NAUTILUS

Monsters

Let's put it this way: Monsters are so *not* Hollywood creations. As these electrifying *Nautilus* stories reveal, monsters arise from the depths of our minds. Our hominin ancestors' innate fears remain with us, sewn into our everlasting myths and folklores, laced into our environments. Mary Shelley's *Frankenstein*, you will read, sprang to life under the ashes of an exploded volcano, which shrouded the English skies for months. Now the word monster is engraved in our language to describe anything that unsettles us, like deep-sea waves, and recondite problems in math. And you know what? Monsters take us out of our everyday selves, spur us to wonder about nature, about things we don't know. And that's a beautiful thing. Happy Halloween.

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Monsters, Marvels, and the Birth of Science

How the unlikely and unexplainable, strange and terrifying, spawned the age of science.

BY STEVE PAULSON

ILLUSTRATION BY ELLEN WEINSTEIN

F**INDING REGULARITY IN NATURE** is the bread and butter of science. We know that reptiles lay eggs, while mammals bear live young; the Earth revolves around the sun every 365.25 days; electrons glom onto protons like bears onto honey. But what if some oddity seems to defy the laws of nature, like the platypus, an egg-laying mammal? What about an anomaly like a two-headed snake? Or a newborn baby who seems to be neither boy nor girl, but something in between?

These questions fascinated the founding fathers of science, and their attempts to explain such rarities and marvels helped shape modern science. In fact, nearly all the great philosophers and scientists of 17th century Europe—Descartes, Newton, and Bacon notably among them—were obsessed with anomalies. If they couldn't explain the unlikely—a solar eclipse, a comet hurtling toward Earth, a narwhal tusk (was it a unicorn?)—all bets were off about an underlying explanation of nature.

They seemed to be a telegram from God announcing the end of time, the end of the world.

Lorraine Daston, executive director of the Max Planck Institute for the History of Science in Berlin, has spent decades studying the emergence of modern science. One formative experience, she says, was a graduate-school seminar where she and fellow student Katharine Park noticed something strange. The philosophers they studied in their class on 17th century metaphysics—Bacon, Hobbes, Leibniz, Locke—were obsessed with monstrous creatures. Their professor didn't care, nor did the other students, so Daston and Park carved out their own intellectual turf and wrote a landmark scholarly article about monsters. Years later they expanded the study and in 1998 published the monumental history, *Wonders and the Order of Nature, 1150-1750*.

Nautilus called on Daston to learn how the unlikely in nature, strange and unexplainable occurrences, were viewed at the dawn of science. In conversation Daston has a dazzling ability to leap across centuries, ranging over high culture and low, from Aristotle to *The National Enquirer*. Her insights into history illuminate the practice of science today. Daston spoke to *Nautilus* from Berlin.

Centuries ago, monsters seemed to embody the unlikely in nature. Why were early philosophers and scientists so fascinated by monsters?

They were interested in exceptions to the rule. One has to keep in mind that the 16th and 17th centuries were times of extraordinary religious, economic, and intellectual upheaval. From both the Far East and the New World, Europe was deluged by novelties of all kinds, such as animals that no one could possibly imagine, like birds of paradise and armadillos. On the religious front, monsters were seen as portents foretelling the apocalypse—the Second Coming. It was also a time of intellectual revolution. Copernicus published his book on the solar system in 1543. That same year, Andreas Vesalius published his book on the anatomy of the human body.

For European thinkers in the early 17th century, the scientific ground on which they stood was extremely unstable. Everything was changing, and people like Francis Bacon realized it was possible that the best minds over the last two millennia had been dead wrong about everything. He used monsters and other marvels as a kind of intellectual hygiene to jolt people out of their assumptions about the natural world. In Aristotelian natural philosophy, monsters and other anomalies were seen as outliers, to be acknowledged but not explained. Bacon turned the tables and used monsters as a weapon against the ruling orthodoxy in natural philosophy and natural history.

Were monsters seen as frightening?

That was certainly one view. Birth deformations, like two-headed cats and conjoined twins, were terrifying but also electrifying. They seemed to be a telegram from God announcing the end of time, the end of the world. But in another context, they were seen as wonders—not as terrifying, but astonishing, a sign of the fecundity, the creativity and variety of nature. So the

emotional response could flip over from one moment to the next, from horror to wonder and back again. In one early 17th century sermon in an English parish about the birth of conjoined twins, the minister harangued his parishioners not to treat this monstrous birth as a wonder to be gawked at and admired, but as a horrifying portent that they should repent immediately.

How did this struggle to explain unlikely occurrences relate to the birth of modern science?
These anomalies were seen as challenges. By the 17th century, it was pretty clear that Aristotelian natural philosophy was doomed. The question was what would replace it, and there were lots of fiercely competing theories. Monsters and other marvels offered extreme cases. Could your revision of natural philosophy explain such things? This made monsters and wonders more prominent in the late 16th and early 17th centuries than they've ever been before or since in the history of science. For the most part, science is interested in the regularities of nature—and that makes sense. Why would you devote time, thought, and ingenuity to explaining what only happens once in a blue moon? But in this period, anomalies very briefly took center stage when it came to scientific explanations.

What about the founders of modern science—Galileo, Descartes, Newton, Leibniz? What was their interest in nature's oddities?
Descartes thought that if you're putting forward a new theory of everything, you should be able to explain these outlier cases. He even thought you could explain what was considered an old medieval marvel, in which the corpse of a murder victim would bleed again in the presence of the murderer or the murder weapon. Leibniz sent a report of a dog that could talk to the journal of the Paris Academy of Royal Sciences. It could bark out six words in French, including "chocolat." Everyone was trafficking in marvels in the 17th century.

You've described this transitional period between premodern and modern science as "the great age of wonder." What kinds of wonders were scientists finding?
Let's take astronomy. In 1609, Galileo turned his telescope to the heavens. He discovered the surface of the

moon was pockmarked by craters. He discovered four moons of Jupiter, which he described as "marvels." He discovered the phases of Venus. He published these findings in 1610, and it caused a sensation. This book sold like hot cakes. Rumors were even more salacious in European gossip circuits. There were spectacular novelties coming from the New World and also from China and the Far East, streaming into the markets of London and Amsterdam.

So this was partly the result of new global commerce.
A lot of these marvels could have been seen as commodities. When we think of the ancestors of our museums—the "cabinets of curiosity," *wunderkammern*—they are chock-full of marvels and monsters of all kinds. We wouldn't see some of these things as marvels, such as paper money from China. But from the standpoint of late-16th-century Europeans, the concept of accepting paper money instead of gold or silver was almost as much a marvel as an armadillo.

Wunderkammern is usually translated as "cabinets of curiosity," but isn't "cabinets of wonder" a better translation?
"Chambers of wonders" would be the most literal translation.

Do "wonder" and "curiosity" mean the same thing?
No. What's distinctive about this period is that wonder and curiosity are yoked together. Aristotle had said wonder is "the beginning of philosophy," but the aim of his natural philosophy was to make wonder disappear as soon as possible. It was a sign that you were ignorant at best, or at worst you were timorous or fearful. Since ancient times, curiosity was associated with vice rather than virtue, with people who meddled in other people's business. You were meddling in secrets that shouldn't concern you—the secrets of Nature, of God, of the Prince.

Of course, the classic cautionary tale about curiosity is Adam and Eve, who tasted fruit from the forbidden Tree of Knowledge. It was the original sin.
Absolutely. And then what happens in the 16th and 17th centuries is fascinating. Curiosity goes from being a real vice to a virtue. It becomes a form of audacity. "Dare

to know" becomes a motto that natural philosophers are proud to make their own, and wonder goes from being a sign of ignorance to a desire for knowledge. The clearest expression of this is in Descartes' 1649 treatise *Passions of the Soul*. First wonder and then curiosity are engaged, and the two work together. Wonder is like the spark that ignites the fuse of curiosity. Curiosity then marshals the intellect and all the senses in the quest to find the cause of wonder.

Tell me about the *wunderkammern*, these cabinets of wonder. What did people collect?
What didn't they collect? In order to qualify for a *wunderkammer*, the objects had to be unusual. So they could simply be exotic—such as paper money from China or pointed toe slippers from Turkey. Or wondrous because they're mistakes of nature, like two-headed snakes. Or they could be wondrous because they are virtuoso works of art—a thousand faces carved upon one cherry stone. The ways they're displayed are intended to accentuate the hodge-podgery of it all, to accentuate diversity, miscellany, and also plenitude. Maybe you've seen pictures of these floor-to-ceiling displays, which have everything from Ceylon shields to a stuffed Laplander to a crocodile hanging from the ceiling. The aim of a *wunderkammer*, especially a prince's collection, was to overwhelm you. They were often shown to ambassadors, to impress the ambassador with the power of the prince. Today's museums have a lot in common with these early *wunderkammern*. They're meant to astonish us, to jolt us out of our everyday thoughts: "Fancy seeing that!" And they're meant to provoke our curiosity, to make us inquisitive about some new class of objects. Probably only in museums is that alliance of wonder and curiosity still preserved in its full intensity.

Yet from our modern perspective, this mix of man-made objects and oddities of nature is strange. The distinction between nature and art seems so obvious today.
It would also have been obvious in the 14th and 15th centuries. So it's really interesting what happens in the early modern period. Monsters and other marvels were used as catalysts to accelerate new theories of knowledge. Again, it's Bacon's formulation. These marvels are experiments that Nature is performing on herself.

Since ancient times, curiosity was associated with vice rather than virtue, with people who meddled in other people's business.

And if we want to create a new way of tempering steel or dying fabric, we should look very closely at these experiments that Nature is performing on the margins of its regular order. Then we should imitate Nature.

Was Nature seen as God's great artistic creation?
The more devout would have formulated it that way. And for 16th and 17th century philosophers, Nature is allowed to joke. What we would now call a fossil—the impress of a fern in rock—might have been interpreted in the early 17th century as a joke of Nature. "Oh, what the heck! I'm tired of creating leaf-like forms in trees and plants. Let's try it in stone." But God is not allowed to joke. So Nature had the freedom to experiment, which was exactly what the natural philosophers needed Nature for. To suggest that God was experimenting would have bordered on the blasphemous.

Today we categorize and collect objects of nature and art in entirely different ways. Paintings and sculptures go in art museums, while seashells and stuffed animals go in natural history museums. Apparently those distinctions were not made in cabinets of wonder.
It was all one great, glorious miscellany. I think you can date the end of the age of wonder precisely by that division of labor between art museums and natural history museums in the mid-to-late 18th century.

Why did wonder go out of fashion?
From the scientific standpoint, if you look at the annals of the first scientific societies—the Royal Society of

Monsters and other marvels were used as catalysts to accelerate new theories of knowledge.

