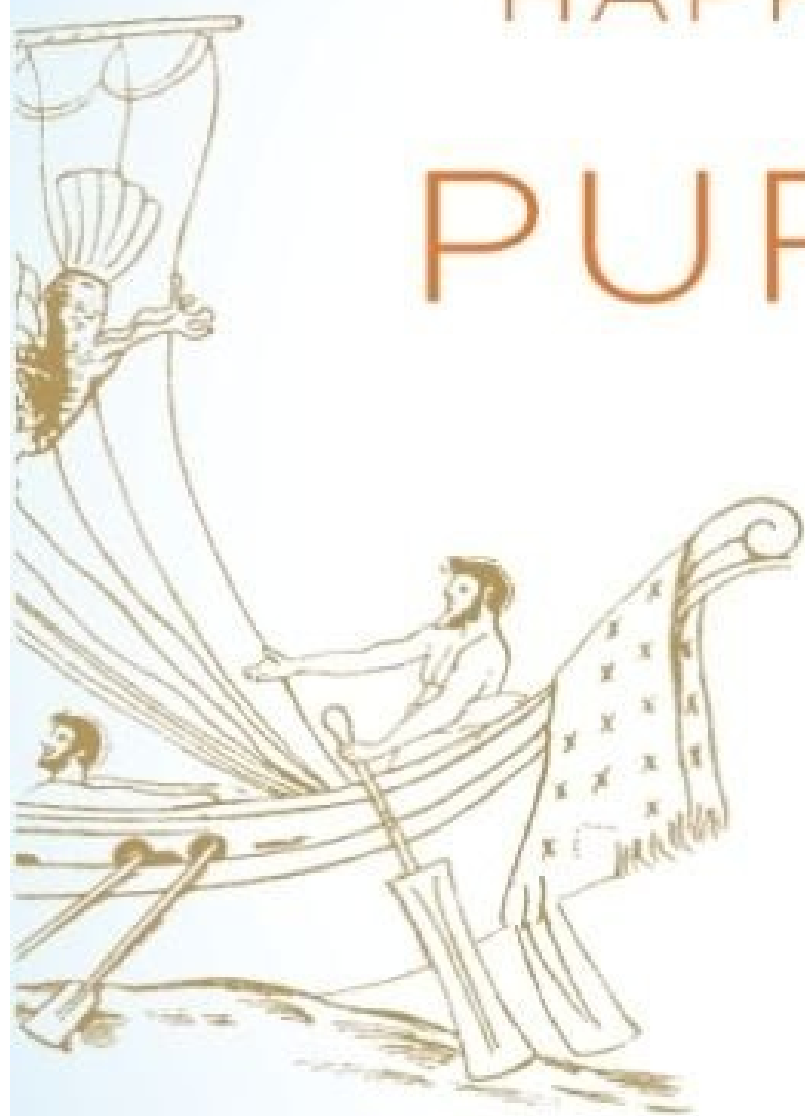
The
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What
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Can Teach Us
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*What Neuroscience
Can Teach Us about
the Good Life*

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ALSO BY SHIMON EDELMAN

Computing the Mind: How the Mind Really Works
Representation and Recognition in Vision

**TO IRA AND ITAMAR—
Teach your parents well**

AUTHOR'S NOTE

According to one popular conception of science that goes all the way back to Francis Bacon's invention of it in 1620, scientific endeavor is all about getting answers from nature. That said, given that the quality of answers one gets depends conspicuously on the quality of the questions one asks, scientific inquiries lacking in intrepidity, imagination, and insight are likely to yield little more than scientifically validated tedium.

In the science of human existence, one half expects things to be easier. As someone who lives its subject matter, am I not in the best position to ask questions that go to the heart of it? And yet, it often seems to me that the real important questions hover at right angles to reality, manifesting themselves merely by a faint sense of unease or a premonition that I am about to miss the point of what is happening.

By acting swiftly and decisively, it is sometimes possible to apprehend a fleeting question and put it away for study. Here, I make a public example of four such questions, captured while stalking me on a hike through the canyon country of southern Utah:

1. A juniper tree, hanging on to a gravelly mound in a bend of the canyon until the next flash flood.
2. A set of lizard tracks in the drying mud.
3. A dusty drive toward a far trailhead, down a narrow wash bordered by steep banks, arriving at length at an impassable sand trap.
4. A butterfly.

