how to hatch a dinosaur

Step 1:
GET A CHICKEN.

Step 2:
HIJACK ITS DNA.

Step 3:
STAND BACK.

People have told Jack Horner he's crazy before, but he has always turned out to be right. In 1982, on the strength of seven years of undergraduate study, a stint in the Marines, and a gig as a paleontology researcher at Princeton, Horner got a job at Montana State University's Museum of the Rockies in Bozeman. He was hired as a curator but soon told his bosses that he wanted to teach paleontology. "They said it wasn't going to happen," Horner recalls. Four years and a MacArthur genius grant later, "they told me to do whatever I wanted to." Horner, 65, continues to work at the museum, now filled with his discoveries. He still doesn't have a college degree.

PHOTOGRAPH BY **Joe Pugliese**

When he was a kid in the 1950s, dinosaurs were thought to have been mostly cold, solitary, reptilian beasts—true monsters. Horner didn't agree with this picture. He saw in their hundreds-of-millions-of-years-old skeletons hints of sociability, of animals that lived in herds, unlike modern reptiles. Then, in the 1970s, Horner and his friend Bob Makela excavated one of the most spectacular dinosaur finds ever—a massive communal nesting site of duck-billed dinosaurs in northwest Montana complete with fossilized adults, juveniles, and eggs. There they found proof of crazy idea number one: The parents at the site cared for their young. Judging by their skeletons, the baby duckbills would have been too feeble to forage on their own.

Horner went on to find evidence suggesting that, once hatched, the animals were fast-growing (crazy idea number two) and possibly warm-blooded (that would be three), and he continues to be at the forefront of the search for ancient bits of organic matter surviving intact in fossils (number four). Add in his work as a technical consultant on the *Jurassic Park* movies and Horner has probably done more to shape the way we currently think about dinosaurs than any other living paleontologist.

All of which means that people are more cautious about calling him crazy these days, even when he tells them what he plans to do next: Jack Horner wants to make a dinosaur. Not from scratch—don't be ridiculous. He says he's going to do it by reverse-evolving a chicken. "It's crazy," Horner says. "But it's also possible."

Over the past several decades, paleontologists—including Horner—have found ample evidence to prove that modern birds are the descendants of dinosaurs, everything from the way they lay eggs in nests to the details of their bone anatomy. In fact, there are so many similarities that most scientists now agree that birds actually *are* dinosaurs, most closely related to two-legged meat-eating theropods like *Tyrannosaurus rex* and velociraptor.

But "closely related" means something different to evolutionary biologists than it does to, say, the people who write incest laws. It's all relative: Human

Hints of long-extinct creatures occasionally emerge in real life—they're called atavisms.

beings are almost indistinguishable, genetically speaking, from chimpanzees, but at that scale we're also pretty hard to tell apart from, say, bats.

Hints of long-extinct creatures, echoes of evolution past, occasionally emerge in real life—they're called atavisms, rare cases of individuals born with characteristic features of their evolutionary antecedents. Whales are sometimes born with appendages reminiscent of hind limbs. Human babies sometimes enter the world with fur, extra nipples, or, very rarely, a true tail. Horner's plan, in essence, is to start off by creating experimental atavisms in the lab. Activate enough ancestral characteristics in a single chicken, he reasons, and you'll end up with something close enough to the ancestor to be a "saurus." At least, that's what he pitched at this year's TED conference, the annual technology, entertainment, and design gathering held in Long Beach, California. "When I was growing up in Montana, I had two dreams," he told the crowd. "I wanted to be a paleontologist, a dinosaur paleontologist—and I wanted to have a pet dinosaur."

Already, researchers have found tantalizing clues that at least some ancient dinosaur characteristics can be reactivated. Horner is the first to admit that he doesn't know enough to do the work himself, so he's actively seeking a developmental biology postdoctoral fellow to join his lab group in Montana. Horner has the big ideas, and he has some seed funding.

Now all he needed to make it happen, he told his TED audience, was a few breakthroughs in developmental biology and genetics and all the chicken eggs he could get his hands on. "What we're trying to do is take our chicken, modify it, and make," he said, "a chickenosaurus."

Horner's effort to reverse-evolve a dinosaur is not how most people envision T. rex making a comeback. That scientific scenario was essentially the premise of Michael Crichton's *Jurassic Park*—namely that bloodsucking insects trapped in prehistoric amber could contain enough dinosaur DNA for scientists to clone the great beasts. Horner threw himself into assessing this idea after the book came out in 1990, and he was hired as a consultant on the film trilogy. He ultimately concluded that DNA breaks down too fast in amber and in bones (no matter how exquisitely well preserved). In other words, dinosaur cloning was not feasible. But Horner hadn't given up on owning a dinosaur just yet. "I didn't really think we could do it," he says, "until I had a much better understanding of what it was that we couldn't do."