London and the Paris Academy of Royal Sciences—the first six to 30 years are filled with reports of monsters and marvels. They read like *Ripley's Believe It or Not* or *The National Enquirer*. Sometimes I suspect the reporters of The National Enquirer go back to the early scientific journals for their ideas. Bacon thought we have to look at these anomalies if we're really going to discover the deep secrets of nature.

But by the 1730s and '40s, scientists had wearied of anomalies and began to feel it was time to return to the main business of science, which was to explain regularities. There was also ecclesiastical uneasiness with these marvels because they were objects of religious fervor. This was the time of the Reformation and Counter-Reformation, and new sects were sprouting up like mushrooms. The leaders of these new sects would often point to marvels as signs that God was on their side.

You've used the term "natural philosophy" to describe the work of these early thinkers. Is this another term for "science"?

I'm not just being a finicky historian. I don't want to equate natural philosophy with what we know today as modern science. The institution of science happens much later in the 19th century, so it was rare to make a living practicing science. Natural philosophers also asked bigger questions than scientists would. Newton thought it was perfectly in order to speculate on the relationship between gravitation and the nature of God. This would be completely unacceptable to a modern scientist. So natural philosophy is the ancestor of modern science, but they are not identical.

We've been talking about wonders and marvels. There's also the different emotional experience of

"wonder" itself, which is closer to awe. Does wonder have its own history?

It does. We in the modern period associate wonder with a childlike stance, a freshness of vision. But in the medieval and early modern period, there's nothing childish about it. Wonder could very easily tip over into horror or terror. There's a kind of Bermuda Triangle of terror, horror, and wonder, which have deep subterranean connections with each other. They all involve the perception that something extraordinary has happened. And they wobble. They can easily transmute from one into the other.

Wonder is tinged with awe—which can put it into the realm of the supernatural, perhaps even the divine—and it's also tinged with fear. It's an uncomfortable emotion. You don't have wonder. Wonder has you. It grabs you by the lapels and shakes you. Wonder is also associated with fear, and it's very embarrassing for a learned person to be seen as fearful. Wonder is for the ignorant, the unlettered. You, the university professor of natural philosophy, wish to show that you are not terrified of an eclipse because you can explain it, even predict it.

So this is really a question of what can be explained, which is the essence of science.

And it's really interesting to see what happens during the mid-18th century, when natural philosophers begin to abandon the marvels and return to the regularities. They transform wonder from the astonishing and the inexplicable to that which they explain. There's a concerted attempt to transfer wonder from monstrous births to very ordinary and even disgusting objects, like insects. There's a whole genre of natural history involving the marvels of insects, which is an attempt to domesticate the emotion of wonder for things we can explain.

It's extremely difficult to get into the mindset of people who lived 300 years ago, to overcome our tendency to impose our own biases on the past. It would be easy to write them off as ignorant or uneducated. Is that part of your work, to say they were just different, not lesser, than we are today?

That's very well put. The whole premise of doing the history of pre-modern science is that these were extraordinarily intelligent and often courageous people

You don't have wonder. Wonder has you. It grabs you by the lapels and shakes you.

who, without any of the institutional props of universities or laboratories, were trying their damnedest to figure out how the world works, at the expense of their fortunes, often their health, and sometimes their lives.

The Scientific Revolution was remarkable. But some people think we've lost something in our current age of rationality and science. They talk about how the world has become "disenchanted," that we've lost the capacity to be swept away by wonder. Do you see that as a problem?

I don't. It's very difficult to square this morose and elegiac discourse about the disenchantment of the world, which was very common in the early 20th century, with any working scientist who is afire with enthusiasm and delight and wonder about what he or she is working on. I mean, why do these people voluntarily work 80 hours a week?

In the epilogue of Wonders and the Order of Nature, you quote William James, the great philosopher and psychologist, who lived a century ago. He believed science would be renewed by what he called "the dust-cloud of exceptional observations." He was also fascinated by spiritualism. He and his small cohort of scientists actually investigated seances, which most scientists scoffed at. Did James have a point?

He absolutely had a point. He wrote about "radical empiricism." That's what the interest in wonders was. It was the desire to exclude absolutely nothing from the purview of inquiry—not to narrow one's gaze for expedience or orthodoxy, but to accept the world as it presents itself to us.

I think all science involves a receptivity to the anomalous, perhaps not in the splashy sense of a marvel, but simply an eye attuned to, "Oh, that's odd, that hasn't happened before." There's the famous story of penicillin's discovery. No doubt others before Alexander Fleming saw mold growing in petri dishes, but he was receptive to the oddity of it, the strangeness of it, and pursued it. And that story is told over and over again in the annals of scientific anecdote. It's a kind of observational openness to small deviations from the norm and the willingness to hunt them to ground.

The scientific sensibility is now attuned to objects that most of us would not consider intrinsically wondrous in the way a two-headed snake would be. It's as if scientists are connoisseurs of marvels, just as real gourmets with refined silver palettes are looking for esoteric combinations of flavors. Someone without a refined palette might be swept away by a fairly ordinary meal. Scientists are looking for much more unusual and esoteric combinations.

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The Volcano That Shrouded the Earth and Gave Birth to a Monster

Three years of darkness and cold spawned crime, poverty, and a literary masterpiece.

**BY GILLEN D'ARCY WOOD**

ILLUSTRATIONS BY WESLEY ALLSBROOK

T WO HUNDRED YEARS AGO, the greatest eruption in Earth's recorded history took place. Mount Tambora—located on Sumbawa Island in the East Indies—blew itself up with apocalyptic force in April 1815.

After perhaps 1,000 years' dormancy, the devastating evacuation and collapse required only a few days. It was the concentrated energy of this event that was to have the greatest human impact. By shooting its contents into the stratosphere with biblical force, Tambora ensured its volcanic gases reached sufficient height to disable the seasonal rhythms of the global climate system, throwing human communities worldwide into chaos. The sun-dimming stratospheric aerosols produced by Tambora's eruption in 1815 spawned the most devastating, sustained period of extreme weather seen on our planet in perhaps thousands of years.

Within weeks, Tambora's stratospheric ash cloud circled the planet at the equator, from where it embarked on a slow-moving sabotage of the global climate system at all latitudes. Five months after the eruption, in September 1815, meteorological enthusiast Thomas Forster observed strange, spectacular sunsets over Tunbridge Wells near London. "Fair dry day," he wrote in his weather diary—but "at sunset a fine red blush marked by diverging red and blue bars."
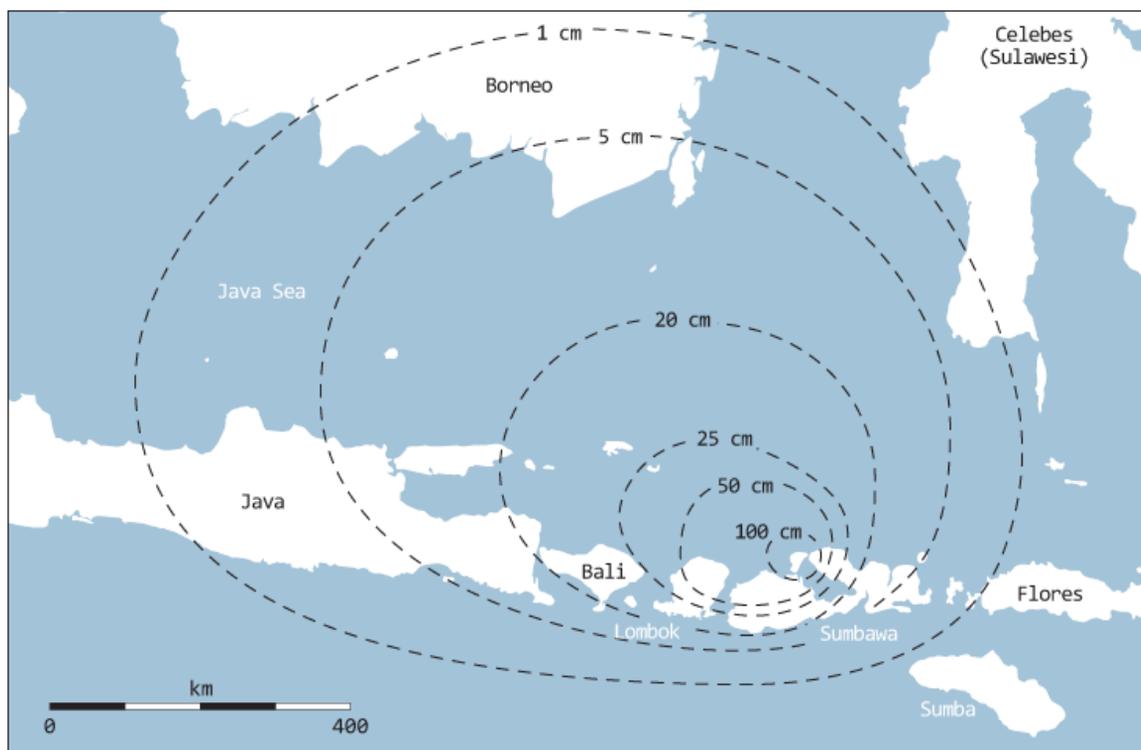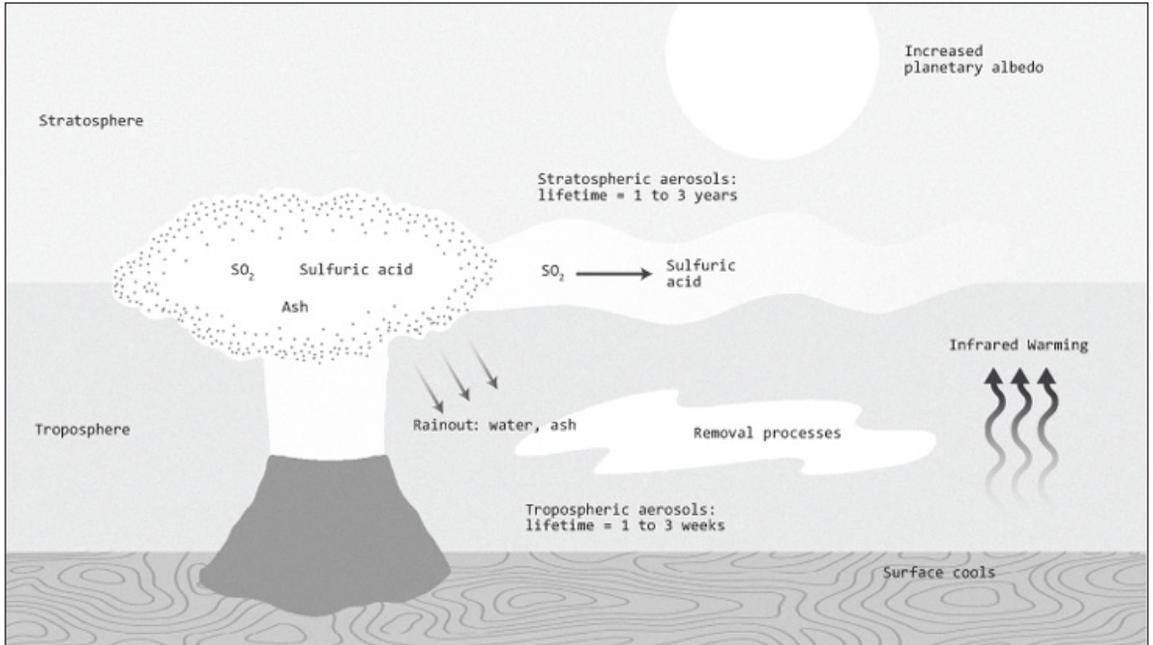
RAIN OF ASH This map shows the density of ash fall issuing from Tambora's eruption. The thickness of the ash is shown in centimeters. Prevailing trade winds drove the ash clouds north and west as far as Celebes (Sulawesu) and Borneo, 1,300 kilometers away. The volcanic eruptions could be heard twice as far away.