As you can see, such questions lose little of their cunning even in captivity, where they pretend that they are not questions at all, or that they are of no concern to the busy scientist and should be released into the custody of poets or philosophers. Such guile is best overcome by setting aside the conventional divisions between science and the humanities. This is why in this book my take on the life of the mind and how to make the most of it, while decidedly scientific, is not entirely conventional.

Home Is Where the Mind Is

No justice, no peace.
A journey is mapped out.

Allons! whoever you are, come travel with me!
Traveling with me, you find what never tires.

—WALT WHITMAN,
Leaves of Grass: Song of the Open Road (1892, 82:9)

No Justice, No Peace

When I was eight years old, I read a book in which a few lines of a poem were quoted. The book was *Monday Starts on Saturday* by Arkady and Boris Strugatsky. The poem was by Christopher Logue, in a Russian translation. (I forgot to tell you that this was happening back in the USSR; the book's real title was *Понедельник начинется в субботу*.) The book, subtitled very aptly "A Fair Tale for Younger Research Scientists," was about the daily life of applied magicians who work wonders by running experiments and solving equations. Whether or not this book contributed to my own eventual choice of career, I enjoyed it immensely. The poem, in contrast, must have gone right over my head—I have no recollection of it from that reading. As I discovered much later, it was an excerpt from Logue's "Epitaph":

You ask me:
What is the greatest happiness on earth? Two things:
changing my mind
as I change a penny for a shilling;
and
listening to the sound of a young girl
singing down the road
after she has asked me the way.

In subsequent rereadings of the book (once every few years ever since that first time), I have found myself becoming more and more intrigued by the poem. Maybe this is because happiness, with which it deals so deftly, is presented in the book as a challenge to the leading character, who works as the head of the

computing center at the National Research Institute for Miracles and Magic. (Even ~~at that time I was a computer scientist myself, albeit with very little magic and no miracles at all to my credit.~~) The challenge is implicit in a complaint voiced by an elderly graduate student, Magnus, who for decades now has been writing a dissertation for the Department of Linear Happiness and who offers Logue's poem as an example of the difficulties he faces:

Magnus sighed.

—Some say one thing, others—another.

—Tough,—I said with sympathy.

—Isn't it? How would you make sense of all this? To listen to the sound of a girl singing. . . . And not just any singing, but the girl is supposed to be young, down the road from him, and that too only after having asked him the way. . . . Is this any way to behave? As if such things could be algorithmized, huh?

For many years, I let those questions be. As a little boy, I was pretty happy not understanding algorithms, or girls. As a teenager, I was too busy trying to actually get a live girl to ask me the way. (As this was still in the USSR, I was unaware that the pursuit of happiness, along with life and liberty, is an inalienable human right, or I would have felt more relaxed about it.) As a computer scientist, I may have been mildly intrigued by whether or not happiness could be captured by an algorithm, but by then I had my own dissertation to worry about. Then I became a professor of psychology (a natural career move for a certain type of computer scientist . . . stick around and you'll see why), and things gradually took an unexpected turn.

I now had an excuse to think, on company time, about anything at all having to do with the human condition—a development that made me feel like a bear that wakes from hibernation to learn that a natural foods store specializing in bulk trail mix and artisanal honey has been built over its den. My research interests, which for many years had been confined to just a couple of the mind's faculties—mostly vision, then also language—began to broaden. Having discovered the same principles at work in both, I became curious about the rest.

By then, I was teaching a big introductory course on cognition, which, I felt, had to encompass everything that's known about how the mind works. Teaching, when taken seriously, does wonders to one's capacity for critical thinking; I realized that although the existing psychology textbooks were up to the moment on facts, they were decades behind on understanding. I ended up writing a text of my own, which I subtitled "How the Mind Really Works."¹

For a while, the possibility of understanding things for myself with sufficient clarity to enable me to share my understanding with others made me vaguely happy. Then I perceived that the mandate that I claimed for myself came with a rider. If I truly grasped how the mind works, I should be able also to transcend all the usual vague intuitions about when, why, and how a person feels happy and replace them with sound scientific insight.

