PART I

THE MISUNDERSTOOD FISH

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

—T. S. Eliot

What we casually refer to as “fish” is in fact a collection of animals of fabulous diversity. According to FishBase—the largest and most often consulted online database on fishes—33,249 species, in 564 families and 64 orders, had been described as of January 2016. That’s more than the combined total of all mammals, birds, reptiles, and amphibians. When we refer to “fish” we are referring to 60 percent of all the known species on Earth with backbones.

Almost all modern fishes are members of one of two major groups: bony fishes and cartilaginous fishes. Bony fishes, scientifically termed *teleosts* (from the Greek *teleios* = complete, and *osteon* = bone), make up the great majority of fishes today, numbering about 31,800 species, including such familiar ones as salmons, herrings, basses, tunas, eels, flounders, goldfishes, carps, pikes, and minnows. Cartilaginous fishes, or *chondrichthyans* (*chondr* = cartilage, and *ichthys* = fish), number about 1,300 species, including sharks, rays, skates, and chimaeras.* Members of both groups have all ten body systems of the land-dwelling vertebrates: skeletal, muscular, nervous, cardiovascular, respiratory, sensory, digestive, reproductive, endocrine, and excretory. A third distinct group of fishes is the jawless fishes, or *agnathans* (*a* = without, and *gnatha* = jaws), a small division of about 115 species comprising lampreys and hagfishes.

We conveniently classify animals with backbones into five groups: fishes, amphibians, reptiles, birds, and mammals. This is misleading because it fails to represent the profound distinctions among fishes. The bony fishes are at least as evolutionarily distinct from the cartilaginous fishes as mammals are from birds. A tuna is actually more closely related to a human than to a shark, and the coelacanth—a “living fossil” first discovered in 1937—sprouted closer to us than to a tuna on the tree of life. So there are at least *six* major vertebrate groups if one counts the cartilaginous fishes.

The illusion of relatedness among all fishes is partly attributable to the constraints of evolving to move efficiently in water. The density of water is about 800 times greater than that of air, so aquatic living has, in vertebrates, tended to favor streamlined shapes, muscular bodies, and flattened appendages (fins) that generate forward propulsion while minimizing drag.

Living in a denser medium also greatly reduces the pull of gravity. The buoyant effect of water frees aquatic organisms from the ravages of weight on terrestrial creatures. Thus, the largest animals—the whales—live in water, not on land. These factors also help explain the small relative brain size (the ratio of brain weight to body weight) of most fishes, which has been used against them in our cerebrocentric view of other life forms. Fishes benefit from having large, powerful muscles to propel them through water, which is more resistant than air, and living in a practically weightless environment means there is no premium on limiting body size relative to brain size.

In any event, brain size is only marginally meaningful in terms of cognitive advancement. As the author Sy Montgomery notes in an essay on octopus minds, it is well known in electronics that anything can be miniaturized. A small squid can learn mazes faster than dogs do, and a small goby fish can memorize in one trial the topography of a tide pool by swimming over it at high tide—a feat few if any humans could achieve.

The earliest fishlike creatures arose in the Cambrian period, some 530 million years ago.* They were small and not very exciting. The big breakthrough in the evolution of fishes (and all their descendants) was the appearance of jaws about 90 million years later in the Silurian period. Jaws allowed these pioneer vertebrates to grab and break up food items and to expand their heads to powerfully suck in prey, which greatly extended the available dinner menu. We might also think of jaws as nature’s first Swiss Army knife, for they come with other functions, including manipulating objects, digging holes, carrying material to build nests, transporting and protecting young, transmitting sounds, and communicating (as in, don't come any closer or I'll bite you). Having jaws set the stage for an explosion of piscine life during the Devonian period—also known as "the age of fishes"—including the first super-predators. Most of the Devonian fishes were *placoderms* (plate-skinned), having heavy, bony armor over the head end and a cartilaginous skeleton. The largest placoderms were formidable. Some species of *Dunkleosteus* and *Titanichthys* measured well over thirty feet. They had no teeth, but could shear and crush with two pairs of sharp bony plates forming the jaws. Their fossils are often found with boluses of semi-digested fish bones, suggesting that they regurgitated these in the manner of modern owls.

