Extinction Is Forever… Or Is It?

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Efforts to bring back long-lost species continue to stir debate.

*An estimated 3–5 billion passenger pigeons (***Ectopistes migratorius***) lived in the United States when the Europeans arrived. By the early 1900s, no wild birds remained. Attempts to breed captive passenger pigeons, such as the one shown here in the Cincinnati Zoo, failed. Photograph: Ltshears.*

In 1984, the creation of a wooly mammoth–elephant hybrid hit the headlines in more than 350 US newspapers. The news source: the April issue of *MIT Technology Review*. The creature, "montelephas," was an April Fool's gag, but the ensuing media storm revealed that the plausibility of such a freakish beast was no joke. Public fascination with this fictional story line was further ignited 9 years later with the movie blockbuster *Jurassic Park*. The plot: Extinct creatures walked the Earth again, cloned from ancient DNA. However, the movie's most memorable scene—the gaping wonder of the fictional scientists first encountering a herd of re-created dinosaurs—is becoming more believable. Although ancient terrible lizards are unlikely candidate organisms, given the degraded or nonexistent state of their long-dead genetic material, DNA from the bones and feathers of museum specimens and tissue samples in frozen zoos theoretically make possible the de-extinction of creatures such as the gastric brooding frog, the wooly mammoth, the Tasmanian tiger, and the passenger pigeon.

De-extinction is no longer fiction. It has already taken place, if only for 7 minutes, in the case of a wild goat called the bucardo, *Capra pyrenaica pyrenaica*, a species of ibex that once roamed the mountains of the Iberian Peninsula. The bucardo was declared extinct in 2000, after a falling tree in northern Spain killed the last known individual, a female named Celia. Scientists had collected and frozen ear scrapings from this sole survivor before her death. Three years later, her clone was brought to life, albeit a short one, by fusing Celia's somatic cells with denucleated egg cells from a domestic goat. A goat served as the baby bucardo's surrogate mother.

The cloning of a sheep—Dolly, in 1996—followed by the bucardo birth, has shifted the de-extinction conversation from *can we* to *should we,* opening a Pandora's box. What are the risks and benefits, and how do we navigate the complex morass of technological possibility and the potential ecological and societal outcomes? De-extinction is a murky and contentious subject that merits examination from scientific, ethical, legal, and economic perspectives.

Rethinking extinction

To reflect on how our contemporary view of extinction's finality might be in flux, I headed to the Royal British Columbia Museum in Victoria, Canada, to get a close-up view of organisms that no longer exist. I saw the museum's well-known mammoth model, the only known mount of the extinct Dawson's caribou, a great auk egg, and stuffed passenger pigeons. The mammoth replica is a fantastic beast. Had I stood between its tusks, I would have measured only halfway

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up to the top of its bulbous, shaggy head. Collections manager Marji Johns handed me a segment of fossilized and remarkably heavy mammoth molar and a hand-size fragment of mammoth skull. But it was the passenger pigeon that stirred in me the most unexpectedly visceral response. It was larger and more beautiful than the illustrations I had seen, the male's iridescent breast feathers still bright with color. Filled with a mixture of fascination and regret, I felt extraordinarily privileged to share a fleeting moment with three carcasses of this obsolete organism. It's difficult to imagine the transition from sky-darkening flocks to this handful of dry museum specimens. In the 1800s, John James Audubon watched a flock pass overhead for 3 days, which he estimated at about 300 million pigeons per hour. In their miles-wide nesting colonies, the birds' droppings were described as so thick they killed the forest understory.

