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CHAPTER 1

REVERSING EXTINCTION

A few years ago, a colleague of mine practically bit my head off for getting the end date of the Cretaceous period wrong by *a little bit*. I was presenting an informal seminar about my research to graduate students at my university, which at the time was Penn State. My seminar was about mammoths—in particular, about when, where, and why mammoths went extinct, or at least what we've learned about the mammoth extinction by extracting bits of mammoth DNA from frozen mammoth bones. Before talking about this very recent extinction, I opened with a discussion of older and more famous extinctions. My offending slide cited the date for the end of the Cretaceous period and beginning of the Paleogene, also known as the K-Pg boundary and best known as the time of the extinction of the dinosaurs, at "around 65 million years ago." That date, I was told, was inexcusably imprecise. The K-Pg boundary occurred 65.5 ± 0.3 million years ago (at least that was the scientific consensus of the time), and I was *not* to be forgiven those 200,000 to 800,000 years.

While I appreciate that my fellow academics would have preferred meticulous attention to detail, I did not bring up the dinosaurs to discuss the precise timing of their demise. My goal was simply to make the point that while we think we now know why the dinosaurs went extinct so many millions of years ago, we still argue about what caused extinctions that took place within the last ten thousand years. Did the mammoths and other ice age animals go extinct because Earth's climate was suddenly too warm to support them? Or did our ancestors hunt them to death? The question remains open, perhaps because we are not particularly comfortable with the answer.

The last dinosaurs went extinct after a massive asteroid struck just off the coast of Mexico's Yucatan Peninsula. Similar cataclysmic events—major explosive volcanic eruptions or impacts of large asteroids or comets—are thought to have caused the other four mass extinctions in Earth's history. Each time, dense clouds of dust and other debris were suddenly ejected into the atmosphere, blocking out the sunlight. Without sunlight, the plants suffered and many species died. As the plant communities collapsed, so did the animals that ate the plants, and then the animals that ate the animals that ate the plants, and so on up the food chain until somewhere between 50 percent and 90 percent of all species that were alive at the time of the catastrophic event became extinct.

The mammoth extinction is different. We know of no single catastrophic event that happened within the last 10,000 years that might have caused mammoths to go extinct. Recent genetic research shows that mammoth populations probably started to decline sometime during or just after the peak of the last ice age some 20,000 years ago, as the rich arctic grasslands—often called the steppe tundra—on which they relied for food were gradually replaced by modern arctic vegetation. Mammoths were extinct in continental North America and Asia by around 8,000 years ago but survived for another few thousand years in two isolated locations in the Bering Strait: the Pribilof Islands off the western coast of Alaska, where mammoths survived until around 5,000 years ago, and Wrangel Island off the northeastern coast of Siberia, where they survived until around 3,700 years ago.

We know from the fossil record that mammoths, steppe bison, and wild horses dominated the Arctic landscape for a long time before the peak of the last ice age. In fact, they were the most abundant large mammals in the North American Arctic for most of the last 100,000 years. This was a very cold period of Earth's history and included two ice ages—one that peaked at around

80,000 years ago and another that peaked around 20,000 years ago—separated by a long cold interval. It was only after the peak of the most recent ice age that the climate really began to warm up, transitioning into the present warm interval (the Holocene epoch) by around 12,000 years ago. Because mammoths, steppe bison, and wild horses disappeared only *after* the Holocene had begun, it is reasonable to conclude that these species may simply have been adapted to living in a cold climate. When the world warmed up, the cold-adapted went extinct.

While this explanation is attractively simple, it has some problems. Most importantly, while we know from the fossil record that woolly mammoths lived in North America throughout at least the last 200,000 years, that period does not include only very cold intervals. In fact, around 125,000 years ago, Earth was as warm as or warmer than it is today. This was the peak of what we call the last interglacial period, which lasted from around 130,000 years ago until the beginning of the ice age around 80,000 years ago. Remains of mammoths, steppe bison, and wild horses are found in the fossil record of the last interglacial, indicating that they were able to survive despite the warmer climate. Their bones were, however, much less abundant during the interglacial than they were during the later, cold interval. According to the fossil record from the interglacial, a different community of animals dominated the warm Arctic from that which dominated when it was cold. The community of the interglacial period included giant sloths, camels, mastodons, and giant beavers: animals that were adapted to life in a warm climate.