To my dismay, I realized that I would have no peace until the possibility of

happiness being amenable to a scientific—perhaps even algorithmic—treatment was given, if not a decisive resolution, then at least a fair hearing. This book is my attempt at cajoling my conscience into letting me off that particular hook.

A Journey Is Mapped Out

To forestall the crushing skepticism that people tend to develop soon after hearing about someone embarking on this kind of project, let me explain why I think it is both timely and feasible. In the past several decades, tremendous progress has been made in understanding the mind/brain. It turns out that the principles that determine how the brain gives rise to the mind are very general and are statable in a pretty concise form, and have everything to do with computation. Given that the brain is the organ with which people experience happiness, understanding the brain offers for the first time a real chance for understanding how and why happiness happens, and perhaps for developing some recipes—algorithms!—for pursuing it more effectively.²

The focus on the pursuit of happiness, endorsed by the Declaration of Independence, fits well with the idea of life as a journey—a bright thread that runs through the literary canon of the collective human culture.³ With the world at your feet, the turns that you should take along the way depend on what you are at the outset and on what you become as the journey lengthens. Accordingly, the present book is an attempt to understand, in a deeper sense than mere metaphorical, what it means to be human and how humans are shaped by the journey through this world, which the poet John Keats called “the vale of soul-making”—in particular, how it puts within the soul’s reach “a bliss peculiar to each one’s individual existence.”⁴

The fundamental insight that serves as the starting point for my story is that the mind is inherently and essentially a bundle of ongoing computations, the brain being one of many possible substrates that can support them. I make the case for these claims by constructing, in plain sight and out of readily available material, a conceptual toolbox that affords the reader a glimpse of the computation underlying the mind’s faculties: perception, motivation and emotions, action, memory, thinking, social cognition, and language. This conceptual building culminates in an explanation that states, in plain language, the nature of the phenomenal self and of consciousness. Readers who are interested in the details that I omit can follow the leads offered by the many notes at the end of the book.⁵

These conceptual tools prove to be useful in making new sense of the notion of the pursuit of happiness. Quite satisfyingly, it emerges that the framers of the Declaration of Independence presaged the findings of the scientific inquiry into happiness: the dynamics of the self and of happiness is such that the pursuit itself—the journey rather than the destination—is what really matters (hence the title of the book). This insight, such as it is, informs the book’s conclusion: the seeker

after happiness returns home, only to grow restless and eventually succumb to the lure of a new journey. On the basis of the understanding developed throughout the book, the following practical advice is offered as a way of summing up its lessons in seven words: when fishing for happiness, catch and release.

Computing the Mind

A great metaphor that isn't. Concerning computation. No cognition without representation. Three things everyone should know about life, the universe, and everything. Promethean probabilities and amazing Bayes. Minds within brains. Minds without brains.

And if the body were not the Soul, what is the Soul?

—WALT WHITMAN,
Leaves of Grass: I Sing the Body Electric (19:1)

A Great Metaphor That Isn't

Let me tell you a short story about the brain. The brain is the most complex object known to science. Because scientists have been unable to explain exactly how the brain gives rise to the mind, they keep resorting to technological metaphors of complexity. The best metaphors are those that draw on concepts associated with newfangled technologies, which still exude a certain aura of mystery. In the past such metaphors came from mechanics (“the brain is an intricate clockwork”) and electronics (“the brain is a vast telephone exchange”). For some time now everyone's favorite source of metaphors has been computer engineering. Still, no matter how much we like to compare brains (“meat computers”) and computers (“electronic brains”), the computer metaphor is merely the latest installment in a long series of fads to which brain science periodically succumbs.

If you find yourself liking this story, you are in good company. The “computer metaphor” view of how the mind works sounds sophisticated and modest at the same time and is particularly intellectually appealing to progressive-minded people who know their history of science and value openness toward the prospect of continued replacement of good theories by better ones. It is also popular with science writers, including those practicing cognitive scientists who are eager to share their findings and insights with anyone who is interested in how the mind works. For them, the computer metaphor offers a neat way to introduce and explain the tremendous progress made by cognitive science in the three decades since computational theorizing first started to prove uncannily effective. Better

yet, they can do so without actually calling the reader a computing machine.

But what if you really are one?