Although they all went out with the Devonian and have been gone for over 300 million years, nature was kind to the placoderms in preserving some specimens so delicately that paleontologists have been able to deduce some intriguing facets of their lives. One particularly revealing find, from the Gogo fossil sites of Western Australia, is *Materpiscis attenboroughi* (translation: Attenborough's mother fish), named for the iconic British nature documentary presenter David Attenborough, who waxed enthusiastic over this species in his 1979 documentary series *Life on Earth*. This perfectly preserved 3-D specimen allows careful peeling away of layers to reveal the insides of the fish. And what should show up there but a well-developed baby *Materpiscis attenboroughi* attached to its mother by an umbilical cord. This discovery rocked the evolutionary boat by setting back the origins of internal fertilization by 200 million years. It also eroticized the lives of early fishes. As far as we know there is only one way to achieve internal fertilization: sex with an intromittent organ. So it appears that fishes were the first to enjoy "the fun kind" of sex. About this discovery and John Long, the Australian paleontologist who brought it to light, Attenborough expressed ambivalence during a public lecture: "This is the first known example of any vertebrate copulating in the history of life … and he names it after me."

Sex notwithstanding, the bony fishes, which arose about the same time as the placoderms, had a brighter future. Although they suffered major losses during the third great extinction that closed out the Permian period, they steadily diversified over the next 150 million years of the Triassic, Jurassic, and Cretaceous periods. Then, about 100 million years ago, they truly began to flourish. From that time to today the number of known families of bony fishes has more than quintupled. Fossil records do not divulge their secrets willingly, however, so there may be many earlier fish families still hidden in the rocks.

Like their bony counterparts, the cartilaginous fishes also steadily recovered from the Permian setback, albeit without the explosive diversification of later times. As far as we know, there are more kinds of sharks and rays today than at any point in history. And we're beginning to discover that their real lives belie their pugnacious reputation.

Diverse and Versatile

Because their lives are more difficult to observe than those of most terrestrial animals, fishes are not easily fathomed. According to the National Oceanic and Atmospheric Administration, less than 5 percent of the world's oceans have been explored. The deep sea is the largest habitat on Earth, and most of the animals on this planet live there. A seven-month survey using echo soundings of the mesopelagic zone (between 100 and 1,000 meters—330 to 3,300 feet—below the ocean surface), published in early 2014, concluded that there are between ten and thirty times more fishes living there than was previously thought.

And why not? You might have encountered the popular notion that living at great depths is a terrible hardship for the creatures there. It's a shallow idea, for surely deep-sea creatures are no more inconvenienced by the enormous pressure of the overlying ocean than we are by the approximately ten-tons-per-square-meter pressure (often expressed as 14.7 pounds per square inch) of the atmosphere above us. As the ocean ecologist Tony Koslow explains in his book *The Silent Deep*, water is relatively incompressible, so deep-sea pressures have less impact than we usually think, because pressure from within the organism is about the same as that on the outside.

Technology is just beginning to afford us a glimpse of the ocean depths, but even in reachable habitats many species remain undiscovered. Between 1997 and 2007, 279 new species of fishes were found in Asia's Mekong River basin alone. The year 2011 saw the discovery of four shark species.

Given the current rate, experts predict the total count of all fishes will level off at around 35,000. With the advance of techniques for distinguishing species at the genetic level, I think it could be many thousands more than that. When I studied bats as a graduate student in the late 1980s, 800 species had been identified. Today, the count has ballooned to 1,300.

From diversity springs variety, and from the rich variety of fishdom spring some noteworthy superlatives and bizarre life-history patterns. The smallest fish—indeed, the smallest vertebrate—is a tiny goby of one of the Philippine lakes of Luzon. Adult *Pandaka pygmaea* are only a third of an inch in length and weigh about 0.00015 of an ounce. If you were to put 300 of them on a scale they wouldn't equal the weight of an American penny.

At less than half an inch, some male deep-sea anglerfishes are not much bigger, but what they lack in size they make up for in the sheer audacity of their mode of existence. On finding a female, males of some deep-sea anglerfish species latch their mouths onto her body and stay there for the remainder of their lives. It doesn't matter much where they fix their bite on the female—it could be on her abdomen or her head—they eventually become fused to her. Many times smaller, the male resembles little more than a modified fin, living off her blood supply and fertilizing her intravenously. One female may end up with three or more males sprouting from her body like vestigial limbs.

It looks like a lurid form of sexual harassment; scientists have called it *sexual parasitism*. But the origins of this unconventional mating system are not so ignoble. It is estimated that female deep-sea anglerfishes occur at a density of about one per 800,000 cubic meters (28 million cubic feet) of water, which means a male is searching for a football-size object in a darkened space about the volume of a football stadium. Thus, it is desperately hard for anglerfishes to find each other in the vast darkness of the abyss, making it wise to hang on to your partner if you find one. At the time that Peter Greenwood and J. R. Norman revised *A History of Fishes* in 1975, no free-swimming adult male anglerfish had been found, leading ichthyologists to speculate that the only alternative to successful latching is death. But the University of Washington's Ted Pietsch—curator of fishes at the Burke Museum of Natural History and Culture, and the world's leading authority on deep-sea anglerfishes—tells me that there are now hundreds of (formerly) free-living males in specimen collections around the world.