If we look further back in time in the fossil record, a pattern begins to emerge. The Pleistocene epoch lasted from around 2.5 million years ago until around 12,000 years ago, when the Holocene epoch began. During the Pleistocene, our planet experienced at least twenty major shifts between cold, glacial intervals (ice ages) and warmer interglacial intervals. Average temperatures swung a whopping 5°–7°C with each climatic shift. Glaciers advanced or retreated, causing plants and animals to scramble (figuratively) to find suitable habitat. When the climate was cold, cold-adapted species were widespread. When it was warm, these cold-adapted species survived in isolated patches of refugial habitat, often at the edges of their former ranges. During the warm periods, warm-adapted species were widespread, and these warm-adapted species became restricted to warm refugia when it was cold. Range shifts were common during the Pleistocene, but extinctions were rare. And then, around 12,000 years ago, the climate swung from cold to warm, just as it had many times before. This time, however, cold-adapted fauna did not simply become less abundant. This time, many of them went extinct.

What was different about this most recent climate shift? The answer is not entirely clear. However, one potential explanation stands out: By the beginning of the Holocene, a new species had appeared on nearly every continent. This new species had a remarkably big brain and a capacity to transform its habitat to suit its needs, rather than seek habitats to which it was best adapted. This species was also alarmingly destructive. Wherever it went, its arrival seemed to coincide with the extinction of other, mostly large-bodied species. This species was, of course, humans.

Was it our fault that mammoths and other ice age animals went extinct? Interestingly, there is strong evidence that climate, and not humans, may have triggered the declines toward extinction. Humans and mammoths lived together in the arctic regions of Europe and Asia for many thousands of years during the last of the Pleistocene ice ages. The archaeological record shows that humans did hunt mammoths during this time, but since mammoths survived until much later, this hunting pressure was clearly not sufficient to drive mammoths to extinction. In North America, there is even clearer evidence that climate is to blame for diminishing mammoth populations. Humans did not arrive in North America until well after the populations of mammoths, steppe bison, and wild horses had already begun to decline toward extinction. Given this evidence, it is tempting to conclude that these extinctions were not our fault. After all, if we were not there, we could not have done it.

It is important, however, to understand the difference between declining populations and disappearing populations. Estimates of population size based on the fossil record or from genetic data can pinpoint when species began to decline from their ice age peaks but not when they actually went extinct. If we focus on disappearance rather than on decline, it is difficult to say with confidence that humans did not play a pivotal role in these extinctions. Populations of cold-adapted animals declined during every warm interval, not just during the most recent warm interval. In the past, however, these populations survived by finding and hiding out in refugial habitats, biding their time until the next cold period got under way. They probably did exactly that when the present warm interval began. This behavior, however, may have made them more vulnerable to extinction once humans were in the picture.

Ultimately, mammoths, steppe bison, and wild horses probably went extinct because of a combination of climate change, human hunting, and the disappearance of the steppe tundra. Rapid warming after the last ice age led to a decline in crucial habitat. Fewer herbivores trampling and consuming the vegetation meant that nutrients recycled more slowly, reducing the productivity of the ecosystem. To make matters worse, a new and intelligent predator appeared that was capable of zeroing in on any remaining ice-age habitat as ideal hunting grounds. Growing human populations and increasingly sophisticated human technologies further isolated these refugial populations from each other and from the resources they needed to survive. For some species, refugial populations may have held on well past the beginning of the Holocene. For example, our DNA work has shown that steppe bison survived in isolated patches in the far northern Rocky Mountains until as recently as one thousand years ago. As we learn more about the timing and pattern of these and other recent extinctions, there is little doubt that the role of humans will become increasingly clear.

THE SIXTH EXTINCTION

More than 3,700 years after the last mammoth died on Wrangel Island, we are witnessing an alarming number of contemporary extinctions, and the rate of extinction appears to be increasing. Some scientists have gone so far as to refer to the Holocene extinctions as the Sixth Extinction, suggesting that the crisis in the present day has the potential to be as destructive to Earth's biodiversity as the other five mass extinctions in our planet's history.

The word alone—extinction—frightens and intimidates us. But why should it? Extinction is part of life. It is the natural consequence of speciation and evolution. Species arise and then compete with each other for space and resources. Those that win survive. Those that lose go extinct. More than 99 percent of species that have ever lived are now extinct. Indeed, our own species' dominance is possible only because the extinction of the dinosaurs made space for mammals to diversify, and eventually we outcompeted the Neandertals.