Like the passenger pigeon, the bucardo is just one of many species extinguished by humans. In the mountainous regions of France, Portugal, Spain, and Andorra, the bucardo was adapted to its extreme environment but driven over the edge by over exuberant hunters. Efforts to resurrect the extinct species began in the autumn of 2002 but weren't successful until the summer of 2003. The resulting baby bucardo died minutes after birth, asphyxiating from lung defects. It is a challenge well known in the cloning of ruminants. Even the famous Dolly had imperfect lungs. Nevertheless, the bucardo, delivered by cesarean section, marked a turning point in the history of biology, say George Church and Ed Regis in their 2012 book, *Regenesis: How Synthetic Biology Will Reinvent Nature and Ourselves*. "For on that date, all at once, extinction was no longer forever."

The discussion of de-extinction has been accelerated by several recent meetings, including a series of TEDx talks in March 2013 sponsored by National Geographic and the Long Now Foundation, a private, non-profit organization, whose project "Revive and restore" is raising funds "to enhance biodiversity through the genetic rescue of endangered and extinct species." A May 2013 meeting at Stanford Law School was focused on de-extinction ethics, law, and politics. And a conference entitled "Thinking extinction" was held at Laurentian University, in Sudbury, Ontario, Canada, in November 2013, touching on de-extinction from scientific and philosophical perspectives.

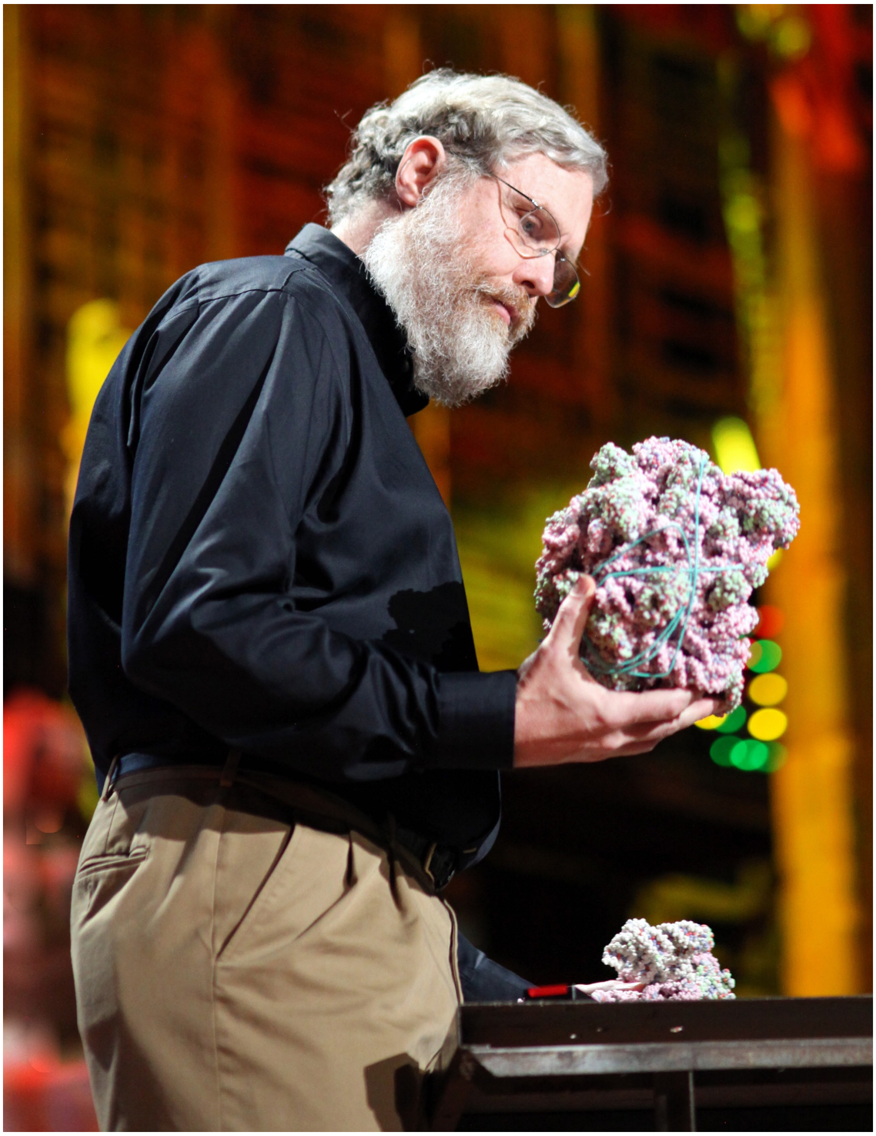
The first extinct mammal brought back to life—briefly—was the bucardo* (Capra pyrenaica pyrenaica)*. Sketch by Joseph Wolf from* Wild Oxen, Sheep and Goats of All Lands, Living and Extinct *(1898) by Richard Lydekker.