In our daily lives we routinely encounter devices that can only be understood in terms of computation. Take grocery-store cash registers as an example. These come in different sizes and colors and may rely on diverse mechanical and electronic components, but they all have one inalienable, categorical, defining feature in common: they compute. Take away a cash register's ability to compute and you're left with a heap of junk, the machine equivalent of a dead body. In the deepest possible sense, computing is what cash registers are fundamentally about. It would be intellectually irresponsible to insist that doing sums is only one among many equally valid ways of describing the function of a cash register or to argue that a cash register is only metaphorically a computing machine.

This observation sets the stage for the unveiling of what is undoubtedly both the most important and the least-kept secret of cognitive science. Although it has entire books devoted to it, this secret has so far managed to elude the attention of most of the general public and even of some cognitive scientists. It has been able to hide in plain sight because of its revolutionary implications. (We humans often blissfully ignore inconvenient truths, even as we stare them in the face.) Here is the secret, then: computation is just as much a defining feature of brains as it is of cash registers. Moreover, in both cases it is the most important such characteristic: a cash register's very existence (let alone its mechanics or electronics) can be really understood only by resorting to the concept of computation, and so can the brain's.¹

Because it takes a while to do justice to the idea that cognition is computation, let me offer you right away a few quick examples that illustrate it. My first example is as simple as black on white—the black of the print against the white of the paper in front of you. Just as all cats are black in the dark, both the paper and the print would be equally invisible if it were not for the light that illuminates the page. Intuitively, the paper reflects more of the light that falls on it than the print does, which is why the letters are seen as darker than their background. It would seem, therefore, that telling apart the print and the paper boils down to gauging the amount of light reflected from each. There is, however, a complication: the amount of light that enters your eye after hitting the page is determined by two independent factors: the quantity of light that is available to begin with (the intensity of the illumination) and the fraction that is reflected from the page (its reflectance).

To fully appreciate the challenge faced (and met!) by your visual system, even as you are reading these lines, let's state it in concrete and precise terms. (It's okay to skip the numerical example that follows if you already saw the light.) Suppose your eye is registering 100 photons per second arriving from the region of the page that you are looking at. This measurement can result from various combinations of illumination and page reflectance: for example, 10,000 photons (strong illumination) falling on it with only 1 percent of them being reflected back (low-reflectance or "dark" surface), or 125 photons (weak illumination) falling, of which 80 percent are reflected (high-reflectance or "light" surface). A quick

reflection (do try it at home!) reveals that there is an infinity of possible pairings of illumination and surface reflectance values that can give rise to the very same number of photons reaching the eye. Which pairing is the right one?

To find that out, the brain must solve a problem that is fundamentally computational: given a product of two numbers (illumination and reflectance) determine what they are individually. Your ability to perceive the ink as black and the paper as white in direct sunlight as well as in deep shade is clear evidence that your brain indeed manages to solve this inherently arithmetical problem. How it does that is beside the point for the moment.² Let's just admit, as we must, that at least one everyday perceptual task can only be solved through computation, because this task cannot even be stated without resorting to numbers (which is why I had no choice but to mention numbers while introducing it just now).

My second example involves the task of thinking. Intuitively, thinking is what follows perception (sizing up the situation you're in) and precedes action (doing something about it). Humans are pretty good at abstract thinking (witness the ability of some of us to stand up to chess-playing computers, sometimes for as long as a couple dozen moves), but it would be more useful for us to focus here on more mundane challenges, such as figuring out which register line in a supermarket checkout area to join. The simplest approach to this problem, which I personally face much more often than I play chess, is to estimate the length of each line in person-units and then to join the shortest one. Those of us with some supermarket experience are likely to see the simple head-counting approach as unsatisfactory. We know that a better estimate of the amount of time one is likely to spend standing in a line depends not only on the number of people ahead of you, but also on the number of items each of them is buying and on the efficiency of the cashier, as measured by the number of items he or she can scan and bag per minute.

This example illustrates nicely the value of thinking before doing: a few seconds spent on observing a line and thinking about what you see can save you quite a few minutes' worth of waiting time, which seems like a reasonable return on investment. During these seconds, your brain forms estimates of the number of people in line and the number of items each one has, multiplies these two numbers together, and divides the product by an estimate of the cashier's efficiency. Do it for each line you're considering, and you have the proper grounds for making an informed choice about the most promising line. Thus, at least some problems that require thinking, just like perception, reduce to the manipulation of numbers according to certain rules, in this case multiplication, division, and comparison.