Artists across Europe took note of the changed atmosphere. William Turner drew vivid red skyscapes that, in their coloristic abstraction, seem like an advertisement for the future of art. Meanwhile, from his studio on Greifswald Harbor in Germany, Caspar David Friedrich painted a sky with a chromic density that—one scientific study has found—corresponds to the "optical aerosol depth" of the colossal volcanic eruption that year.

For three years following Tambora's explosion, to be alive, almost anywhere in the world, meant to be hungry. In New England, 1816 was nicknamed the "Year Without a Summer" or "Eighteen-Hundred-and-Froze-to-Death." Germans called 1817 the "Year of the Beggar." Across the globe, harvests perished in frost and drought or were washed away by flooding rains. Villagers in Vermont survived on porcupine and boiled nettles, while the peasants of Yunnan in China sucked on white clay. Summer tourists traveling in France mistook beggars crowding the roads for armies on the march.

One such group of English tourists, at their lakeside villa near Geneva, passed the cold, crop-killing days by the fire exchanging ghost stories. Mary Shelley's storm-lashed novel *Frankenstein* bears the imprint of the Tambora summer of 1816, and her literary coterie—which included the poets Percy Shelley and Lord Byron—serve as tour guides through the suffering worldscape of 1815–18.

Stratosphere

Increased
planetary albedo

Stratospheric aerosols:
lifetime = 1 to 3 years

SO_2 Sulfuric acid

SO_2 ⟶ Sulfuric
acid

Ash

Infrared Warming

Troposphere

Rainout: water, ash

Removal processes

Tropospheric aerosols:
lifetime = 1 to 3 weeks

Surface cools

Considered on a geological timescale, Tambora stands almost insistently near to us. The Tambora climate emergency of 1815–18 offers us a rare, clear window onto a world convulsed by weather extremes, with human communities everywhere struggling to adapt to sudden, radical shifts in temperatures and rainfall, and a flow-on tsunami of famine, disease, dislocation, and unrest. It is a case study in the fragile interdependence of human and natural systems.

ON SUMBAWA ISLAND, the beginning of the dry season in April 1815 meant a busy time for the local farmers. In a few weeks the rice would be ready, and the raja of Sanggar, a small kingdom on the northeast coast of the island, would send his people into the fields to harvest. Until then, the men of his village, called Koreh, continued to work in the surrounding forests, chop- ping down the sandalwood trees vital to shipbuilders in the busy sea lanes of the Dutch East Indies.

On the evening of April 5, 1815, at about the time his servants would have been clearing the dinner dishes, the raja heard an enormous thunderclap. Perhaps his first panicked thought was that the beach lookout had fallen asleep and allowed a pirate ship to creep in to shore and fire its cannon. But everyone was instead staring up at Mount Tambora. A jet of flame burst skyward from the summit, lighting up the darkness and rocking the earth beneath their feet. The noise was incredible, painful.

Huge plumes of flame issued from the mountain for three hours, until the dark mist of ash became confused with the natural darkness, seeming to announce the end of the world. Then, as suddenly as it had begun, the

THE BIG CHILL This diagram shows the penetration of volcanic matter into the stratosphere. As volcanic sulfur dioxide is chemically transformed into sulfuric acid, an aerosol layer forms, reducing incoming radiation from the sun and cooling the surface, even as the stratosphere itself is warmed.

The Tambora climate emergency offers us a rare, clear window onto a world convulsed by weather extremes. It is a case study in the fragile interdependence of human and natural systems.

column of fire collapsed, the earth stopped shaking, and the bone-jarring roars faded. Over the next few days, Tambora continued to bellow occasionally, while ash drifted down from the sky.

Meanwhile to the southeast in the capital Bima, colonial administrators were sufficiently alarmed by the events of April 5 to send an official, named Israel, to investigate the emergency situation at the volcano, on the Sanggar Peninsula. By April 10, the man's bureaucratic zeal had led him to the very slopes of Tambora. There, in the dense tropical forest, at about 7 p.m., he became one of the first victims of the most powerful volcanic eruption in recorded history.

Within hours, the village of Koreh, along with all other villages on the Sanggar Peninsula, ceased to exist entirely, a victim of Tambora's spasm of self-destruction. This time three distinct columns of fire burst in a cacophonous roar from the summit to the west, blanketing the stars and uniting in a ball of swirling flame at a height greater than the eruption of five days before. The mountain itself began to glow as streams of boiling liquefied rock coursed down its slopes. At 8 p.m., the terrifying conditions across Sanggar grew worse still, as a hail of pumice stones descended, mixed with a downpour of hot rain and ash.

On the northern and western slopes of the volcano, whole villages, totaling perhaps 10,000 people, had already been consumed within a vortical hell of flames, ash, boiling magma, and hurricane-strength winds. In 2004, an archaeological team from the University of Rhode Island uncovered the first remains of a village buried by the eruption: a single house under three meters of volcanic pumice and ash. Inside the walled

remains, they found two carbonized bodies, perhaps a married couple. The woman, her bones turned to charcoal by the heat, lay on her back, arms extended, holding a long knife. Her sarong, also carbonized, still hung across her shoulder.

Back on the mountain's eastern flank, the rain of volcanic rocks gave way to ashfall, but there was to be no relief for the surviving villagers. The spectacular, jet-like "plinian" eruption (named for Pliny the Younger, who left a famous account of Vesuvius's vertical column of fire) continued unabated, while glowing, fast-moving currents of rock and magma, called "pyroclastic streams," generated enormous phoenix clouds of choking dust. As these burning magmatic rivers poured into the cool sea, secondary explosions redoubled the aerial ash cloud created by the original plinian jet. An enormous curtain of steam and ash clouds rose and encircled the peninsula, creating, for those trapped inside it, a short-term microclimate of pure horror.

First, a "violent whirlwind" struck Koreh, blowing away roofs. As it gained in strength, the volcanic hurricane uprooted large trees and launched them like burning javelins into the sea. Horses, cattle, and people alike flew upward in the fiery wind. What survivors remained then faced another deadly element: giant waves from the sea. The crew of a British ship cruising offshore in the Flores strait, coated with ash and bombarded by volcanic rocks, watched stupefied as a 12-foot-high tsunami washed away the rice fields and huts along the Sanggar coast. Then, as if the combined cataclysms of air and sea weren't enough, the land itself began to sink as the collapse of Tambora's cone produced waves of subsidence across the plain.

PIERDON.

A Scene in St. Giles's.

WORST OF TIMES Charles Dickens, whose grim weatherscapes and portraits of poverty are definitive representations of Victorian London, grew up under the ever-cloudy, bone-chilling atmosphere created by the Tambora eruption.

On the sunless days following the cataclysm, corpses lay unburied all along the roads on the inhabited eastern side of the island between Dompu and Bima. Villages stood deserted, their surviving inhabitants having scattered in search of food. With forests and rice paddies destroyed, and the island's wells poisoned by volcanic ash, some 40,000 islanders would perish from sickness and starvation in the ensuing weeks, bringing the estimated death toll from the eruption to over 100,000, the largest in history.

While the skyward eruptions lasted only about three hours each, the boiling cascade of pyroclastic streams down Tambora's slopes continued a full day. Hot magma gushed from Tambora's collapsing chamber down to the peninsula, while columns of ash, gas, and rock rose and fell, feeding the flow. The fiery flood that consumed the Sanggar Peninsula, traveling up to 19 miles at great speeds, ultimately extended over a 216-square-mile area, one of the greatest pyroclastic events in the historical record. Within a few short hours, it buried human civilization in northeast Sumbawa under a smoking meter-high layer of ignimbrite.

Tambora's cacophony of explosions on April 10, 1815, could be heard hundreds of miles away. All across the region, government ships put to sea in search of imaginary pirates and invading navies. In the seas to the north off Macassar, the captain of the East India Company vessel Benares gave a vivid account of conditions in the region on April 11:

The ashes now began to fall in showers, and the appearance altogether was truly awful and alarming. By noon, the light that had remained in the eastern

part of the horizon disappeared, and complete darkness had covered the face of day ... The darkness was so profound throughout the remainder of the day, that I never saw anything equal to it in the darkest night; it was impossible to see your hand when held up close to the eye.

Across a 600-kilometer radius, darkness descended for two days, while Tambora's ash cloud expanded to cover a region nearly the size of the continental United States. The entire Southeast Asian region was blanketed in volcanic debris for a week. Day after dark day, British officials conducted business by candlelight, as the death toll mounted.

Months after the eruption, the atmosphere remained heavy with dust—the sun a blur. Drinking water contaminated by fluorine-rich ash spread disease and with 95 percent of the rice crop in the field at the time of the eruption, the threat of starvation was immediate and universal. In their desperation for food, islanders were reduced to eating dry leaves and their much-valued horseflesh. By the time the acute starvation crisis was over, Sumbawa had lost half its population to famine and disease, while most of the rest had fled to other islands.

Tambora's violent impact on global weather patterns was due, in part, to the already unstable conditions prevailing at the time of its eruption. A major tropical volcano had blown up six years prior, in 1809. This cooling event, hugely amplified by the sublime Tambora eruption in 1815, ensured extreme volcanic weather across the entire decade.

A flurry of research since the discovery of the 1809 eruption has resulted in the identification of the 1810–19 decade as a whole as the coldest in the historical record—a gloomy distinction. A 2008 modeling study concluded Tambora's eruption to have had by far the largest impact on global mean surface air temperatures among volcanic events since 1610, while the 1809 volcano ranked second over that same period, measuring just over half Tambora's decline. Two papers published the following year confirmed the status of the 1810s as "probably the coldest during the past 500 years or longer," a fact directly attributable to the proximity of the two major tropical eruptions.

The spectacular eruption increased that cooling to a truly dire extent, contributing to an overall decline of global average temperatures of 1.5 degrees Celsius across the decade. One-and-a-half degrees might seem a small number, but as a sustained decline characterized by a sharp rise in extreme weather events—floods, droughts, storms, and summer frosts—the chilled global climate system of the 1810s had devastating impacts on human agriculture, food supply, and disease ecologies.