I think people are scared of extinction for three reasons. First, we fear missed opportunities. A species that is lost is gone forever. What if that species harbored a cure for some terrible disease or was critically important in keeping our oceans clean? Once that species is gone, so is that opportunity. Second, we fear change. Extinction changes the world around us in ways that we both can and cannot anticipate. Every generation thinks of our version of the world as the authentic version of the world. Extinction makes it harder for us to recognize and feel grounded in the world we know. Third, we fear failure. We enjoy living in a rich and diverse world and feel an obligation, as the most powerful species that has ever lived on this planet, to protect this diversity from our own destructive tendencies. Yet we chop down forests and destroy habitats. We hunt and poach species even when we know they are perilously close to extinction. We build cities, highways, and dams and block migration routes between populations. We pollute the oceans, rivers, land, and air. We move around as fast as we can on airplanes, trains, and boats and introduce foreign species into previously undisturbed habitats. We fail to live up to our obligation to protect or even coexist with the other species with which we share this planet. And when we stop to think about it, it makes us feel terrible.

Extinction is much easier for us to swallow when it is clearly *not* our fault. Why did the mammoth go extinct? As humans, we want the answer to be *something natural*. Natural climate change, for example. We would prefer to learn that mammoths went extinct because they needed the grasslands of the steppe tundra to survive and that they simply starved to death as the steppe tundra disappeared after the last ice age. We would prefer not to learn that mammoths went extinct because our ancestors greedily harvested them for their meat, skins, and fur.

While some of us may not care about extinction as long as we are not personally affected, many of us find extinction unacceptable, particularly if it is our fault. Most contemporary extinctions are easy to ignore, as they have little influence on our day-to-day lives. The cumulative effect of these extinctions is, however, a future of very reduced biodiversity. This future could be one in which so many changes have occurred to the terrestrial and marine ecosystems that we, ourselves, are suddenly vulnerable to extinction. It doesn't get much more personal than that.

REVERSING EXTINCTION

It's not completely surprising that the idea of *de*-extinction—that we might be able to bring species that have gone extinct back to life—has attracted so much attention. If extinction is not forever, then it lets us off the hook. If we can bring species that we have driven to extinction back to life, then we can right our wrongs before it is too late. We can have a second chance, clean up our act, and restore a healthy and diverse future, before it is too late to save our own species.

While it is still not possible to bring extinct species back to life, science is making progress in this direction. In 2009, a team of Spanish and French scientists announced that a clone of an extinct Pyrenean ibex, also known as a bucardo, was born in 2003 to a mother who was a hybrid of a domestic goat and a different species of ibex. To clone the bucardo, the scientists used the same technology that had been used in 1996 to successfully clone Dolly the sheep. That technology requires living cells, so in April 1999, ten months before her death, scientists captured the last living bucardo and took a small amount of tissue from her ear. They used this tissue to create bucardo embryos. Only one of 208 embryos that were implanted into the surrogate mothers survived to be born. Unfortunately, the baby bucardo had major lung deformity and suffocated within minutes.

In 2013, Australian scientists announced that they successfully made embryos of an extinct frog—the Lazarus frog—by injecting nuclei from Lazarus frog cells that had been stored in a freezer for forty years into a donor cell from a different frog species. None of the Lazarus frog embryos survived for more than a few days, but genetic tests confirmed that these embryos did contain DNA from the extinct frog.

The Lazarus frog and bucardo projects are only two of the several de-extinction projects that are under way today. These two projects involve using frozen material that was collected prior to extinction and, consequently, are among the most promising of the existing de-extinction projects. Other de-extinction projects, including mammoth and passenger pigeon de-extinction, face more daunting challenges, of which finding well-preserved material is only one. These projects are proceeding nonetheless and, in the case of the mammoth, along several different trajectories. Akira Iritani of Japan's Kinki University is trying to clone a mammoth using frozen cells and claims that he will do so by 2016. George Church at Harvard University's Wyss Institute is working to bring the mammoth back by engineering mammoth genes into elephants. Sergey Zimov of the Russian Academy of Science's Northeast Science Station worries less about about how mammoths will be brought back than about what to do with them when it happens. He established Pleistocene Park near his home in Siberia and is preparing his park for the impending arrival of resurrected mammoths.