My third and for now last example has to do with a drinking problem, albeit not of the kind that necessarily involves alcohol. This particular problem arises in the planning of bodily movements. Imagine yourself sitting at a dining table, with your hand around a glass of water that rests in front of you. You are thirsty, but before you can quench your thirst your brain must crunch some numbers. Because the incident that we are imagining is set in the three-dimensional space of the dining

room, it takes three numbers to specify the location of the hand that is holding the glass. If you single out one corner of the room and measure how far your hand is from each of the three surfaces (two walls and the floor) that meet at that corner, you can pinpoint its location precisely. As far as your brain is concerned, however, many more than three numbers are needed. This is because the brain does not measure or control directly the distances between your hand and the walls.

What the brain controls is the angles of the various joints of the body, of which there are many. Looking just at your upper extremities, you can count three independently controllable angles at the shoulder (direction in the horizontal plane, direction in the vertical plane, and rotation), two at the elbow, and two at the wrist. So the very formulation of the problem of planning how to get your hand with the glass from its resting position on the table to your mouth involves a whole series of pretty scary-sounding computations. First, the brain must establish a correspondence between locations specified in the “room” format (as triplets of numbers) and the same locations specified in the “body” format (as lists of seven numbers). Second, it must use this correspondence to compute the seven-number setting that would bring your hand with the glass to your mouth.

Formidable as it is, this is merely a simplified version of the actual, full-blown problem of hand movement control, which requires more than bringing the glass to your mouth (rather than, say, to your ear). For one thing, you would probably like to be able to do it without spilling the water along the way or smashing it on your teeth at the end. Let me set these complications aside and reiterate instead the key point: in the three examples offered here, the problems that arise, which I chose from the three main areas of cognition—perception, action, and what’s in between—are all inherently computational. These problems, which the brain encounters and solves as a matter of daily routine and usually outside of conscious deliberation, cannot even be stated without recourse to numbers, and the solution must therefore involve some kind of number crunching.

This realization spells a certain kind of doom for the venerable computer metaphor for the brain, with which I opened this chapter. In science, a metaphor may wither away after being made irrelevant by new insights into the phenomenon that motivated it in the first place. Alternatively, it may crystallize into an accepted explanation, if theoretical advances and empirical findings vindicate it. Such is the fate of the computer metaphor in brain science—a truly great metaphor that isn’t.

Concerning Computation

Given that the computer metaphor for the brain looks like it has the embarrassing (for a metaphor) quality of being literally true, we must make sure that we understand what computation is, if we ever want to be able to fully understand brains. Luckily, understanding the basic nature of computation does not require

degree in computer science. Contrary to what one is inclined to believe, most instances of computation in the universe happen without involving any kind of particularly complex, contrived, or specially engineered device. Computation is all around us; in fact, it is as common as anything can be, for the following simple reason: every physical process that unfolds over time computes something.

Think about it. How would a pebble that you release from your grasp be able to strike the ground precisely at the correct instant if it could not figure out—compute—its trajectory, given the acceleration of gravity and its initial position? How would a stove-top heating element be able to reach precisely the correct temperature if it could not figure out the current that flows through it, given the grid's voltage and its own resistance? In a very concrete sense, a falling pebble computes its trajectory by following Newton's laws, just as a heating element computes the current that flows through it by following Ohm's law.

There is of course nothing mysterious about objects obeying the laws of physics. On the contrary, it would be a mystery (in other words, a sign of a subtler law at work) if they did not, or if exceptions or exemptions were possible. This situation seems to be not to everyone's liking: riding a ski chairlift one winter day, I saw on a pylon an ad that began: GRAVITY: IT'S MORE OF A NUISANCE THAN A LAW—a bizarre notion, given that not just skiing but actually getting down at all from the mountain and seeing your loved ones ever again (rather than flying off screaming into space) would be impossible, were it not for gravity. Like it or not, the implacability of the laws of physics is what makes the world go round, so to speak, and in doing so carry out a vast panoply of computations.