The Scottish meteorologist George Mackenzie kept meticulous records of cloudy skies between 1803 and 1821 over various parts of the British Isles. Where lovely clear summer days in the earlier period (1803–10) averaged over 20, in the volcanic decade (1811–20) that figure dropped to barely five. For 1816, the Year Without a Summer, Mackenzie recorded *no clear days at all*.

ON THE EVE OF THE SUMMER OF 1816, 18-year-old Mary Godwin took flight with her lover, Percy Shelley, and their baby for Switzerland, escaping the chilly atmosphere of her father's house in London. Mary's young stepsister, Claire Clairmont, accompanied them, eager to reunite with her own poet-lover, Lord Byron, who had left England for Geneva a week earlier. Mary's other sister, the ever dispensable Fanny, was left behind.

The dismal, often terrifying weather of the summer of 1816 is a touchstone of the ensuing correspondence between the sisters. In a letter to Fanny, written on her arrival in Geneva, Mary describes their ascent of the Alps "amidst a violent storm of wind and rain." The cold was "excessive" and the villagers complained of the lateness of the spring. On their alpine descent days later, a snowstorm ruined their view of Geneva and its famous lake. In her return letter, Fanny expresses sympathy for Mary's bad luck, reporting that it was "dreadfully dreary and rainy" in London too, and very cold.

Stormy nor'easters are standard features of Genevan weather in summertime, careening from the mountains to whip the waters of the lake into a sirocco of foam. Beginning in June 1816, these annual storms attained a manic intensity not witnessed before or since. "An almost perpetual rain confines us principally to the house," Mary wrote to Fanny on the first of June from Maison Chappuis, their rented house on the shores of Lake Geneva: "One night we enjoyed a finer storm than I had ever before beheld. The lake was lit up—the pines on Jura made visible, and all the

scene illuminated for an instant, when a pitchy blackness succeeded, and the thunder came in frightful bursts over our heads amid the darkness." A diarist in nearby Montreux compared the bodily impact of these deafening thunderclaps to a heart attack.

In fact, the year 1816 remains the coldest, wettest Geneva summer since records began in 1753. That unforgettable year, 130 days of rain between April and September swelled the waters of Lake Geneva, flooding the city. Up in the mountains the snow refused to melt. Clouds hung heavy, while the winds blew bitingly cold. In some parts of the inundated city, transport was only possible by boat. A cold northwest wind from the Jura mountains—called *le joran* by locals—swept relentlessly across the lake. The Montreux diarist called the persistent snows and *le joran* "the twin evil genies of 1816." Tourists complained they couldn't recognize the famously picturesque landscape because of the constant wind and avalanches, which drove snow across vast areas of the plains.

On the night of June 13, 1816, the Shelleys' splendidly domiciled neighbor, Lord Byron, stood out on the balcony of the lakeside Villa Diodati to witness "the mightiest of the storms" that he—well-traveled aristocrat that he was—had ever seen. He memorialized that tumultuous night in his wildly popular poem "Childe Harold's Pilgrimage":

> The sky is changed—and such a change! Oh night,
> And storm, and darkness, ye are wondrous strong ...
> And now again 'tis black,—and now, the glee
> Of the loud hills shakes with its mountain-mirth,
> As if they did rejoice o'er a young earthquake's birth.

In Byron's imagination, the Tamboran storms of 1816 achieve volcanic dimensions—like an "earthquake's birth"—and take delight in their destructive power.

What caused the terrible weather conditions over Britain and western Europe in 1816–18? The relation between volcanism and climate depends on eruptive scale. Volcanic ejecta and gases must penetrate skyward high enough to reach the stratosphere where, in its cold lower reaches, sulfate aerosols form. These then enter the meridional currents of the global climate system, disrupting normal patterns of temperature and precipitation across the hemispheres. Tambora's April 1815 eruption launched enormous volumes of long-suppressed volcanic rock and gases more than 25 miles into the stratosphere. This volcanic plume—consisting of as much as 12 cubic miles

GHOST STORY One night in1816, in a villa on Lake Geneva, in the dark, dismal atmosphere created by Tambora's eruption, poets (at left) Lord Byron and Percy Shelley, and writer Mary Shelley, told ghost stories that gave birth to Frankenstein's monster and the Byronic Dracula.

Tambora's influence on human history does not derive from extreme weather events considered in isolation but in the myriad environmental impacts of a climate system gone haywire.

of total matter—eventually spread across 386,000 square miles of the Earth's atmosphere, an aerosol umbrella six times the size of the cloud produced by the massive 1991 eruption of Mount Pinatubo in the Philippines.

In the first weeks after Tambora's eruption, a vast volume of coarser ash particles—volcanic "dust"—cascaded back to Earth mixed with rain. But ejecta of smaller size—water vapor, molecules of sulfur and fluorine gases, and fine ash particles—remained suspended in the stratosphere, where a sequence of chemical reactions resulted in the formation of a 60-megaton sulfate aerosol layer. Over the following months, this dynamic, streamer-like cloud of aerosols—much smaller in size than the original volcanic matter—expanded by degrees to form a molecular screen of planetary scale, spread aloft by the winds and meridional currents of the world. In the course of an 18-month journey, it passed across both south and north poles, leaving a telltale sulfate imprint on the ice for paleoclimatologists to discover more than a century and a half later.

Once settled in the dry firmament of the stratosphere, Tambora's global veil circulated above the weather dynamics of the atmosphere, comfortably distanced from the rain clouds that might have dispersed it. From there, its planet-girdling aerosol film continued to scatter shortwave solar radiation back into space until early 1818, while allowing much of the longwave radiant heat from the earth to escape. The resultant three-year cooling regime, unevenly distributed by the currents of the world's major weather systems, barely affected some places on the globe (Russia, for instance, and the trans-Appalachian United States) but precipitated a drastic 5 to 6 degrees Fahrenheit seasonal decline in other regions, including Europe.

The first extreme impact of a major tropical eruption is felt in raw temperature. But in western Europe, biblical-style inundation during the 1816 summer growing season wrought the greatest havoc. Because of the tilt of the Earth in relation to the sun and the different heat absorption rates of land and sea, solar insolation of the planet is irregular. Uneven heating in turn creates an air pressure gradient across the latitudes of the globe. Wind is the weatherly expression of these temperature and pressure differentials, transporting heat from the tropics to the poles, moderating temperature extremes, and carrying evaporated water from the oceans over the land to support plant and animal life. The major meridional circulation patterns, measuring thousands of miles in breadth, transport energy and moisture horizontally across the globe, creating continental-scale weather patterns. Meanwhile, at smaller scales, the redistribution of heat and moisture through the vertical column of the atmosphere produces localized weather phenomena, such as thunderstorms.

In the summer after Tambora's eruption, however, the aerosol loading of the stratosphere heated the upper layer, which bore down upon the atmosphere.

FRANKENSTEIN.

"By the glimmer of the half-exchinguished
light, I saw the dull, yellow eye of the
creature open: it breathed hard, and a
convulsive motion agitated its limbs,
*** I rushed out of the room."

Page 43.

YELLOW EYE An illustration from an 1831 edition of Frankenstein features this indelible line from the novel: "By the glimmer of the half-extinguished light, I saw the dull, yellow eye of the creature open."

The "tropopause" that marks the ceiling of the Earth's atmosphere dropped lower, cooling air temperatures and displacing the jet streams, storm tracks, and meridional circulation patterns from their usual course. By early 1816, Tambora's chilling envelope had created a radiation deficit across the North Atlantic, altering the dynamics of the vital Arctic Oscillation. Slower-churning warm waters north of the Azores pumped over-loads of moisture into the atmosphere, saturating the skies while enhancing the temperature gradient that fuels wind dynamics. Meanwhile, air pressure at sea level plummeted across the mid-latitudes of the North Atlantic, dragging cyclonic storm tracks southward. Pioneering British climate historian Hubert Lamb has calculated that the influential Icelandic low-pressure system shifted several degrees latitude to the south during the cold summers of the 1810s compared to 20th-century norms, settling in the unfamiliar domain of the British Isles, and thus ensuring colder, wetter conditions for all of western Europe.

Both computer models and historical data draw a dramatic picture of Tambora-driven storms hammering Britain and western Europe. A recent computer simulation conducted at the National Center for Atmospheric Research in Boulder, Colorado showed fierce westerly winds in the North Atlantic in the aftermath of a major tropical eruption, while a parallel study based on multiproxy reconstructions of volcanic impacts on European climate since 1500 concluded that volcanic weather drives the increased "advection of maritime air from the North Atlantic," meaning "stronger westerlies" and "anomalously wet conditions over Northern Europe."

Back at the ground level of observed weather phenomena, an archival study of Scottish weather has found that, in the 1816–18 period, gale-force winds battered Edinburgh at a rate and intensity unmatched in over 200 years of record keeping. In January 1818, a particularly violent storm nearly destroyed the beloved St. John's Chapel in the heart of the city. The slowing of oceanic currents in response to the overall deficit of solar radiation post-Tambora had left unusual volumes of heated water churning through the critical area between Iceland and the Azores, sapping air pressure, energizing westerly winds, and giving shape to titanic storms.

It was in this literally electric atmosphere that the Shelley party in Geneva, with Byron attached, conceived the idea of a ghost story contest, to entertain themselves indoors during this cold, wild summer. On the night of June 18, 1816, while another volcanic summer thunderstorm raged around them, Mary and Percy Shelley, Claire Clairmont, Byron, and Byron's doctor-companion John Polidori recited the poet Coleridge's recent volume of gothic verse to each other in the candlelit dimness at the Villa Diodati. In his 1986 movie about the Shelley circle that summer, British film director Ken Russell imagines Shelley gulping tincture of opium while Claire Clairmont performs fellatio on Byron, recumbent in a chair. Group sex in the drawing room might be implausible, even for the Shelley circle, but drug taking is very likely, inspired by Coleridge, the poet-addict supreme. How else to explain Shelley's running screaming from the room at Byron's recitation of the psychosexual "Christabel," tormented by his vision of a bare-chested Mary Shelley with eyes instead of nipples?

From such antics, Byron conceived the outline of a modern vampire tale, which the bitter Polidori would later appropriate and publish under Byron's name as a satire on his employer's cruel aristocratic hauteur and sexual voracity. For Mary, the lurid events of this stormy night gave literary body to her own distracted musings on the ghost story competition, instituted two nights earlier. She would write a horror story of her own, about a doomed monster brought unwittingly to life during a storm. As Percy Shelley later wrote, the novel itself seemed generated by "the magnificent energy and swiftness of a tempest." Thus it was that the unique creative synergies of this remarkable group of college-age tourists—in the course of a few weeks' biblical weather—gave birth to two singular icons of modern popular culture: Frankenstein's monster and the Byronic Dracula.