In exchange for the male being the ultimate couch potato, the female never has to wonder where her mate is on a Saturday evening. It turns out that some males do indeed amount to little more than an appendage.

Another fish superlative is their fecundity, which is also unmatched among vertebrates. A single ling, five feet long and weighing fifty-four pounds, had 28,361,000 eggs in her ovaries. Even that pales compared to the 300 million eggs carried by an ocean sunfish, the largest of all bony fishes. That such a grand creature can be the product of such a paltry parental investment as a teeny egg released into the water column might contribute to the common bias that fishes are unworthy of our consideration. But it bears reminding that all living things start from a single cell. And as we'll see in the section on "Parenting Styles," parental care is well developed in many fishes.

From its humble beginnings as an egg smaller than this letter "o," a mature adult ling can grow to be close to six feet long, and it is another superlative of fishes that they can increase so much in size from the start of their independent life cycle. But the growth champion among vertebrates may be the pointed-tailed ocean sunfish. While not streamlined (the family name, Molidae, refers to their millstone shape), they grow from one-tenth of an inch to ten feet in length, and can weigh 60 million times more as an adult.

Sharks lie at the opposite end of the spectrum of fish fecundity. Some species reproduce at a rate of only one baby a year. And that's only after they reach sexual maturity, which for some species can take a quarter century or more. In parts of their range, spiny dogfish sharks—a heavily fished species that you might have dissected in a college biology course—average thirty-five years old before they are ready to breed. Sharks have a placental structure as complex as that of mammals. Pregnancies are few and far between, and gestation can be lengthy. Frilled sharks carry their babies for over three years, the longest known pregnancy in nature. I sure hope they don't get morning sickness.

Dogfishes can't fly, nor can any other fishes, but they just might be the world's superlative for gliding. Best known of these are the flying fishes, of which there are about seventy species inhabiting the surfaces of the open ocean. Flying fishes have greatly enlarged pectoral fins that function as wings. In preparation for launch, they can reach speeds of forty miles per hour. Once airborne, the lower lobe of the tail may be dipped into the water and used as a supercharger to extend flights to 1,200 feet or more. Flights are usually just above the surface, but sometimes gusts of wind carry these aerialists fifteen to twenty feet high, which may explain why they sometimes land on ship decks. I wonder if the respiratory limitations of being a water breather have kept flying fishes from becoming truly flapping their "wings" for fully sustained flight? Fishes of several other types also launch themselves into the air, including the characins of South America and Africa, and—never mind that their name sounds more like a circus act—the flying gurnards.

Speaking of superlatives, and names, surely one of the longest belongs to Hawaii's state fish, the rectangular triggerfish, known by the locals as humuhumunukunukuapua'a (translation: the fish that sews with a needle and grunts like a pig). Perhaps the award for least flattering name should go to an anglerfish dubbed the hairy-jawed sack-mouth, and for most preposterous to the sarcastic fringehead. For the title of crudest, I nominate a small coastal dweller, the slippery dick (*Halichoeres bivittatus*).

But really, the most exciting breaking news on fishes is the steady stream of discoveries on how they think, feel, and live their lives. Scarcely a week now passes without a revealing new discovery of fish biology and behavior. Careful observations on reefs are uncovering nuanced social dynamics of cleaner–client fish mutualisms that defy the human conceit that fishes are dim-witted pea brains and slaves to instinct. And the notorious three-second fish memory has been debunked by simple laboratory investigations. In the pages ahead we'll explore how fishes are not just sentient, but aware, communicative, social, tool-using, virtuous, even Machiavellian.

Lowly Not

Among the vertebrate animals—mammals, birds, reptiles, amphibians, and fishes—it is the fishes that are the most alien to our sensibilities. Lacking detectable facial expressions and appearing mute, fishes are more easily dismissed than our fellow air breathers. Their place in human culture falls almost universally into two entwined contexts: (1) something to be caught, and (2) something to be eaten. Hooking and yanking them from the water has not just been seen as benign but as a symbol of all that's good about life. Fishing appears gratuitously in advertising, and the logo of one of America's most beloved film production studios, DreamWorks, features a Tom Sawyer-esque boy relaxing with a fishing pole. You may have met self-professed vegetarians who nonetheless eat fishes, as if there were no moral distinction between a cod and a cucumber.