Most of these computations are very limited in the spatial and temporal reach of their effects. Such is the fate of the computation performed by the pebble that you release and let fall to the ground. The law-abiding pebble faithfully computes its own trajectory and manages to arrive at its resting place at a precisely timed moment, yet this computation is pretty inconsequential: a few grains of sand may be kicked around, but once they settle the only readily discernible change in the state of affairs of the universe is that the pebble, which was previously in my hand, is now on the ground. Who cares?

That particular computation was useless, but it could have been otherwise, if only the fall of the pebble were to have some significant and enduring consequences or repercussions on other events. Here is how this could happen. Imagine that you are defending a castle. Your assigned post is immediately above the portcullis, and your duty is to drop an anvil onto the head of any attacker who comes too close to it. Your store of ammunition is limited (the besiegers just intercepted an inbound shipment of blacksmith supplies), and so you would like to time the release of each anvil so that it arrives at a certain small volume of space simultaneously with the head of the intended target. This can be easily arranged through practice with some pebbles. All you need to do is mark the position of the knight who is charging at the gate as you release the pebble; if the pebble then strikes the charging knight's helmet (you'll hear it), you can be reasonably sure that the next time a knight's charge takes him through the marked position you may drop the actual anvil instead of the practice pebble.

You may be surprised to realize that what I just described happens to be a ~~computer-controlled ballistic missile launch system~~. The missile is, of course, the anvil, which is ballistic by definition, because it has no onboard means of propulsion. And what about the launch-control computer? Since you are in charge of releasing and observing the pebble, you are one of its parts. Another part is the earth, whose gravity field so conveniently imparts an equal acceleration to anvils and to pebbles (as Galileo famously discovered four hundred years ago). Yet another part is the pebble that you use to simulate the anvil's projected descent. Unlike the listless, lonely pebble from the earlier example, about whose fall nobody cares, this one is lovingly tracked and the computation it carries out (just by being itself and acting naturally) is made use of. Its use lies in serving as a stand-in for or a representation of the anvil: the actual fall of the pebble, as it unfolds over time, represents the potential descent of the anvil.

Because the fall of the pebble is precisely analogous to the fall of the anvil that it represents (their trajectories unfold at exactly the same rate), the anvil-aiming computer of which the pebble is part is an analog computer. The familiar digital computers differ from analog ones in one key respect: they deal in representations that are made to correspond to their objects through some arbitrary but consistent rules rather than through direct physical analogy. A good example of a digital representation is the code agreed upon in April 1775 by Paul Revere and Robert Newman, the sexton of the Old North Church in Boston, for representing the mode of the expected British assault: one if by land, two if by sea.

There is nothing inherent in assault by land that dictates that it should be represented by one lantern in the belfry as opposed to two. It is in this sense that the Revere-Newman code is symbolic and arbitrary. Switching to a more modern example, consider how my notebook's battery meter represents the remaining charge. If I have worked for an hour since the last full charge and the meter now shows "75%," I conclude that the battery will last for three more hours. The connection between the symbols "75%" and what I take them to represent is entirely a matter of convention; the same information could have been equally well represented by the symbols "3/4." Alternatively, I can switch the battery meter from the digital representation mode to analog, in which case it would look like a little "thermometer" whose mercury is three-quarters of the way up to the maximum mark.

What is common to all these examples of representation is that some physical symbol—an object, event, or process—stands in for some other object, event, or process for the benefit of a third party. Thus, some squiggles on my notebook screen represent for me the battery level; the appearance of a lantern in a belfry conveys to Paul Revere a piece of battle intelligence; the fall of a pebble tells the castle defender how the fall of an anvil would proceed. Understanding representation gives us a crucially important conceptual handle on computation. The key insight is this: useful computation hinges on the possibility of some objects or processes representing others. Indeed, the reliance on representation is the defining characteristic of useful computation, which distinguishes it from

No Cognition Without Representation

Against the constant, pervasive background hum of the universe relentlessly computing its next state given its past history, the relationship of representation between two computations that always co-occur in a particular order or unfold over time in lockstep with one another—stands out as a great rarity. Merely drawing a parallel between some carefully chosen aspects of two events is not at all difficult, especially if it is numerical or otherwise abstract; finding a repeated co-occurrence or a parallel that persists over time is.