A week after the memorable night of June 18, Byron and Shelley almost came to grief sailing on Lake Geneva, caught unawares as another violent storm swept in from the east. "The wind gradually increased in violence," Shelley recalled, "until it blew tremendously; and, as it came from the remotest extremity of the lake, produced waves of a frightful height, and covered the whole surface with a chaos of foam." By some miracle

they found a sheltered port, where even the storm-hardened locals exchanged "looks of wonder." Onshore, trees had blown down or been shattered by lightning.

The pyrotechnical lightning displays of June 1816 ignited the literary imagination of Mary Shelley. In *Frankenstein*, she uses the experience of a violent thunderstorm as the scene of fateful inspiration for her young, doomed scientist:

When I was about fifteen years old ... we witnessed a most violent and terrible thunderstorm. It advanced from behind the mountains of Jura; and the thunder burst at once with frightful loudness from various quarters of the heavens. I remained, while the storm lasted, watching its progress with curiosity and delight. As I stood at the door, on a sudden I beheld a stream of fire issue from an old and beautiful oak, which stood about twenty yards from our house; and so soon as the dazzling light vanished, the oak had disappeared, and nothing remained but a blasted stump.

Frankenstein's life is changed in this moment; he devotes himself, with maniacal energy, to the study of electricity and galvanism. In the fierce smithy of that Tamboran storm, Frankenstein is born as the anti-superhero of modernity—the "Modern Prometheus"—stealer of the gods' fire.

TAMBURA'S INFLUENCE ON HUMAN HISTORY does not derive from extreme weather events considered in isolation but in the myriad environmental impacts of a climate system gone haywire. As a result of the prolonged poor weather, crop yields across the British Isles and western Europe plummeted by 75 percent and more in 1816–17. In the first summer of Tambora's cold, wet, and windy regime, the European harvest languished miserably. Farmers left their crops in the field as long as they dared, hoping some fraction might mature in late-coming sunshine. But the longed-for warm spell never arrived and at last, in October, they surrendered. Potato crops were left to rot, while entire fields of barley and oats lay blanketed in snow until the following spring.

In Germany, the descent from bad weather to crop failure to mass starvation conditions took a frighteningly rapid course. Carl von Clausewitz, the military tactician, witnessed "heartrending" scenes on his horseback travels through the Rhine country in the spring of 1817: "I saw decimated people, barely human, prowling the fields for half-rotten potatoes." In the winter of 1817, in Augsburg, Memmingen, and other German towns, riots erupted over the rumored export of corn to starving Switzerland, while the locals were reduced to eating horse and dog flesh.

Meanwhile, back in England, riots broke out in the East Anglian counties as early as May 1816. Armed laborers bearing flags with the slogan "Bread or Blood" marched on the cathedral town of Ely, held its magistrates hostage, and fought a pitched battle against the militia.

In his magisterial account of the social and economic upheaval in Europe during the Tambora period, historian John Post has shown the scale of human suffering to be worst in Switzerland, home to Shelley and her circle in 1816. Even in normal times, a Swiss family devoted at least half its income to buying bread. Already by August 1816, bread was scarce, and in December, bakers in Montreux threatened to cease production unless they could be allowed to raise prices. With imminent famine came the threat of "soulèvements": violent uprisings. Bakers were set upon by starving mobs in the market towns and their shops destroyed. The English ambassador to Switzerland, Stratford Canning, wrote to his prime minister that an army of peasants, unemployed and starving, was assembling to march on Lausanne.

Most shocking of all was the fate of some desperate mothers. In horrific circumstances repeated around the world in the Tambora period, some Swiss families abandoned their offspring in the crisis, while others chose killing their children as the more humane course. For this crime, some starving women were apprehended and decapitated. Thousands of Swiss with more means and resilience emigrated east to prosperous Russia, while others set off along the Rhine to Holland and sailed from there to North America, which witnessed its first significant wave of refugee European migration in the 19th century. The numbers of European immigrants arriving at U.S. ports in 1817 more than doubled the number of any previous year.

Devastated by famine and disease in the Tambora period, the poor of Europe hurriedly buried their dead before resuming the bitter fight for their own survival. In the worst cases, children were abandoned by their

families and died alone in the fields or by the roadside. The well-born members of the Shelley circle were never reduced to such abysmal circumstances. They did not experience the food crises that afflicted millions among the rural populations of western Europe in the Tambora period. Yet the Shelleys' celebrated writings were enmeshed within the web of ecological breakdown following the Tambora eruption.

Byron and Percy Shelley were companions on a weeklong walking tour of Alpine Switzerland in June 1816, during which they debated poetry, metaphysics, and the future of mankind but also found time to remark on the village children they encountered, who "appeared in an extraordinary way deformed and diseased. Most of them were crooked, and with enlarged throats." In *Frankenstein*, the Doctor's benighted creation assumes a similar grotesque shape: a barely human creature, deformed, crooked, and enlarged. Like the hordes of refugees on the roads of Europe seeking aid in 1816–18, the Creature, when he ventures into the towns, is met with fear and hostility, horror and abomination. As the indigent Creature himself puts it, he suffered first "from the inclemency of the season" but "still more from the barbarity of man."

As remarkable a feat of literary imagination as Frankenstein is, Mary Shelley was not wanting for real-world inspiration for her horror story, namely the deteriorating rural populations of Europe, in the climatic upheaval of Mount Tambora. ◎

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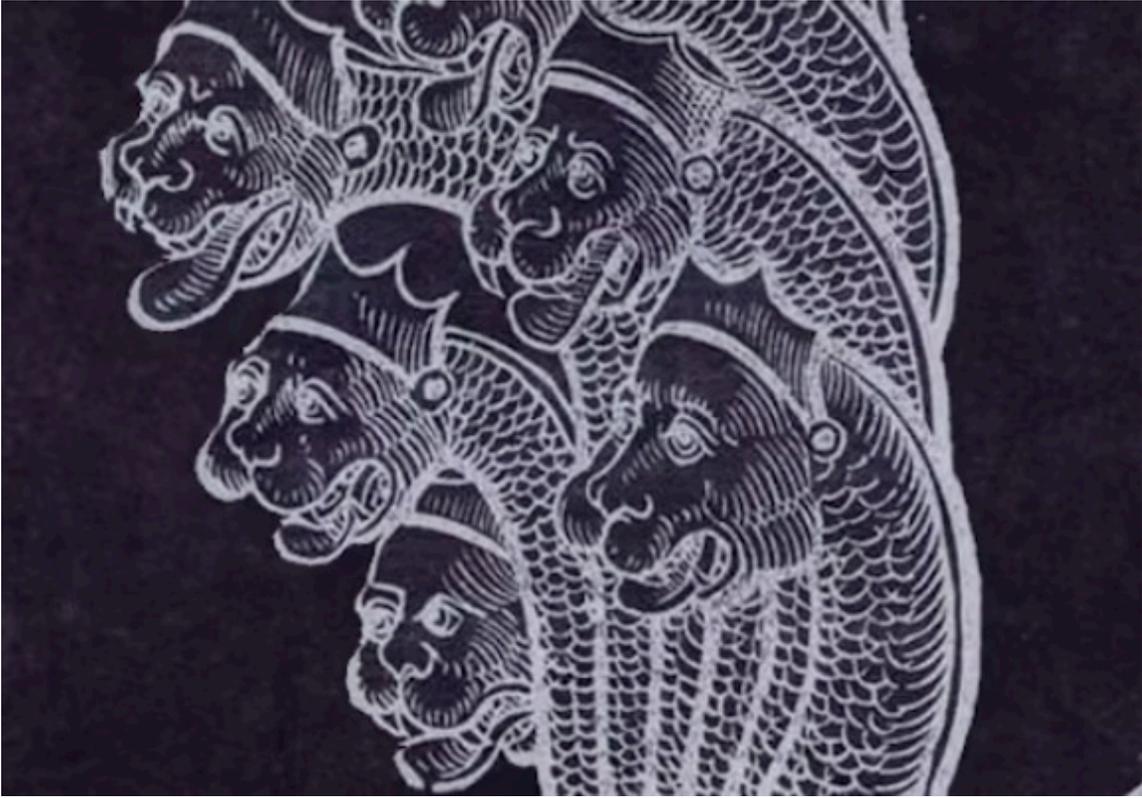
Why Are So Many Monsters Hybrids?

The captivating horror of category violation.

BY STEPHEN T. ASMA

I WAS 13 YEARS OLD when the movie *Alien* was released. It scared me into a month-long spell of anxiety. The hair on the back of my neck was perpetually up and I had the jittery demeanor of a combat veteran. While the full-grown xenomorph alien was chilling, the larval stage face-hugger was terrifying. Not only did it penetrate the human host's throat, planting the chest-burster in the gut, but it was intrinsically grotesque, an odious, zoological mash-up of scurrying spider and slithering snake.

It's easy to interpret our fears of alien predators as nothing more than superficial horror ginned up by the Hollywood fright machine. But they also reveal important truths about human cognition and cultural evolution. We are wired for emotional jolts and these feelings have adaptive benefits. My paralyzing dread of the face-hugger in *Alien* may be a vestige of ancestral primate experiences with snakes and spiders. But the hybrid nature of the *Alien* monster takes us deeper into ourselves and history.

Every culture, it seems, has monstrous mash-ups in their folklore and religion. Composite creatures appear in our earliest literature and turn up in Upper Paleolithic cave paintings. The sphinx in Giza, half-human and half-lion, is at least 4,500 years old. In the *Epic of Gilgamesh* (2100 B.C.), heroes Gilgamesh and Enkidu battle a hybrid monster named Humbaba, described as having a lion's head and hands, but a scaly body. Vishnu, in India, manifests as a fierce lion-man monster, Narasimha, in several Hindu texts. Ganesha, son of Shiva, is humanoid with an elephant head. The many Greek hybrid creatures—centaurs, satyrs, mermaids, Pegasus, Hydra, griffins, chimeras—are constantly resurrected in Hollywood. Literature over the last two millennia, from *Beowulf* to Tolkien to Rowling, has added countless composite creatures and shape-shifters. More recently we have regular hybridizing of humans and computers.

MONSTER MASH The face-hugger in Alien taps into fears and terrors symbolized in folklore and religions through-out human history. 🌀

So why all the taxonomic mashing and mixing? Humans have an innate or an early developmental folk taxonomy of the world, according to psychologist Dan Sperber and anthropologist Pascal Boyer. We have a way of organizing the world into predictable categories for easy understanding, cognition, and manipulation. Even as small children, we seem capable of grouping people, birds, bugs, trees, and fish together into kinds—similar within their category but dissimilar across categories. Not only do kids tend to see whales as "fish," but early natural history made this error too. Our folk taxonomy concerning whales reveals the unsophisticated quality of our natural classifications; if it swims in the water and looks like a fish, it's a fish. To give our brains credit, however, our pre-scientific ancestors didn't need a more nuanced understanding of whales, and we had as much knowledge about them as was probably necessary for survival.