So he started reading developmental biology papers. And in 2005 he read a

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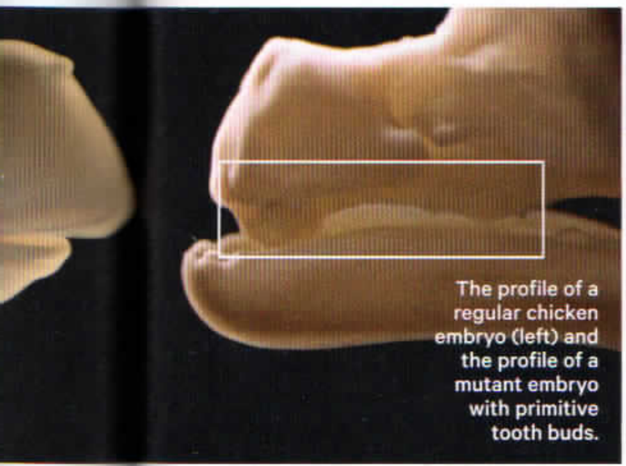
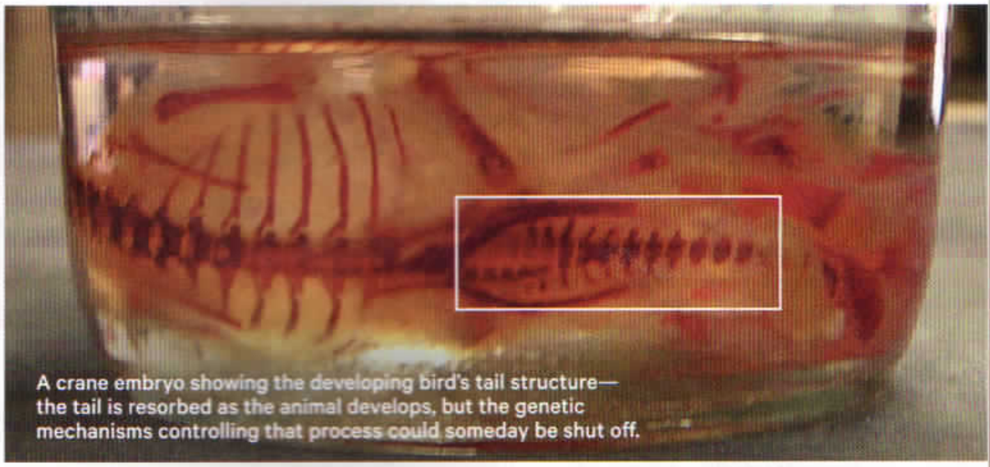
book called *Endless Forms Most Beautiful* by Sean Carroll. In the 1980s, Carroll helped lay the groundwork for the field of evolutionary developmental biology—evo devo—which focuses on figuring out the molecular mechanisms of evolution. It's a basic fact of biology that living things change over generations, shaped by the randomness of genetic mutation and the winnowing effects of the environment. The biologists wanted to determine what, exactly, changes. Using fruit flies, they established that just a handful of genes—most famously the homeotic, or Hox, genes—control the basic framework of a fruit fly's body. Even more surprising, those Hox genes are found in everything from nematode worms to humans, in a nearly identical sequence of amino acids called the homeodomain.

These regulatory genes—the master switches of development—contain the recipes for making certain proteins that stick to different stretches of the genome, where they function like brake shoes, controlling at what time during development, and in what part of the body, other genes (for things like growth-factor proteins or actual structural elements) get turned on. The same basic molecular components get deployed to make the six-legged architecture of an insect or fish fins or elephant trunks. Different body shapes aren't the result of different genes, though genetic makeup certainly plays a role in evolution. They're the result of different uses of genes during development.

So making a chicken egg hatch a baby dinosaur should really just be an issue of erasing what evolution has done to make a chicken. "There are 25 years of developmental biology underlying the work that makes Horner's thought experiment possible," says Carroll, now a molecular biologist at the University of Wisconsin-Madison. Every cell of a turkey carries the blueprints for making a tyrannosaurus, but the way the plans get read changes over time as the species evolves.


The profile of a regular chicken embryo (left) and the profile of a mutant embryo with primitive tooth buds.


A crane embryo showing the developing bird's tail structure—the tail is resorbed as the animal develops, but the genetic mechanisms controlling that process could someday be shut off.

Horner's plan is to create atavisms in the lab.

All Horner had to do was learn how to control the control genes. He had spent decades studying fossilized dinosaur embryos, tracking in minute detail the structural and cellular changes in their skeletons as they grew. Now he immersed himself in what biologists had figured out about the molecular control of those changes. Horner reads scientific papers the way he hunts for fossils—scanning a barren landscape for rare bits of useful material—and he has found enough of them to feel optimistic.