As I ponder this point, I observe nine ducks landing on a pond and am struck by the thought that their number is exactly the same as the number of months I have left until the date on which I promised to deliver this book to the publisher. What am I to make of this observation? It is this kind of coincidence, invariably noted in retrospect, that inspires popular tales of successful auguries, such as the one found in the second book of *The Iliad*. The Greeks, weather-bound at Aulis on the way to Troy, witness an omen: a snake devours a mother sparrow and its eight chicks in their nest, then turns into stone. They are told by Calchas, their chief soothsayer, that the omen means that the coming war with Troy will not be resolved until the tenth year. It is worth noting that this story betrays perfect hindsight on Homer's part: the prophesied tenth year happens to be the very year during which the main events of *The Iliad* are set.³

The strange decision to count together the sparrows and the newly petrified snake to reach the number ten would have ruined the career of a lesser augur than Calchas (who did not seem to have had any problem convincing the Greeks at Aulis that King Agamemnon's daughter had to be sacrificed to Artemis to break the spell of bad weather). Scholars believe that the sparrow omen story confounded Aristotle, who was otherwise a great admirer of *The Iliad*.⁴ Ever since, educated people's readiness to take such omens at face value has been steadily on the wane. Indeed, some people viewed numerological divination with great suspicion already in biblical times, as suggested by the injunction found in *Leviticus*: "Nor shall ye employ auguries, nor divine by inspection of birds." One might like to think that the Old Testament lawgivers sought to protect the people from superstitiously perceiving false patterns in noise (rather than merely to protect their own monopoly on foretelling).

The more complex a set of observations, the more likely it is to give rise to ghostly "patterns," or correlations that arise by chance—an apparent signal in a sea of random noise. Skepticism toward such correlations is the only reasonable default stance in science, and it can only be assuaged through the application of science's single most powerful ghost-busting tool: statistical analysis of data. Patterns that withstand statistical scrutiny are still suspect: they need to be explained, that is,

integrated into a wider framework or theory that makes sense of as much data as possible, in the simplest possible terms. This is how observations (themselves usually guided by informed guesses or hypotheses) get distilled into laws of nature.

Now that we are armed with the scientific method, let us return to the problem of telling apart reliable from unreliable representations—that is, true occurrences between events from chance ones. The first hypothesis to be let go is the one stating that a bunch of objects represents another bunch of different objects simply because their number is the same. As if to prove this point, my nine ducks on a pond are joined by another; I rush home and open my mail to see if the deadline for my manuscript has receded by a month, only to find out that, alas, it is still only nine months away. Apparently, the number of ducks on that particular pond does not, after all, represent the time frame of my contract with the publisher. More generally, attaching wide-ranging representational significance to patterns of bird flocking is empirically unwarranted, as one can quickly learn by observing the efficacy of the hypothesized representations over time.

It would be even better if we could tell ahead of time, from first principles, whether or not one thing—object, event, process—is going to be representative of another. Thanks to the understanding of the natural world that has already been gained by science, it is possible to do so. What is it then that singles out valid instances of representation? There is just one principle that can ensure the validity of a representation: causation, as it is embodied in the various laws of nature.⁵ The fall of a pebble and the fall of an anvil are caused and governed instant by instant by the same universal law—the law that Newton is said to have discovered when he intuited that the motion of the celestial bodies is not any different from the motion of terrestrial ones. Because of that common causality, falling pebbles are representative of falling anvils (and apples and penguins, but not ducks). We may think of the relation between processes that all obey the same mathematical equation as representation by causally justified analogy.

There is another way in which causality can give rise to a valid representation: one event may simply cause the other. This is how the lighting of a lantern in the belfry of a church on the eve of the Battle of Lexington and Concord represented the redcoats' advance (through the mediation of one Robert Newman). Representation that is underwritten by causality in this direct manner is much more versatile than causal analogy: whereas falling objects representative of each other must all resemble each other in certain respects (heft, flightlessness), smoke represents fire by virtue of being caused by it, not by resembling it. Moreover, it does not matter how far from the represented event the causal chain leads before it reaches the representing event, as long as the chain is reliable; thus, a blaring fire alarm represents fire even if it is activated by smoke.

The principle of representation of one event by another through a causal chain whose reliability is guaranteed by the laws of nature is extremely powerful. Once it is discovered by evolution⁶ and unleashed into the biosphere, it becomes a force that can change the face of the planet. Whereas computation as such

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