Most humans seem to share very broad mental categories of taxonomy, like "animal," "inanimate object," but also further distinctions like "slithering animals," "flying animals," and "four-legged animals." Whether these are innate or learned, the adult mind uses these mental categories in processing daily experience. The

Most monsters function as disgusting threats that heroes and gods vanquish, repudiate, and cleanse from the community.

brain employs the categories to parse the "blooming, buzzing confusion" of sensory information. We call this the "predictive processing theory of cognition," emphasizing the brain's pattern-recognition system. Our brains create predictive models of the world that help us extract useful signals from ambient informational noise.

Category violations strongly arouse the human mind. When our expectations about the world— "humans have two arms," "snakes don't fly"—are disrupted by Vishnu, with dozens of arms, or flying snakes in the form of dragons, the images grab our attention and become cognitively "sticky." They stick in our memories, recall very easily, and spread throughout the social group. Hybrid monsters, in other words, make excellent memes. Richard Dawkins first argued that while memes were cultural fragments or cognitive units, they were analogical to genes in the sense that they spread through populations without conscious design or purpose. Unnatural ideas or images survive and spread well because they surprise us, making them harder to forget or ignore.

Anthropologist David Wengrow argues that hybrid monsters proliferated during the Bronze Age, because new trade routes and cultural mixing elicited psychological anxiety. Creating monsters is a way of channeling our cultural and political fears into tangible forms, into objects of loathing and dread.

Monsters might not seem like helpful memes because they frighten us and increase stress, but they are almost always part of a larger cultural cautionary tale. The monster plays an important role in norm enforcement. If you don't follow the rules, the bogeyman will get you. If you don't walk the path of virtue, the devil will take you. If you succumb to gluttony, you'll become a "hungry ghost" in the next life (according to Buddhist traditions). Most monsters function as disgusting threats that heroes and gods vanquish, repudiate, and cleanse from the community. They offer surrogate rehearsals for how the real

community ("us") will resist actual enemies ("them"). Monsters are sticky memes that draw groups together into moral communities.

This means that fantasy helps make some of the core elements of culture itself, because monsters and heroes create social solidarity through cultural kinship. The counterfactual nature of fantasy is one of the earliest and most effective ways to create cultural kinship. Early human groups grew to social scales beyond genetic kinship, and culture helped create fictive kin groups. Non-relatives would feel like brothers: cooperating effectively, sharing resources, and killing and dying for each other. Fictive kin groups don't rally around abstract or rational ethical principles, but they do rally around rituals and cults of Vishnu, or Jesus, or Sun Wukong, or animistic spirits. They rally around hybrids and other sticky memes.

THE STORY OF COGNITIVE HYBRIDS has long focused on the evolution of religion. Religion emerges out of cognitive precursors (or pre-adaptations) like folk taxonomy. If our folk categories carve the world into predictable patterns, then occasional category mismatches will spark unique cognitive arousal, producing supernaturalism. Artifacts that speak, or dead creatures that live again, consist in relatively simple category transpositions. Our brain's predictive patterns get mixed up. And these same category mash-ups produce the creatures of horror.

The theory of category mismatch, though, often lacks the emotional ingredient. It's not enough to assume that upending cognitive categories suddenly produces a supernatural entity. We have a concept of dog in our heads, but imagining a dog with three heads doesn't produce the horrible impact of Cerberus. Rather, the content of cognitive categories contains emotional tone from the beginning. Most objects, animals, and people we encounter in daily life trigger low-level feelings of "approach" or "avoid." But the

emotional aspect of a category like "slitherers" or "crawlers" is especially dramatic.

When we conceptualize gods or monsters or other memes, those concepts are infused with shades of fear, or lust, or anger, and complex mixtures of these. Emotions are the oldest form of coding the world into dangerous and beneficial categories. We share this early coding system with other mammals.

Emotional associations are built into our folk taxonomy. While category mismatches arouse our curiosity and improve memory retention, hybrids that carry strong emotional associations (like arachnophobia) will be especially sticky. Effective horror (and religion) has figured out symbols and stories that unconsciously trigger our primitive emotions. As cultural theorist Mathias Clasen argues in his book *Why Horror Seduces*, similar monsters and horror stories work well on people of very different cultural backgrounds. Horror has universal power. In part, this is because human cognition is universally governed by those folk taxonomy categories, so violations will arouse anyone from Manhattan to Morocco. But more important are the universal emotional systems that link natural predator fear and dread with cultural images.

All mammals are equipped with adaptive instincts like fight or flight, but these are old-brain systems, housed primarily in the brainstem. The emotional circuits of the brain (including limbic areas like the amygdala, hypothalamus, and hippocampus) are interwoven with instinctual motor systems as well as our higher cognition. The late neuroscientist, Jaak Panskepp, a pioneer in the study of emotions and mammals, located seven major emotional systems that mammals share: fear, care, lust, rage, panic, seeking, and play. Each of these circuits has unique pathways through the brain, enlists specific neurotransmitters and hormones, and results in specific mammal behaviors. Fear, for example, has a

STICKY MEMES Hybrid-creature icons like Vishnu, in a Hindu incarnation as Matsya (the form of a fish), invade our memory and bind us in communities.

neurocircuitry that passes from the amygdala through the hypothalamus to the brainstem and out through the spinal cord.

Like any other biological trait, fear is subject to evolution. Darwin repeatedly brought snakes (real and fake) down to the London Zoo primate house. He discovered that chimps had an extreme fear of snakes, and wondered how they possessed such a useful dread of threatening species. How could experiential information about snakes be stored in primate DNA for future transmission?

The category violation hypothesis skirts this problem beautifully. Fear comes from any hybrid cognition or category-jamming and not from the content of the cognition. The cognitive tangle creates the emotional arousal, not the animal or monster itself. Of course, not every mash-up strikes fear in the viewer. I'm not terrified of Walt Disney's ballet-dancing hippopotamus or Thomas the Tank Engine. Moreover, emotions like fear seem dedicated to certain environmental threats, and fear operates faster and more powerfully than mere taxonomy confusion.

It could be that fear of creepy crawlies was never "acquired" from conditioned learning, observation, or experience. Hominids that had a random fear response coupled with the perception of spiders lived to reproduce better than the hominids who had a random fear response coupled with the sight of trees. Fear makes you run away and running away from poisonous spiders is more adaptive than running away from harmless trees. In this view, all humans have an inherited synapse coding that mechanically paints spider-shaped perceptions with fear, independent of "learning" (observing the harm that poisonous spiders do). If the brain makes an epinephrine-soaked spider-shaped predictive pattern, then we run and live long enough to reproduce it.

Psychologists Donald Hebb and Wolfgang Schleidt separately experimented on fear in animals and found that fear is not a result of a hardwired phobia of specific predators, but a developmental pairing of our categories and our feelings. When birds and mammals are born they have flexible categories that store associations. But these categories solidify quickly after birth and become default ways of interpreting the world. When any strange creature appears (one not corresponding to the default categories), the subject becomes aroused

Our brain's predictive patterns get mixed up. And these same category mash-ups produce the creatures of horror.

and fearful. By exposing songbirds to hawk shapes early on (hawks are natural predators) researchers eliminated their hawk fear, but late exposure to goose shapes (no threat) produced fear responses in the songbirds.

According to psychologist Mary Ainsworth's "strange situation" experiments, human default categories solidify around 6 months old, and babies after that time are much more frightened by anything "strange." If human babies spent most of their first year strapped to their mothers or otherwise protected (and off the ground), then creepy crawlies of every variety would, once encountered, radically disturb the default taxonomy laid down in the child's first six months.

This work on cognitive and emotional development explains why there is a relatively small number of universal human phobias, including arachnophobia (fear of spiders), herpetophobia (fear of snakes), nyctophobia (fear of the dark), and a few others like fear of murky or deep water. However, once culture starts hybridizing these elements in religion and horror, the images become extremely sticky memes.

It's no wonder, then, the face-hugger in Alien struck terror in me—and still does. Not only does it spark primeval brain processes, but it also binds me to my cultural heritage, and my very species. Following earlier religious and literary traditions, Hollywood horror unconsciously taps this same deep biocultural reservoir. ⊚

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When Good Waves Go Rogue

Even in calm seas, waves can become monsters.

BY TOM VANDERBILT

ILLUSTRATION BY JOHN HENDRIX

E ARLY IN THE MORNING on Sept. 11, 1995, the cruise liner the Queen Elizabeth 2, on its way from Southampton to New York, was being lashed by the tail end of Hurricane Luis, somewhere off the coast of Newfoundland. As if sensing its imminent demise, Luis had galvanized one last time, twitching to life and whipping the North Atlantic into a torrent of 130 mph winds and 40-foot waves. None of this caused undue concern for the ship's captain, Ronald Warwick, a 30-year sailing veteran well acquainted with rough seas. Luis was hardly unexpected; since leaving England, the ship had steadily tracked the storm's path. "This was fair game for us," the retired Commodore recalls, from his home in Somerset, England. "We are a transatlantic liner."

At dinner, Warwick had advised the ship's passengers that things might get a bit rough during the night, and to secure any loose possessions in their cabin. He then did what any captain would do in heavy seas. With the ship steered into the waves, Warwick slowed it to a few knots. "Heaving to" it is called, the idea being to ride out the waves as gently as possible, while maintaining just enough speed to maintain steering control. Far below the ship's bridge, where winds roared and whipped against the armored windows, a handful of passengers held casual vigil in a bar.

The anomalousness of this one wave still haunts Warwick.

Just after 2 a.m., Warwick and his officers suddenly saw a surging monster of water and convulsive white froth in the near distance. "If you're standing on the bridge of the QE2," he says, "your height of eye above sea level is 90 feet." From what they could discern through the rain-soaked darkness, the crest of the looming wave was as high as the bridge itself. Warwick, who says he had never encountered anything so large in the ocean before, said it was as if they were heading into the "white cliffs of Dover."

A minute or so later, the wave crashed across the forward deck of the QE2. "We didn't go over the top of it," says Warwick. "We virtually went through it." A series of judders shot through the ship. The wall of water crashed down on the ship's deck, buckling its steel plates some 18 inches. Still, this was all within the operating bounds of the ship. "We weren't knocked off our feet or anything," he says. "Most passengers were in bed."

But the anomalousness of this one wave still haunts Warwick. For an old North Sea hand, 40-foot waves, the kind that would terrify most of us, were nothing out of the ordinary. But the emergence from nowhere of a single wave that was more than twice as high as the others was exceptional. Warwick had encountered a rogue wave.

IN THE COMMON PARLANCE, "rogue wave" has come to mean any wave that is unusually large. But a rogue wave does not have to be big on an absolute scale, nor is it necessarily associated with a heavy storm. Burkard Baschek, director of the Institute of Coastal Research, in Geesthacht, Germany, defines it as any wave that is statistically extreme. "[A rogue wave is] at least twice as high as the so-called significant wave height," he says. The significant wave height is defined as the average of the largest one-third of waves at any given moment, "the waves you would see by eye if you're out there and looking at the sea state."