Not all de-extinction projects take a species-centric view. George Church's project is focusing on reviving mammoth-like traits in elephants, for example. While the goal of this project is to create an animal that is mammoth-like, its motivation is to reintroduce elephants into the Arctic. Stewart Brand and Ryan

Phelan have taken an even more holistic view. Together, they created a nonprofit organization called Revive & Restore, and are asking people to consider all the ways in which de-extinction and the technology behind it might change the world over the next few decades or centuries. In addition to initiating the passenger pigeon de-extinction project, Revive & Restore is driving several projects to revive living species that have dangerously low amounts of genetic diversity. With Oliver Ryder of San Diego's Frozen Zoo, for example, Revive & Restore is isolating DNA from archived remains of black-footed ferrets, which are nearly extinct in the present day. They hope to identify genetic diversity that was present in black-footed ferrets prior to their recent decline and, using de-extinction technologies, to engineer this lost diversity back into living populations.

In March 2013, Revive & Restore organized a TEDx event at National Geographic's headquarters in Washington, DC, to focus on the science and ethics of de-extinction. This media event was the first attempt to address de-extinction at a more sophisticated level than attention-grabbing headlines. When the event concluded, pubic opinion about de-extinction was mixed. Some people loved and others hated the idea that extinctions might be reversed. Fears were expressed about the uncertain environmental impacts of reintroduced resurrected species. Some ethicists argued that de-extinction is morally wrong; others insisted that it is morally wrong *not* to bring things back to life, if indeed it were possible to do so. Voices were also raised in opposition to the cost of de-extinction and whether the potential benefits justified this cost. What was lost in the noise of the ensuing public debates, however, was discussion of the current state of the science of de-extinction: what is possible now, and what will ever be possible? And, perhaps more importantly, there was little conversation and certainly no consensus about what the goal of de-extinction should be. Should we focus on bringing species back to life or on resurrecting extinct ecosystems? Or should the focus be on preserving or invigorating ecosystems in the present day? Also, and importantly, what constitutes a successful de-extinction?

In this book, I aim to separate the science of de-extinction from the science fiction of de-extinction. I will describe what we can and cannot do today and how we might bridge the gap between the two. I will argue that the present focus on bringing back particular species—whether that means mammoths, dodos, passenger pigeons, or anything else—is misguided. In my mind, de-extinction has a place in our scientific future, but not as an antidote to extinctions that have already occurred. Extinct species are gone forever. We will never bring something back that is 100 percent identical—physiologically, genetically, and behaviorally identical—to a species that is no longer alive. We can, however, resurrect some of their extinct traits. By engineering these extinct traits into living organisms, we can help living species adapt to a changing environment. We can reestablish interactions between species that were lost when one species went extinct. In doing so, we can revive and restore vulnerable ecosystems. This—the resurrection of ecological interactions—is, in my mind, the real value of de-extinction technology.

A SCIENTIFIC VIEW OF DE-EXTINCTION

I am a biologist. I teach classes and run a research laboratory at the University of California, Santa Cruz. My lab specializes in a field of biology called "ancient DNA." We and other scientists working in this field develop tools to isolate DNA sequences from bones, teeth, hair, seeds, and other tissues of organisms that used to be alive and use these DNA sequences to study ancient populations and communities. The DNA that we extract from these remains is largely in terrible condition, which is not surprising given that it can be as old as 700,000 years.

During my career in ancient DNA, I have extracted and studied DNA from an assortment of extinct animals including dodos, giant bears, steppe bison, North American camels, and saber-toothed cats. By extracting and piecing together the DNA sequences that make up these animals' genomes, we can learn nearly everything about the evolutionary history of each individual animal: how and when the species to which it belonged first evolved, how the population in which it lived fared as the climate changed during the ice ages, and how the physical appearance and behaviors that defined it were shaped by the environment in which it lived. I am fascinated and often amazed by what we can learn about the past simply by grinding up and extracting DNA from a piece of bone. However, regardless of how excited I feel about our latest results, the most common question I am asked about them is, "Does this mean that we can clone a mammoth?"

Always the mammoth.

The problem with this question is that it assumes that, because we can learn the DNA sequence of an extinct species, we can use that sequence to create an identical clone. Unfortunately, this is far from true. We will never create an identical clone of a mammoth. Cloning, as I will describe later, is a specific scientific technique that requires a preserved *living* cell, and this is something that, for mammoths, will never be found.