How do we do it?

Three methods might be used to bring back extinct organisms. The first, nuclear transfer cloning, produced Dolly and the baby bucardo. The premise: Remove the nucleus from a somatic (body) cell of the animal to be cloned, transfer it into a host's denucleated, unfertilized egg cell (oocyte), and then implant the renucleated embryonic cell into the womb of the chosen surrogate mother. Dolly, the first mammal successfully cloned, was produced in 1996 from the stored, frozen udder cell of a ewe that had died 3 years earlier. So, we have already surpassed the goal of cloning the living from the dead.

A second technique, genetic engineering, uses incomplete DNA sequences gleaned from museum specimens, for example, and inserts DNA fragments from close living relatives or from those manufactured synthetically to fill in the gaps. George Church, professor of genetics at Harvard Medical School, is at the forefront of synthetic biology. His lab's innovations are hastening and reducing the cost of genome sequencing and genetic engineering. "We could edit genomes on the order of thousands to millions of base pairs," says Church. When we get into the billions, it's challenging but within reach, he explains, since our ability to sequence genomes, synthesize raw DNA, and edit genomes is advancing by factors of 10 every few years. His own lab pioneered storing DNA sequences on silicon dioxide chips (like computer memory chips), and Church and his colleagues have recently developed a new technique, called CRISPR (for *clustered regularly interspaced short palindromic repeats*), which allows simultaneous batch modification of multiple genetic sites. Although 700,000 years is viewed as the age limit for any chance of harvestable genetic material, "what's possible keeps getting pushed back in time because of better and better sequencing methods," he says.

A third possible de-extinction method is back breeding. Its premise: Scientists identify desired traits in the closest living relative and use artificial selection to breed successive generations of offspring until the progeny bear resemblance to their extinct cousins. An example of this is under way in the Netherlands, where a private foundation, the Tauros Programme, is funding the back breeding of domestic cattle in an attempt to rewild areas of Europe with aurochs, a species of wild cattle extinct since 1627.



Geneticist George Church, shown here with a molecular model at the 2010 TED (Technology, Entertainment, and Design) conference, thinks synthetic biology may make de-extinction possible. Photograph: Steve Jurvetson.

We can, but should we?

Ron Sandler, associate professor of philosophy and director of the Ethics Institute at Northeastern University, says that there is nothing intrinsically objectionable about the idea of bringing back extinct species but questions what is valuable or good about doing so. It is important to specify the scale, says Sandler. "Are we talking about bringing back a couple of individuals just to see if we can do it, for scientific purposes, or to better understand synthetic genomics? Are we bringing them back to try to establish a small, highly managed population in a controlled setting, like a zoo? Or are we bringing something back for potential reintroduction into an ecological system?" Another crucial dimension is that "the longer [an animal has] been extinct, the greater are the challenges of de-extinction, and the less likely it is that there are appropriate habitats for the species to be reintroduced to," says Sandler.

There are two ways of thinking about what de-extinction would mean, he adds, either as an incredible

The great auk (*Pinguinus impennis*) was hunted to extinction, with the last known breeding pair killed off the coast of Iceland in 1844. This specimen is from the Academy of Natural Sciences of Drexel University. Photograph: Jim, the Photographer.

technoscience achievement or as a potentially useful conservation tool. “Thinking about whether these different rationales hold up when exposed to critical evaluation is important,” he says. In terms of prioritizing extinction prevention, says Sandler, de-extinction “doesn’t actually do that.”

