BASICS

Seeing the Natural World With a Physicist's Lens

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If you've ever stumbled your way through a newly darkened movie theater, unable to distinguish an armrest from a splayed leg or a draped coat from a child's head, you may well question some of the design features of the human visual system. Sure, we can see lots of colors during the day, but turn down the lights and, well, did you know that a large bucket of popcorn can accommodate an entire woman's shoe without tipping over?

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Yet for all these apparent flaws, the basic building blocks of human eyesight turn out to be practically perfect. Scientists have learned that the fundamental units of vision, the photoreceptor cells that carpet the retinal tissue of the eye and respond to light, are not just good or great or phabulous at their job. They are not merely exceptionally impressive by the standards of biology, with whatever slop and wiggle room the animate category implies. Photoreceptors operate at the outermost boundary allowed by the laws of physics, which means they are as good as they can be, period. Each one is designed to detect and respond to single photons of light — the smallest possible packages in which light comes wrapped.

"Light is quantized, and you can't count half a photon," said William Bialek, a professor

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of physics and integrative genomics at Princeton University. “This is as far as it goes.”

So while it can take a few minutes to adjust to the dark after being fooled by a flood of artificial light, our eyes can indeed seize the prize, and spot a dim salting of lone photons glittering on the horizon.

Photoreceptors exemplify the principle of optimization, an idea, gaining ever wider traction among researchers, that certain key features of the natural world have been honed by evolution to the highest possible peaks of performance, the legal limits of what Newton, Maxwell, Pauli, Planck et Albert will allow. Scientists have identified and mathematically anatomized an array of cases where optimization has left its fastidious mark, among them the superb efficiency with which bacterial cells will close in on a food source; the precision response in a fruit fly embryo to contouring molecules that help distinguish tail from head; and the way a shark can find its prey by measuring micro-fluxes of electricity in the water a tremulous millionth of a volt strong — which, as Douglas Fields observed in Scientific American, is like detecting an electrical field generated by a standard AA battery “with one pole dipped in the Long Island Sound and the other pole in waters of Jacksonville, Fla.” In each instance, biophysicists have calculated, the system couldn’t get faster, more sensitive or more efficient without first relocating to an alternate universe with alternate physical constants.

The tenets of optimization may even help explain phenomena on a larger scale, like the rubberiness of our reflexes and the basic architecture of our brain.

For Dr. Bialek and other biophysicists, optimization analysis offers the chance to identify general principles in biology that can be encapsulated in an elegant set of equations. They can then use those first principles to make predictions about how other living systems may behave, and even test their predictions in real-life, wetware settings — an exercise that can quickly mount in quantitative complexity for even the seemingly simplest cases.

On Wednesday, Dr. Bialek will discuss his take on biological optimization at the Graduate Center of the City University of New York, in a public lecture fetchingly titled “More Perfect Than We Imagined: A Physicist’s View of Life.” Dr. Bialek is a visiting professor at the graduate school, where he has helped establish an “initiative for the theoretical sciences” devoted to the grand emulsification of mathematics, neuroscience, condensed-matter physics, quantum computation, computational chemistry and the occasional seminar on the physics of mousse and marshmallows.

Wherever he is perched, Dr. Bialek seeks to train the tools of physics on biology, a discipline that historically has favored research and experimentation over theory and computation, and that sometimes can seem so number-averse you’d think it was an they were extensions of the humanities department.

“Because mathematics is so central to how we think about the world, physicists often are speaking a different language than biologists, asking different questions,” said Dr. Bialek, his impish, abstractedly cerebral face and full, free-wheeling beard giving him something of a jolly professor manner. “Of course this can lead to conflict.”

In one optimization study, Dr. Bialek and his colleagues considered the dynamics of a major signaling molecule in the fruit fly embryo called bicoid.

It was known that bicoid bits were dispensed into the crown end of a fruit fly egg by the mother, that the molecules diffused tailward during development, and that the relative concentration of bicoid at any given spot helped determine the segmentation of a budding fruit fly’s form. But how, exactly, did the fly translate something as amorphous and borderless as a seeping oil spill into the ordered grid of a body plan?

The researchers calculated that, to operate optimally, each cell in the developing embryo

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would match the strength of its bicoid signal against an overall range of possible signal strengths, essentially by comparing notes with its neighbors. Sure enough, experiments later showed that embryonic fly cells perform precisely this sort of quantitative matching in response to a bicoid stimulus package. “It’s one of those things where we could have failed dramatically,” said Dr. Bialek, “but we succeeded better than we could have expected.”

Other researchers have shown that an E. coli microbe navigating its way through a chemically chaotic environment and over to food relies on a similar algorithm of compare-contrast-act, although in this case the note-trading takes place between surface receptors on the bacterium’s front and aft. “The reliability of its decision-making is so high,” said Dr. Bialek, “that it couldn’t do much better if it counted every single molecule in its environment.”

Emanuel Todorov, a neuroscientist at the University of Washington, said that one way to identify likely cases of optimization is to find biological systems that are ubiquitous, ancient and resistant to change.

“The muscles of most species are very similar,” he said, “and inside every muscle fiber are the same long, organic molecules, the same actin, myosin and troponin that latch onto each other to generate force.” The engine of all animal motion, he said, is close to being an optimized machine that itself needs no forward march.

Dr. Todorov has studied how we use our muscles, and here, too, he finds evidence of optimization at play. He points out that our body movements are “nonrepeatable”: we may make the same motion over and over, but we do it slightly differently every time.

“You might say, well, the human body is sloppy,” he said, “but no, we’re better designed than any robot.”

In making a given motion, the brain focuses on the essential elements of the task, and ignores noise and fluctuations en route to success. If you’re trying to turn on a light switch, who cares if the elbow is down or to the side, or your wrist wobbles — so long as your finger reaches the targeted switch?

Dr. Todorov and his coworkers have modeled different motions and determined that the best approach is the wobbly, ever-varying one. If you try to correct every minor fluctuation, he explained, not only do you expend more energy unnecessarily, and not only do you end up fatiguing your muscles more quickly, you also introduce more noise into the system, amplifying the fluctuations until the entire effort is compromised.

“So we reach the counterintuitive conclusion,” he said, “that the optimal way to control movement allows a certain amount of fluctuation and noise” — a certain lack of control.

The brain, too, seems built to tolerate bloopers and static hiss. Simon Laughlin of Cambridge University has proposed that the brain’s wiring system has been maximally miniaturized, condensed for the sake of speed to the physical edge of signal fidelity.

According to Charles Stevens of the Salk Institute, our brains distinguish noise from signal through redundancy of neurons and a canny averaging of what those neurons have to say.

We are like microbes trepanning for food, and why not? Bacteria have been here for nearly four billion years. They have optimized survival. They can show us the way.

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