This means you have probably experienced a rogue wave and not noticed. How? "If you're out in calm conditions," says Baschek, "and the waves are one meter high, and suddenly you experience a two meter wave, so what?" In fact, Baschek says one wave per day, somewhere in the world's oceans, is a rogue wave. While at the University of California, Los Angeles (UCLA), he analyzed data from a number of buoys off the west coast of the United States and, extrapolating the figures globally, estimated that ships trawling the North Atlantic (like the QE2) would "encounter 20-30 of these rogue waves during their service lives of 25 years," or about one a year.

That rogue waves are, at base, mathematical objects has meant that sailors, then scientists, have been slow to grasp their nature. Late into the 19th century, the line between sailors' lore and science could be as blurred as a fog-bound horizon, with reputable journals routinely reporting on the sightings of "monsters of the sea." By the mid-20th century, though, most of these monsters had been dispelled or explained—but not rogue waves, which continue to be misidentified and incompletely understood today. Even one of civilization's most famous waves, Hokusai's *The Great Wave off Kanagawa*, is often misinterpreted as a tsunami—the woodcut has even been used as the symbol of a UNESCO tsunami warning sign—when it is actually more likely a rogue wave, as several scholars have argued.[1,2]

The science of rogue waves began to take shape in the early 1960s, not in the ocean but in a wave tank—essentially a long, shallow trough with a "paddle" for generating waves of varying frequencies—in Cambridge University's Engineering Department. There, the physicist and fluid dynamics expert T. Brooke Benjamin, aided by a graduate student named Jim Feir, were having trouble trying to prove something that had long been assumed: the stability of the so-called "Stokes wave," the sort of Ur-wave, or prototypical wave, of fluid dynamics, theorized by the renowned 19th-century Cambridge University mathematician George

SURF'S UP *The Great Wave off Kanagawa* by Hokusai is often assumed to depict a tsunami, but is more likely to be a rogue wave.

Gabriel Stokes. Stokes, inspired by a British engineer's faintly astonished report of a "solitary heap of water," pushed along by a slowing boat, that had maintained its speed and shape for nearly two miles as it traveled through a canal, looked for an equation that could describe a wave propagating in shallow water without changing shape.[3]

It had been rather taken for granted that the Stokes "wave trains," as they were called, were essentially stable. But engineers working in wave tanks — testing ships' hydrodynamics and the like—were finding instabilities.[4] As they set out in their own search of stability, Feir and Benjamin noticed something odd. Their colleague, J.C.R. Hunt, wrote that the two "observed how waves generated at the wave maker started as a regular train with constant frequency and wavelength,

but then about 5 m down the tank began to form into groups of waves with varying frequencies and wavelengths."[5] Thinking it might be a problem with the wave generating hardware, they first worked out a solution to keep the frequency from shifting. They then moved to a larger tank, with a programmable wave maker. But the results were the same. As the wave moved down the tank, it was buffeted by "sidebands" of higher and lower frequency. Critically, these sidebands grew exponentially in amplitude, or height, as they traveled down the tank.

The effect, now known as the "Benjamin-Feir instability," offered a hint as to how rogue waves form. As J.B. Zirker describes in his book, *The Science of Ocean Waves*, the wave group, once it found a kind of sweet spot of modulation, stole energy from itself to produce a single

One of civilization's most famous waves is often misinterpreted as a tsunami.

high wave—higher than might be expected from the normal dynamics of the waves—then "returned" it to the primary wave. "The sidebands grew exponentially in height at the expense of the primary wave, which eventually disintegrated," he writes. "Nobody had ever seen or expected the likes of this before."

What ultimately made the concept of rogue waves so striking was not simply that they could grow to unexpected heights, but that they occurred more frequently than they were expected to. As Eric Heller, a physicist at Harvard University, explains it, much of the thinking on large wave creation was influenced by M.S. Longuet-Higgins, the noted mathematician and oceanographer, who was, as he wrote in one study, trying to "study theoretically the statistical properties of a random, moving Gaussian surface." In other words, the ocean.

"His theory was based on the random addition of waves," Heller says. "He was uniformly adding them up over large areas and asking how many unlucky additions you would get resulting in large waves." It was a linear process. According to Heller, there was just one problem: "There were more freak wave events [in reality] than that theory could ever really account for. Light bulbs went off in people's heads—it must be nonlinear evolution!"

And so rogue waves crashed into the longstanding "Gaussian seas" model of randomly distributed wave heights. They were not quite as long-tail as had been thought, and new probabilities, like the so-called "Tayfun distribution" (which coincidentally sounds like "typhoon" but is named for a Turkish scholar) have gained currency to predict the likelihood of rogue waves.

ONE OF THE BIGGEST BOONS to the study of rogue waves came not in the laboratory, but in the ocean itself. On the night in 1995 that the QE2 was struck by the giant wave, there was another witness, one who experienced the wave from a deeply immersive position: "Buoy 44139," an instrumented floating beacon monitored by the Canadian Forces Meteorological Office at Halifax. The statistical graph it generated during the torment is simple, yet chilling. There is a slightly jagged saw-tooth line of wave heights, the 40-foot rollers that Warwick had hove to against. But then, with no anticipatory buildup, there rises a single, dramatic peak, leaping toward the top of the page, almost, literally, "off the charts." Just as suddenly, it plunges again, as if it were never there.

Buoys like 44139, equipped with accelerometers and other measuring devices, brought precision to an arena where sailor's accounts and estimations had dominated. Before their advent, gauging the heights of waves was an inexact process. One early, and complicated, effort involved photographing the ocean from an airplane and mathematically estimating wave height via the reflection of light.[6]

But buoys are far from perfect. They get overtopped by waves, or knocked on their sides. There is also an issue of selection bias. Most instrumented buoys are located close to shore, says Baschek, while the largest rogue waves occur more frequently on the open ocean. Not all buoys can measure the direction of waves. And the big wave measurements that have been captured— the QE2, or, in another well-known instance earlier that same year, a 30-meter wave captured on the oil

platform Draupner off the coast of Norway—are single point measurements. "It's a buoy or a radar point," he says. "But you have no idea what the crest length is. If you measure a rogue wave, is it one local spray, or is it going over miles and miles? How long does it persist? Does this rogue wave form right before your buoy and fall apart right after that? This is also something you don't know."

As a striking reminder of how science, even with its ever more sophisticated and powerful measurement capabilities, is still catching up with the enormity of the ocean, it was only in 2011 that the long-suspected, but never observed, phenomena of "merging tsunami"— two waves (formed non-linearly) becoming (linearly) a more powerful one—was finally observed in the wild, thanks to a procession of satellites orbiting over the tsunami. The capture of the merging tsunami was a "one in 10 million chance" random observation, as an investigator put it.[7]

For these reasons, even in this age of networked data and supercomputer simulations, some of the best data on rogue waves continues to come from the men and women who work on the sea. ◉

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REFERENCES

1. Cartwright, J.H.E. & Nakamura, N. What Kind of a Wave is Hokusai's *Great Wave Off Kanagawa*. *Notes and Records: The Royal Society Journal of the History of Science* **63**, 119–135 (2009).

2. Dudley, J.M., Sarano, V., & Dias, F. "On Hokusai's *Great Wave Off Kanagawa:* Localization, linearity and a rogue wave in sub-Antarctic Waters. *Notes and Records: The Royal Society Journal of the History of Science* **67**, 159-164 (2013).

3. Zirker, J.B. *The Science of Ocean Waves* Johns Hopkins University Press (2013).

4. Drazin, P.G. & Reid, W.H. *Hydrodynamic Stability* Cambridge University Press (2004).

5. Hunt, J.C.R. Nonlinear and Wave Theory Contributions of T. Brooke Benjamin (1929-1995) *Annual Review of Fluid Mechanics* **38**, 1-25 (2006).

6. Jahne, B., Schmidt, M., & Rocholz, R. Combined optical slope/height measurements of short wind waves: principle and calibration. *Measurement Science and Technology* **16**, 1937-1944 (2005).

7. Buis, A. & Cole, S. NASA finds Japan tsunami waves merged, doubling power. NASA.gov (2011).

Math's Beautiful Monsters

How a destructive idea paved the way for modern math.

BY ADAM KUCHARSKI

ILLUSTRATIONS BY SHOUT

MUCH LIKE ITS CREATOR, Karl Weierstrass' monster came from nowhere. After four years at university spent drinking and fencing, Weierstrass had left empty handed. He eventually took a teaching course and spent most of the 1850s as a schoolteacher in Braunsberg. He hated life in the small Prussian town, finding it a lonely existence. His only respites were the mathematical problems he worked on between classes. But he had nobody to talk to about mathematics, and no technical library to study in. Even his results failed to escape the confines of Braunsberg. Instead of publishing them in academic journals as a university researcher would, Weierstrass added them to articles in the school prospectus, baffling potential students with arcane equations.

Eventually Weierstrass submitted one of his papers to the respected *Crelle's Journal*. While his previous articles had made barely a ripple, this one created a flood of interest. Weierstrass had found a new way to deal with a fiendish class of equations known as Abelian functions. The paper only contained an outline of his methods, but it was enough to convince mathematicians they were dealing with a unique talent. Within a year, the University of Königsberg had given Weierstrass an honorary doctorate, and soon afterward the University of Berlin offered him a professorship. Despite having gone through the intellectual equivalent of a rags to riches story, many of his old habits remained. He would rarely publish papers, preferring instead to share his work among students. It was not just the publication process he had little regard for: He was also not afraid to target mathematics' sacred cows.

If Newton had known about such functions, he would have never created calculus.

Weierstrass soon took aim at the research of Augustin-Louis Cauchy, one the century's most eminent mathematicians. Much of Cauchy's work focused on calculus and rates of change (or "derivatives"). He had created what was in essence a calculus dictionary, specifying the subject's most important concepts. But when Weierstrass read its definitions, he found them to be wordy and vague. There was too much hand waving, and not enough detail.

He decided to revise Cauchy's dictionary by replacing the prose with logical conditions. Chief among this early work was the redefinition of a derivative. To calculate the gradient of a curve at a certain point—and hence its rate of change—Isaac Newton had originally considered a line that passed through the point of interest and a nearby point on the curve. He then moved that nearby point closer and closer, until the slope of the line was equal to the gradient of the curve. But it was difficult to define the concept mathematically. What dictated whether two points were "close" to each other?

In Cauchy's verbose definition, the gradient would "approach indefinitely to a fixed value, in a manner so as to end by differing from it by as little as one wishes." Weierstrass did not think this was clear enough. He wanted a more practical definition, so decided to convert the concept into a formula. Rather than manipulating abstract ideas, mathematicians would instead be able to rearrange equations. In doing so, he was laying the foundations for his monster.