As he wrote in his 2012 book, *The Ethics of Species: An Introduction*, Sandler says that what is important about species is not just that they exist but that their existence is in context, as part of relationships, performing specific functions. “So it’s polar bears roaming the Arctic and salmon swimming in the rivers—not polar bears in Central Park Zoo—that have value. If we want to preserve not just the organism but what’s valuable about the species itself, it requires preserving those relationships.” That means not allowing climate change, habitat destruction, pollution, extraction, and fisheries to undermine them, he adds. There is little point to bringing back a bucardo, for example, if it spawns the most highly prized illegal sport hunting in the world.

De-extinction is highly controversial in the conservation and ecology realm. Stuart Pimm, professor of conservation at the Nicholas School of the Environment at Duke University, told me, “De-extinction is a spectacular waste of everyone’s time.” Pimm says that he’s written all he has to say about the topic in recent blog posts at *National Geographic Daily News* and *Edge*. There, Pimm articulates that, “Millions of species risk extinction. De-extinction can only be an infinitesimal part of solving the crisis that now sees species of animals (some large but most tiny), plants, fungi, and microbes going extinct at a thousand times their natural rates.” Contemplating de-extinction, he adds, “sets up the expectation that biotechnology can repair the damage we’re doing to the planet’s biodiversity,” something he thinks is merely a seductive fantasy.

Paul Ehrlich, professor of biology at Stanford University, is similarly unimpressed, calling de-extinction in his recent post on Yale University’s *environment360* “a fascinating but dumb idea.” Ehrlich was unavailable for interview, but in that post, published by the Yale School of Forestry and Environmental Studies, he had this to say:

> Resurrecting a population and then reinserting it into habitats where it could supply the ecosystem services of its predecessor is a monumentally bigger project than recreating a couple of pseudomammoths to wander around in a

> zoo. The passenger pigeon is often mentioned as a target for de-extinction. Passenger pigeons once supplied people with abundant meat and likely helped to suppress Lyme disease. To create even a single viable population might well require fabricating a million birds or so, since the species apparently survived by a strategy of predator saturation. And if the swarm were synthesized, where could it be introduced? The vast forests the pigeons required are partly gone and badly fragmented at best, and one of the birds' food sources—the American chestnut—is functionally extinct... In practical terms, in the near future in which action is required, extinction is certainly forever.

Conservation biologists are understandably cautious. Speaking at the series of TEDx talks given on 15 March 2013 at National Geographic headquarters in Washington, DC, Stanley Temple, professor emeritus in conservation in the Department of Forest and Wildlife Ecology at the University of Wisconsin–Madison, described conservation biology as a three-legged stool. The supporting legs: protect, conserve, and restore. In a somewhat awkward analogy, posits Temple, adding a fourth leg—revive—may be destabilizing. "One of the urgencies about conservation biology is the idea that

Passenger pigeons depended on the American chestnut tree (*Castanea dentata*), which is functionally extinct, as a food source. Plant breeders are developing blight-resistant chestnut trees in hopes of resurrecting this key species of the Appalachian forest ecosystem. Top: Photograph: Jean-Pol Grandmont, taken in Belgium. Bottom: Specimens planted on a reclaimed mine site in Ohio. Photograph: Wayne National Forest.