Fortunately, we don't have to clone a mammoth to resurrect mammoth traits or behaviors, and it is in these other technologies that de-extinction research is progressing most rapidly. We could, for example, learn the DNA sequence that codes for mammoth-like hairiness and then change the genome sequence of a living elephant to make a hairier elephant. Resurrecting a mammoth trait is, of course, not the same thing as resurrecting a mammoth. It is, however, a step in that direction.

Scientists know much more today than was known even a decade ago about how to sequence the genomes of extinct species, how to manipulate cells in laboratory settings, and how to engineer the genomes of living species. The combination of these three technologies paves the way for the most likely scenario of de-extinction, or at least the first phase of de-extinction: the creation of a healthy, living individual.

First, we find a well-preserved bone from which we can sequence the complete genome of an extinct species, such as a woolly mammoth. Then, we study that genome sequence, comparing it to the genomes of living evolutionary relatives. The mammoth's closest living relative is the Asian elephant, so that is where we will start. We identify differences between the elephant genome sequence and the mammoth genome sequence, and we design experiments to tweak the elephant genome, changing a few of the DNA bases at a time, until the genome looks a lot more mammoth-like than elephant-like. Then, we take a cell that contains one of these tweaked, mammoth-like genomes and allow that cell to develop into an embryo. Finally, we implant this embryo into a female elephant, and, about two years later, an elephant mom gives birth to a baby mammoth.

The technology to do all of this is available today. But what would the end product of this experiment be? Is making an elephant whose genome contains a few parts mammoth the same thing as making a mammoth? A mammoth is more than a simple string of As, Cs, Gs, and Ts—the letters that represent the nucleotide bases that make up a DNA sequence. Today, we don't fully understand the complexities of the transition from simply stringing those letters together in the correct order—the DNA sequence, or genotype—to making an organism that looks and acts like the living thing. Generating something that looks and acts like an extinct species will be a critical step toward successful de-extinction. It will, however, involve much more than merely finding a well-preserved bone and using that bone to sequence a genome.

When I imagine a successful de-extinction, I don't imagine an Asian elephant giving birth in captivity to a slightly hairier elephant under the close scrutiny of veterinarians and excited (and quite possibly mad) scientists. I don't imagine the spectacle of this exotic creature in a zoo enclosure, on display for the gawking eyes of children who'd doubtless prefer to see a *T. rex* or *Archaeopteryx* anyway. What I do imagine is the perfect arctic scene, where mammoth (or mammoth-like) families graze the steppe tundra, sharing the frozen landscape with herds of bison, horses, and reindeer—a landscape in which mammoths are free to roam, rut, and reproduce without the need of human intervention and without fear of re-extinction. This—building on the successful creation of one individual to produce and eventually release entire populations into the wild—constitutes the second phase of de-extinction. In my mind, de-extinction cannot be successful without this second phase.

The idyllic arctic scene described above might be in our future. However, before a successful de-extinction can occur, science has some catching up with the movies to do. We have yet to learn the full genome sequence of a mammoth, for example, and we are far from understanding precisely which bits of the mammoth genome sequence are important to make a mammoth look and act like a mammoth. This makes it hard to know where to begin and nearly impossible to guess how much work might be in store for us.

Another yet-to-be-solved problem is that some important differences between species or individuals, such as when or for how long a particular gene is turned on during development or how much of a particular protein is made in the gut versus in the brain, are inherited epigenetically. That means that the instructions for these differences are not coded into the DNA sequence itself but are determined by the environment in which the animal lives. What if that environment is a captive breeding facility? Baby mammoths, like baby elephants, ate their mother's feces to establish a microbial community capable of breaking down the food they consumed. Will it be necessary to reconstruct mammoth gut microbes? A baby mammoth will also need a place to live, a social group to teach it how to live, and, eventually, a large, open space where it can roam freely but also be safe from poaching and other dangers. This will likely require a new form of international cooperation and coordination. Many of these steps encroach on legal and ethical arenas that have yet to be fully and adequately defined, much less explored.