Why have we tended to relegate fishes beyond the outer orbit of our circle of moral concern? For one thing, they are "cold-blooded," a layman's term that has little credibility in science. I do not see why having a built-in thermostat or not should have anything to do with an organism's moral status. In any event, most fishes' blood does not run cold. Fishes are ectothermic, meaning that their body temperatures are governed by outside factors, notably the water they are living in. If they live in warm tropical waters, their blood runs warm; if they live in the frigid reaches of the ocean depths or the polar regions, as many fishes do, then their body temperatures hover around freezing.

But even that description falls short. Tunas, swordfishes, and some sharks are partly endothermic—they can maintain body temperatures warmer than their surroundings. They achieve this by capturing heat generated by their powerful active swimming muscles. Bluefin tunas keep their muscle temperatures between 82 and 91 degrees Fahrenheit in waters ranging from 45 to 81 degrees. Similarly, many sharks have a large vein that warms the central nervous system by draining warm blood from the core swimming muscles to the spinal cord. The large, predatory billfishes (marlins, swordfishes, sailfishes, spearfishes) use this heat to warm their brains and eyes for optimal functioning in deeper, cooler waters. In March 2015, scientists described the first truly endothermic fish, the opah, which maintains its body temperature at about 9 degrees Fahrenheit above the cold waters it swims in at depths of several hundred feet, thanks to heat generated by the flapping of its long pectoral fins and conserved by a countercurrent heat exchange system in its gills.

Another prejudice we hold against fishes is that they are "primitive," which in this context has a host of unflattering connotations: simple, undeveloped, dim, inflexible, and unfeeling. Fishes were "born in front of my sunrise," wrote D. H. Lawrence in his 1921 poem "Fish."

No one is questioning that fishes have been around a long time, but therein lies the fallacy of labeling fishes as primitive. This bias presumes that those that stayed in the water stopped evolving the moment a few of them went ashore, a notion completely at odds with the tireless process of evolution. The brains and bodies of all extant vertebrates are a mosaic of primitive and advanced characteristics. Given time, and there's been plenty, natural selection keeps what works and winnows the rest, mainly through a process of gradual refinement.

All of the fish species that were living at the dawn of legs and lungs are long gone. About half of the fishes we see on the planet today belong to a group called the Percomorpha, which underwent an orgy of speciation just 50 million years ago (mya) and reached peak diversity around 15 mya, when the ape family, Hominoidea, to which we belong, was also evolving.

So about half of fish species are no more "primitive" than we are. But the descendants of early fishes have been evolving eons longer than their terrestrial counterparts, and on these terms fishes are the most highly evolved of all vertebrates. You might be surprised to know that fishes have the genetic machinery to make fingers—something that shows how similar fishes are to modern mammals. They just don't develop fingers, but fins instead, since fins are better for swimming than fingers are. And don't forget your segmented musculature. The *rectus abdominus*—the washboard stomach that graces the torso of our fittest athletes (and exists in all of us, albeit buried under a bit too much adipose tissue)—harkens back to the axial muscle segmentation first laid down by the fishes. As the title of Neil Shubin's popular book *Your Inner Fish* reminds us, our ancestors (and those of modern fishes) were early fishes, and our bodies are packed with modified structures traceable to those of our common aquatic forebears.

An older organism isn't necessarily simpler. Evolution does not trend relentlessly toward increased sophistication and size. Not only were the largest dinosaurs much larger than modern reptiles, paleontologists have recently unearthed evidence that they were social creatures with parental care and modes of communication at least as complex as those of modern reptiles. Similarly, the largest terrestrial mammals died out thousands or millions of years ago, at a time when mammalian diversity flourished. The true *age of mammals* is over. We tend to think of the last 65 million years as the Age of Mammals, but teleost fishes have been diversifying much more during that time. The Age of Teleosts may not sound quite as sexy, but it's more accurate.

Just as evolution does not proceed inescapably toward increased complexity, nor is it a process of perfection. For all the elegance with which adaptations allow animals to function optimally, it is a fallacy that animals are perfectly tailored to their environments. They can't be, because environments aren't static. Weather patterns, geological shifts such as earthquakes and volcanoes, and the constant process of erosion present moving targets. Even beyond these instabilities, nature is not fully efficient. There are inevitably compromises. Human examples include our appendix, our wisdom teeth, and the blind spot where the optic nerve interrupts the retina. For fishes, there is the closing of the gill covers necessary for respiration, which causes a forward thrust. If a fish wishes to remain stationary, as a resting fish usually does, she needs to compensate for the gill thrust. This is why you will rarely see a stationary fish whose pectoral fins are not in motion.

As we learn more about fishes, be it their evolution or their behavior, our capacity to identify with them grows, along with our ability to relate their existence to our own. Central to empathy—the capacity to place oneself in another's shoes, or in this case, fins—is an understanding of the experiences of the other. Central to that is an appreciation of their sensory worlds.