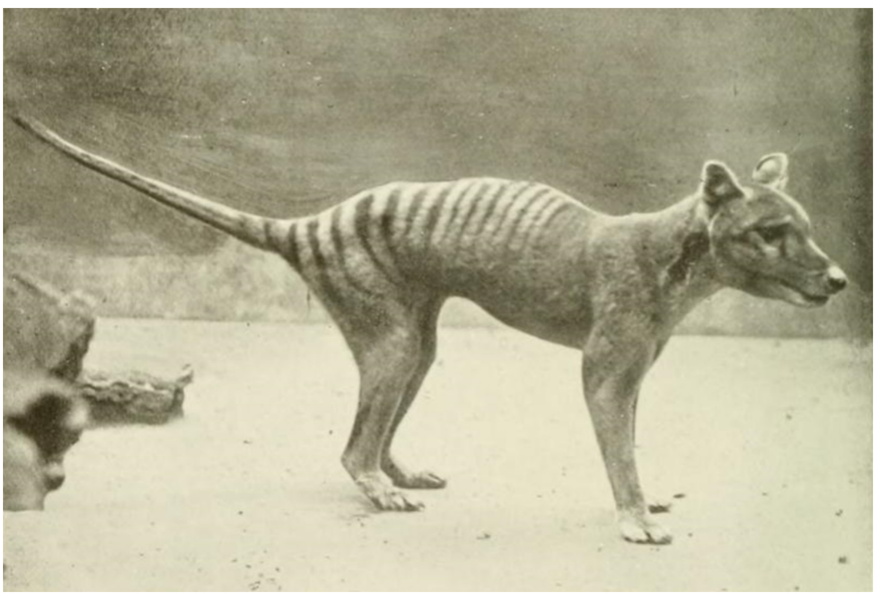
there are no second chances. The precautionary principle tells you that we better not let species go extinct because we're not going to bring them back. If we can [bring them back], obviously a lot changes, and we worry about unintended consequences. De-extinction might indeed undermine conservation biology efforts." So, says Temple, "we need to think carefully before the saber-toothed cat is out of the bag."

"There are definitely some deep questions here," says Hank Greely, professor at Stanford Law School and director of the Center for Law and the Biosciences. Apart from straightforward questions of limiting the techniques if they cause undue suffering, these can get into the deep issue of the animal equivalent of the nonidentity problem. "Are you better off never having been born or being born in miserable circumstances? How do we answer that question?" asks Greely. "So from the perspective of the individual quasimammoth, which would still be significantly Asian elephant but partially mammoth, is it better for it to be put in a zoo or animal park than never to have been created at all?" From a legal standpoint, Greely is not sure that we would need new statutes, but he sees a need for some kind of lab-animal review to guide this research. Other legal questions include whether we'd treat de-extinct organisms as intellectual property, with patents, as is done with genetically modified organisms. "That's not clear," says Greely. "Maybe they would be, and maybe that's not such a bad thing."

A misplaced focus on species?

Ehrlich suggests that our modern species-centric view has led to a conservation focus on species rather than on populations. "Populations are the entities that deliver crucial ecosystem services to society and the ecological engines that sustain and create species. Of course, when all populations of a species are gone, that species will be extinct, but there are orders of magnitude more populations than species disappearing today," he writes.

Theoretically, says Church, it is possible, "and desirable from a molecular standpoint," to bring back a population with viable genetic diversity. Using the example of passenger pigeons, Church explains that at least 1500 museum specimens are available for genome sequencing. "At this point, since [reengineering a passenger pigeon] is still fairly expensive, you could pick the parts of your genome you'd like to introduce into sibling species, and it will start taking on the traits of the more ancient species. So you can prioritize the traits that are important. Eventually, the cost may come down to the point where you can literally change every single base pair, and then use the equivalent of cloning," he explains. To what extent de-extinct species would be affected by epigenetic programming, whether they can learn appropriate behaviors from foster parents, and whether they will still thrive in their target environments are knowledge gaps remaining to be filled.



Known as the Tasmanian tiger or wolf, despite being a marsupial,* Thylacinus cynocephalus *was mistaken as a predatory threat by livestock farmers and was exterminated by the early twentieth century. Photograph: William Percival Westell, taken in 1910.