Despite this somewhat pessimistic outlook, my goal for this book is not to argue that de-extinction will not and should never happen. In fact, I'm nearly certain that someone will claim to have achieved de-extinction within the next several years. I will argue, however, for a high standard by which to accept this claim. Should de-extinction be declared a success if a single mammoth gene is inserted into a developing elephant embryo and that developing elephant survives to become an adult elephant? De-extinction purists may say no, but I would want to know how inserting that mammoth DNA changed the elephant. Should de-extinction be declared a success if a somewhat hirsute elephant is born with a cold-temperature tolerance that exceeds that of every living elephant? What if that elephant not only looks more like a mammoth but is also capable of reproducing and sustaining a population where mammoths once lived? While others will undoubtedly have different thresholds for declaring de-extinction a success than I do, I argue that this—the birth of an animal that is capable, thanks to resurrected mammoth DNA, of living where a mammoth once lived and acting, within that environment, like a mammoth would have acted—is a successful de-extinction, even if the genome of this animal is decidedly more elephant-like than mammoth-like.

MAKING DE-EXTINCTION HAPPEN

Many technical hurdles stand in the way of de-extinction. While science will eventually find a way over these hurdles, doing so will require significant investment in both time and capital. De-extinction will be expensive. There will be important issues to consider about animal welfare and environmental ethics. As with any other research project, the cost to society of the research needs to be weighed against the gains to society of what might be learned or achieved.

If we brought back a mammoth and stuck it in a zoo, then we could study how mammoths are different from living elephants and possibly learn something about how animals evolve to become adapted to cold climates. Some scientists who favor de-extinction see this as a reasonable goal, and many nonscientists would be just as happy to see unextinct species in zoos as they would be to see them in safari parks or unmanaged wild habitat. But is bringing a mammoth back to life so that we can look at it and possibly study it enough of a societal gain to justify the costs of creating that mammoth?

If, like elephants, mammoths helped to maintain their own habitat, then bringing mammoths back to life and releasing them into the Arctic may transform the existing tundra into something similar to the steppe tundra of the ice ages. This might create habitat for living and endangered Arctic species, such as wild horses and saiga antelopes, and other extinct megafauna that might be targets for de-extinction, such as short-faced bears. Is the possibility of revitalizing modern habitats in a way that benefits living species enough to justify the expense? Of course, ecosystems change and adapt over time, and there is no certainty that the modern tundra would convert back to the steppe tundra of the Pleistocene even with free-living populations of unextinct mammoths. Should uncertainty of success influence our analysis of the cost of de-extinction?

What if we identified a very recently extinct species that played a similarly important role in a present-day environment, and brought that species back to life? For example, kangaroo rats are native to the deserts of the American Southwest, but their populations have become increasingly fragmented over the last fifty years, and many subspecies are known to be extinct today. Kangaroo rats are so important to their ecosystem that their disappearance can cause a desert plain to turn into arid grassland in less than a decade. The domino effects of kangaroo rat extinction include the disappearance of plants with small seeds and their replacement by plants with larger seeds (on which the kangaroo rat would have fed), in turn leading to a decline in seed-eating birds. The decrease in foraging and burrowing slows plant decomposition and snowmelt, and the lack of burrows leaves many smaller animal and insect species without shelter. When the kangaroo rat goes extinct, the entire ecosystem is in danger of the same. If bringing the kangaroo rat back could save the entire ecosystem, would that be sufficient to justify the expense?

In the chapters that follow, I will walk through the steps of de-extinction. As I indicated earlier, de-extinction is likely to happen in two phases. The first phase includes everything up to the birth of a living organism, and the second will involve the production, rearing, release, and, ultimately, management of populations in the wild. For each step in the process, I will describe what we now know, what we need to know, what we are likely to know soon, and what's likely to remain unknown. I will discuss both the science and the ethical and legal considerations that are likely to be part of any de-extinction project. Although the book is organized as a how-to manual, de-extinction is not a strictly linear process, and not all steps will apply to every species. Species from which living tissue was cryopreserved prior to their extinction may be clonable in the traditional sense, for example, while other species will require additional steps to create a viable embryo.

As part of my professional relationship with Revive & Restore, I have been involved in research that focuses on two species—mammoths and passenger pigeons—that are presently targets of de-extinction efforts. This will no doubt result in an animal-centric (really mammoth and pigeon-centric) view of the process. Still, many of the details will be broadly applicable across taxonomic lines. My hope is to present a realistic but not cynical view of the prospects for de-extinction, which I believe has the potential to be a powerful new tool in biodiversity conservation.

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Illustrations are indicated with **bold face**