AT THE TIME, MATHEMATICIANS drew much of their inspiration from nature. When Newton first developed calculus, he'd been inspired by the physical world: the trajectory of a planet, the swinging of a pendulum, the motion of falling fruit. This thinking led to a geometrical intuition about mathematical structures. They should make sense in the same way that a physical object would. As a result, many mathematicians concentrated on "continuous" functions. Conceptually, these are functions that can be drawn without taking pen from paper. Plot the speed of a falling apple over time and it will be a solid line; there will be no gaps or sudden jumps. A continuous function was, it was thought, a natural one.

Conventional wisdom held that for any continuous curve, it was possible to find the gradient at all but a finite number of points. This seemed to match intuition: A line might have a few jagged bits, but there would always be a few sections that were "smooth." The French physicist and mathematician André-Marie Ampère had even published a proof of this claim. His argument was built on the "intuitively evident" fact that a continuous curve must have sections that increase, decrease, or remain flat. Which meant that it must be possible to calculate the gradient in these regions. Ampère did not think about what happened when the sections became infinitely small, but he claimed that he didn't need to. His approach was general enough to avoid having to consider things that were "*infiniment petits*." Most mathematicians were happy with his reasoning: By the middle of the 19th century, almost every calculus textbook quoted Ampère's proof.

But during the 1860s, rumors started circulating about a strange creature, a mathematical function that contradicted Ampère's theorem. In Germany, the great Bernhard Riemann told his students that he knew of a continuous function that had no smooth sections, and for which it was impossible to calculate the derivative of the function at any point. Riemann did not publish a proof, and neither did Charles Cellérier at the University of Geneva, who—despite writing that he'd discovered something "very important and I think new"—stuffed the work into a folder that would only become public after his death decades later. Yet if the claims were to be believed, it meant a threat to the very foundations of calculus was forming. This creature threatened to tear apart the happy relationship between mathematical theory and the physical observation on which it was based. Calculus had always been the language of the planets and stars, but how could nature be a reliable inspiration if there were mathematical functions that contradicted the central ideas of the subject?

The monster was finally born in 1872, when Karl Weierstrass announced that he had found a function that was continuous and yet not smooth at any point. He had constructed it by adding together an infinitely long sequence of cosine functions:

$$f(x) = \frac{\cos(3x\pi)}{2} + \frac{\cos(3^2 x\pi)}{2^2} + \frac{\cos(3^3 x\pi)}{2^3} + \cdots$$

As a function, it was ugly and awkward. It was not even clear what it would look like when plotted on a graph. But that didn't matter to Weierstrass. His proof consisted of equations rather than shapes, and this was what made his announcement so powerful. Not only had he created a monster, he'd built it from concrete logic. He had taken his new, rigorous definition of a derivative and shown it was impossible to calculate one for this new function.

THE RESULT THREW THE MATHEMATICS community into a state of shock. The French mathematician Émile Picard pointed out that if Newton had known about such functions, he would have never created calculus. Rather than harnessing ideas about the physics of nature, he would have been stuck trying to clamber over rigid mathematical obstacles. The monster also began to trample over previous research. Results that had been "proven" started to buckle. Ampère had used the vague definitions favored by Cauchy to prove his smoothness theorem. Now, his arguments began to collapse. The vague notions of the past were hopeless against the monster. Worse, it was no longer clear what constituted a mathematical proof. The intuitive, geometry-based arguments of the previous two centuries seemed to be of little use. If mathematics tried to wave the monster away, it would stand firm. With one bizarre equation, Weierstrass had demonstrated that physical intuition was not a reliable foundation on which to build mathematical theories.

Established mathematicians tried to brush the result aside, arguing that it was awkward and unnecessary. They feared that pedants and troublemakers were hijacking their beloved subject. At the Sorbonne, Charles Hermite wrote, "I turn with terror and horror from this lamentable scourge of functions with no derivatives." Henri Poincaré—who was the first to call such functions monsters—denounced Weierstrass' work as "an outrage against common sense." He claimed the functions were an arrogant distraction, and of little use to the subject. "They are invented on purpose to show our ancestors' reasoning is at fault," he said, "and we shall never get anything more out of them."

Many of the old guard wanted to leave Weierstrass' monster in the wilderness of mathematics. It didn't help that nobody could visualize the shape of the animal they were dealing with—only with the advent of computers did it become possible to plot it. Its hidden form made it hard for the mathematics community to grasp how such a function could exist. Weierstrass' style of proof was also unfamiliar to many mathematicians. His argument involved dozens of logical steps, and ran to several pages. The trail of ideas was subtle and technically demanding, with no real-life analogs to guide the way. The instinct was to avoid it.

But monsters have a habit of finding their way in from the cold. Indeed many concepts that now seem obvious, even essential, were once monsters. Negative numbers were shunned by mathematicians for centuries. The ancient Greeks, who dealt chiefly with geometry, saw no need for them. Nor

The $1 million prize remains unclaimed. In many ways, it is a ransom.

did the medieval academics who adopted Greek ideas. The shadow of this monster will occasionally still appear today, such as when a child asks why multiplying two negative numbers together produces a positive one. But overall the beast has been tamed; nobody would dream of exiling it again.

In a similar fashion, Weierstrass' monster began to find acceptance. In 1904, Albert Einstein introduced physicists to the idea of "Brownian motion": Particles in a liquid, he said, follow a random path because fluid molecules are constantly knocking them around. The collisions are so frequent (more than 1021 per second) that no matter how good the microscope, or how detailed the observation, the trajectories are never smooth. At the practical level, it is not possible to find a derivative. If researchers wanted to work with such problems, they would need to confront Weierstrass' monster—and that is exactly what Einstein did. His theory for Brownian motion used functions that were infinitely jagged. It set a long-standing precedent: Physicists have used non-smooth functions as a proxy for Brownian motion ever since.

Once it became clear that the so-called "Weierstrass function" was actually quite useful, researchers began to develop ways to handle non-smooth functions gracefully. Rather than trying to analyze the path of a single particle in a liquid, they would look at the average behavior of many particles. How far were they likely to travel? When might they reach a given point? Outside of Brownian motion, mathematicians also started to rethink the basic tools of calculus. Rates of change had always been defined in terms of distances, and areas under a curve measured geometrically. But when functions were not smooth, these ideas did not make sense.

At the University of Tokyo, Kiyoshi Itō found a way around the problem by thinking in terms of probabilities. It was an unorthodox, not to mention risky, tactic: During the 1940s, hardly anyone viewed probability theory as a rigorous subject. Yet Itō persevered. He treated functions like random processes, and translated Weierstrass' definitions into a new, probability-based language. Two random processes were "close" together, he said, if the expected outcomes were the same. He introduced a method for handling a mathematical function that depends on a non-smooth quantity—like Brownian motion—rather than a more traditional variable, like distance. Using his new methods, he derived "Itō's Lemma" to calculate how such a function changes over time.

By the 1970s, Itō's work had blossomed into a whole new area of mathematics, called stochastic calculus (mathematicians like calling things that are random "stochastic"). It came with a whole new set of tools and theorems, just as calculus had. Today, stochastic calculus is used to study all sorts of phenomena, from neurons firing in a brain to diseases spreading through a population. It is also at the heart of financial mathematics, where it helps banks estimate option prices. It can account for the bumpy behavior of a stock price, and hence reveal how the value of an option changes over time. The resulting equation, which is known as the Black-Scholes formula, is now used on trading floors around the world. Yet Itō was always puzzled when he won plaudits from bankers. As a pure mathematician, he hadn't expected his work to become famous for its applications.

Weierstrass' monster shook things up in geometry too. At the end of the 19th century, Swedish mathematician Helge von Koch had become interested in the idea of non-smooth functions, but he wanted to see their shape. He set out to build a shape (rather than a function) that was nowhere smooth, and hence show that the same monsters were lurking in both algebra and geometry. He might not be able to draw the Weierstrass function, but he would be able to picture its cousin. Working on the problem while hopping from one temporary job to another as a junior professor, von Koch found his creature in 1904. Constructed by taking an equilateral triangle, then adding three smaller triangles to each side, and continuing to do so indefinitely, it was a geometric shape that was continuous but had no derivatives. The shape's distinctive appearance meant it soon became known as the "Koch snowflake."

Koch had succeeded in extending Weierstrass' monster beyond the world of equations and functions. But there was something else noteworthy about his result. Upon closer inspection, it turned out that his snowflake had a curious self-similarity: Magnify one particular section of the snowflake and it would look similar to the zoomed-out shape. Many years later, it would become apparent that the Weierstrass function had the same property.

As time went on, this self-similarity began cropping up in all sorts of places. It would take Benoît Mandelbrot's seminal work during the 1980s to popularize the idea of "fractal" objects, which had shapes that were

repeated at smaller and smaller length scales. From coastlines and clouds to plant and blood vessels, mathematicians discovered that fractals were ubiquitous in nature. Like Koch's snowflake, none were smooth. How could they be? If the shape had smooth sections, the pattern would disappear when magnified sufficiently. As Koch had found, the simplest way to obtain a non-smooth shape was to construct a fractal object. Perhaps it was inevitable that Weierstrass' work would guide mathematicians towards self-similar patterns, introducing researchers to a world of intricate, beautiful structures.

WEIERSTRASS' MONSTER CONTINUES its work in the present day. The Navier-Stokes equations describe the motion of a fluid and underpin modern fluid dynamics and aerodynamics, driving everything from aircraft design to weather prediction. However, although they were first developed in the 1840s, mathematicians still do not know if they can always be solved. In 2000, the Clay Mathematics Institute offered a $1 million prize to anyone that could show that the equations always have smooth solutions—or find an example to the contrary. The problem is considered among the six most important outstanding problems in mathematics because, despite the widespread use of the Navier-Stokes equations, mathematicians do not know whether the equations always produce physically plausible results. The $1 million prize remains unclaimed. In many ways it is a ransom, encouraging mathematicians to hunt for troublesome monsters.

From fluid dynamics to finance, creatures like the Weierstrass function have challenged our ideas about the relationship between mathematics and the natural world. Mathematicians around the time of Weierstrass used to believe that the most useful mathematics was inspired by nature, and that Weierstrass' work did not fit into that definition. But stochastic calculus and Mandelbrot's fractals have proven them wrong. It turns out that in the real world—the messy, complex real world—monsters are everywhere. "Nature has played a joke on the mathematicians," as Mandelbrot put it. Even Weierstrass himself fell victim to the trick. He created his function to argue that mathematics should not be based only on physical observations. His followers believed that Newton had been constrained by real-life intuition and that, once free of these limitations, there were vast, elegant new theories to be discovered. They thought that mathematics would no longer need nature. Yet Weierstrass' monster has revealed the opposite to be true. The relationship between nature and mathematics runs deeper than anyone ever imagined. ◉

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