Counting the cost

Another challenge may be the economic and social costs. Would de-extinction drain resources from saving endangered species and habitats? It's not necessarily a zero-sum game, argues Michael Archer, professor of paleontology in the School of Biological, Earth, and Environmental Sciences at Australia's University of New South Wales and former director of the Australian Museum, in Sydney. Archer is a passionate proponent of the de-extinction of the thylacine (known as the Tasmanian tiger or wolf) and the gastric-brooding frog. He says that much of the de-extinction effort "is coming from private entrepreneurs who do not support modern conservation projects… They are interested in the technology involved in the potential miracle of bringing an extinct animal back to life. That got them to put their hand in their pocket. So if we weren't doing that work, that money was not available for any other kind of conservation project." The kind of science that de-extinction is inspiring also increases knowledge in cross-species cloning, adds Archer, which is potentially useful for endangered species, too.

"An easy mistake to make is to assume that the costs are going to be the same as they are now," says Church. "The price of these things has been dropping exponentially for a decade." Of course, the cost of reintroduction, Church points out, such as for the California condor, is significant and requires addressing the problems that caused the extinction in the first place.

Reintroduction from captivity of organisms extinct in the wild already has precedents and an institutional basis in guidelines by the International Union for Conservation of Nature. Spanning the breach from reintroduction to de-extinction may be only a matter of time. Dolly Jørgensen, an environmental historian in the Department of Ecology and Environmental science at Umeå University, Sweden, who wrote about reintroduction and de-extinction in a 2013 issue of *BioScience* (doi:10.1093/bioscience/63.9.719), thinks that we need to look to history. Her research is focused on examining the history of the reintroduction to Sweden of the beaver, a species that was extinct in most of Europe by the end of the 1800s. She also studies the history of the musk ox, which was reintroduced from Greenland after being absent in Scandinavia for about 10,000 years. With media attention focused on the front end of the de-extinction debate (the making of the animal), Jørgensen (amused that she shares a name with the first cloned mammal), thinks we cannot ignore other aspects of the process. "If it's ever going to be more than just a monster on display, then we have to think that it's going to *go* somewhere." Jørgensen thinks that it is important to examine the pitfalls of reintroductions of the recent past. "If you look at cases where predators have tried to be reintroduced following periods of local extinction—like the lynx in Scotland and wolves in Europe—what you see is that it's a very contested space," she says.

For the European beaver, remnant populations of the decimated species existed in small pockets in several countries, one of which was Norway. A passionate county museum director, Eric Festin, had the idea to repopulate an area named Beaver River Valley (*Bjurälvsdalen* in Swedish) with its long-missing namesake. The reintroduction of less than 100 beavers between 1922 and 1940 has resulted in more than 100,000 beavers now, which Jørgensen says makes it the most successful reintroduction ever. But the consequences include the beavers' habit of damming, which creates newly flooded areas, which, in turn, has an impact on landowners. There are also conflicts with forestry, "because beavers like trees too," says Jørgensen. It's not all bad, she says, but reintroductions have both positive and negative outcomes that may not be foreseen. "You have to be dynamic when a species is actually successful, because you may end up with a problem," she says. "History can be an example to look to, though not necessarily a guide." And whether or not we can achieve—or want to achieve—de-extinction, says Jørgensen "is more than just a scientific question; it's a cultural question too."

The European beaver was extinct in most of Europe by the 1800s but was successfully reintroduced in Sweden. Photograph: Nils Thomasson, provided by Jamtlis arkiv.

De-extinction is a concept that has incited hype, hope, and much intellectual saber rattling. So where do we go from here? In a retrospective look at cloning, the *New York Times*' Nicholas Wade aptly noted, "In retrospect, Dolly the clone was just a sheep, not the start of a great moral collapse." So perhaps we need to take a deep breath, bring all minds to the table, and figure out what is possible before panicking about what might never be.

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