Horner is a big man—6′3″ and over 200 pounds. It's a tight squeeze to reach the desk in his cluttered basement office at the Museum of the Rockies. Surrounded by four large LED monitors, Horner rummages among awards, family photos, and what looks like a triceratops horn in a canvas shopping bag before he finds what he's looking for: a mounted chicken skeleton. "The skeletons of a chicken and a T. rex really are very similar," he says. "We're going to focus on just a few of the major differences." He points out the 10 or so vertebrae, several of them fused and kinked upward, that pass for the tail on a chicken. Two-legged dinosaurs had long, dramatic tails, held up from the ground to counterbalance the body. Fixing the tail will be the first step.

Step two: the hands. Many dinosaurs had two or three fingers, with sharp claws used for grasping and tearing. Birds have a "hand" at the end of each wing, but the three digits are tiny and fused together. The trick will be unfusing them. Step three will be replacing the chicken's tough keratin beak with long rows of pointy dinosaur teeth. "That is one good reason to do this in a chicken instead of an ostrich," says Horner, whose deadpan humor comes in a slow, easy-to-miss burn. "You want something small enough to catch."

He didn't know how to actually do any

of this, of course. It was just a theory. The breakthrough came in a bar. Horner doesn't remember exactly where—paleontologists tend to travel a lot—but he thinks it was in 2005. He was talking with Hans Larsson, a young Canadian paleontologist who had recently started teaching at McGill University; Horner had known him since Larsson was a graduate student at the University of Chicago. Larsson was interested in how dinosaurs lost their tails along the evolutionary road. "As soon as he started talking about looking for the genes that were responsible, I said, 'Well if you could find those, we could just reverse the whole process.'" Larsson was 34 at the time and as trim and energetic as Horner is burly and unhurried—a velociraptor to the older man's triceratops. He was taken aback but didn't dismiss the idea out of hand.

Larsson is a fairly unusual paleontologist in that he studies living animals as well as fossils. He trained in paleontology and biology and today splits his time between dig sites in the Arctic (and elsewhere) and an advanced developmental biology lab. "I became a little bit dissatisfied with just pure paleontology," Larsson says. "It seemed too much like going out and collecting something, adding it to the museum drawer, and not actually testing anything." It's a frustration that every student of extinct animals has to face sooner or later: You can't keep the darned things in a lab and do experiments on them. But because of the principle of genetic conservation—the idea that all living creatures carry a substrate of very similar DNA—Larsson can study chickens, alligators, and even mice to gain insight into dinosaurs.

That work got under way in 2008—in part thanks to Horner, who donated the money to fund a postdoc in Larsson's lab for a year. The first task was to spend several years developing exquisitely sensitive techniques to follow the activity of four key regulatory networks. One of these pathways includes a gene known as Sonic Hedgehog, which controls the proliferation of cells. Another is involved with wing outgrowth. The third helps establish a top-to-bottom axis in developing limbs, and the last controls skeletal patterning. Most of these activities can be manipulated—suppressed or even stopped—using pharmacological agents. Or you can just inject more of the protein that a particular gene makes, increasing its effect. "Our plan is to start working with this toolkit and manipulate it in different parts of the embryo," Larsson says.

EVOLUTION IN RE

Using advanced **genetics and biological hacks,** scientists could **make dinosaur traits** emerge from a chicken embryo. Here's how. —T.H.

Like Horner, Larsson is focused on the tail and wing for now. But he wants to learn how dinosaurs became birds, not turn back the evolutionary clock. That's just Horner's crazy idea.

In 2002, Matthew Harris sat down to dissect a chicken embryo. A grad student in developmental biology at the University of Wisconsin, Harris was trying to figure out how feathers evolved. As is common practice in his field, he had turned to a deformed animal for clues; figuring out what went wrong often shows what's supposed to go right. He was working with a talpid^2, a particularly odd strain of mutant chicken best known for grotesque forelimbs and feet that can sprout up to 10 digits each—so many that fully developed chicks can't muster the biomechanical wherewithal to break out of their shells and hatch. Harris was looking beyond those obvious alterations, searching for oddities in skin, scales, and feathers.

It was one of several old specimens, collected by his PhD adviser, John Fallon, years before, right at the point of hatching. Preserved in thick, syrupy glycerol, the embryo had become nearly transparent. "I brought it out of the jar to look at it, and the outer beak, the rhamphotheca, started to come off," Harris says. "I peeled it back and then stopped—the specimen was smiling back at me." Scores of scientists had studied talpid^2 embryos for years, but Harris saw what no one else did: a neat row of pointy, uniform structures running along the jawline, hidden beneath the hard outer beak. The bird had a mouthful of teethlike buds.

Harris and his colleagues soon discovered that by stimulating production of a protein called beta-catenin in chick embryos, they could get normal, nonmutants to produce neat rows of conical, crocodile-like tooth buds along their upper and lower beaks. "Chicks have the potential to create toothlike structures," Harris says. "They just need the right signal to come through."

Where Harris—now on the faculty at Harvard Medical School—saw an interesting bit of developmental biology, Horner saw yet another stepping stone to his dinosaur. The beta-catenin trick made growing chickenosaurus teeth relatively easy. Unfor- | CONTINUED ON PAGE 186

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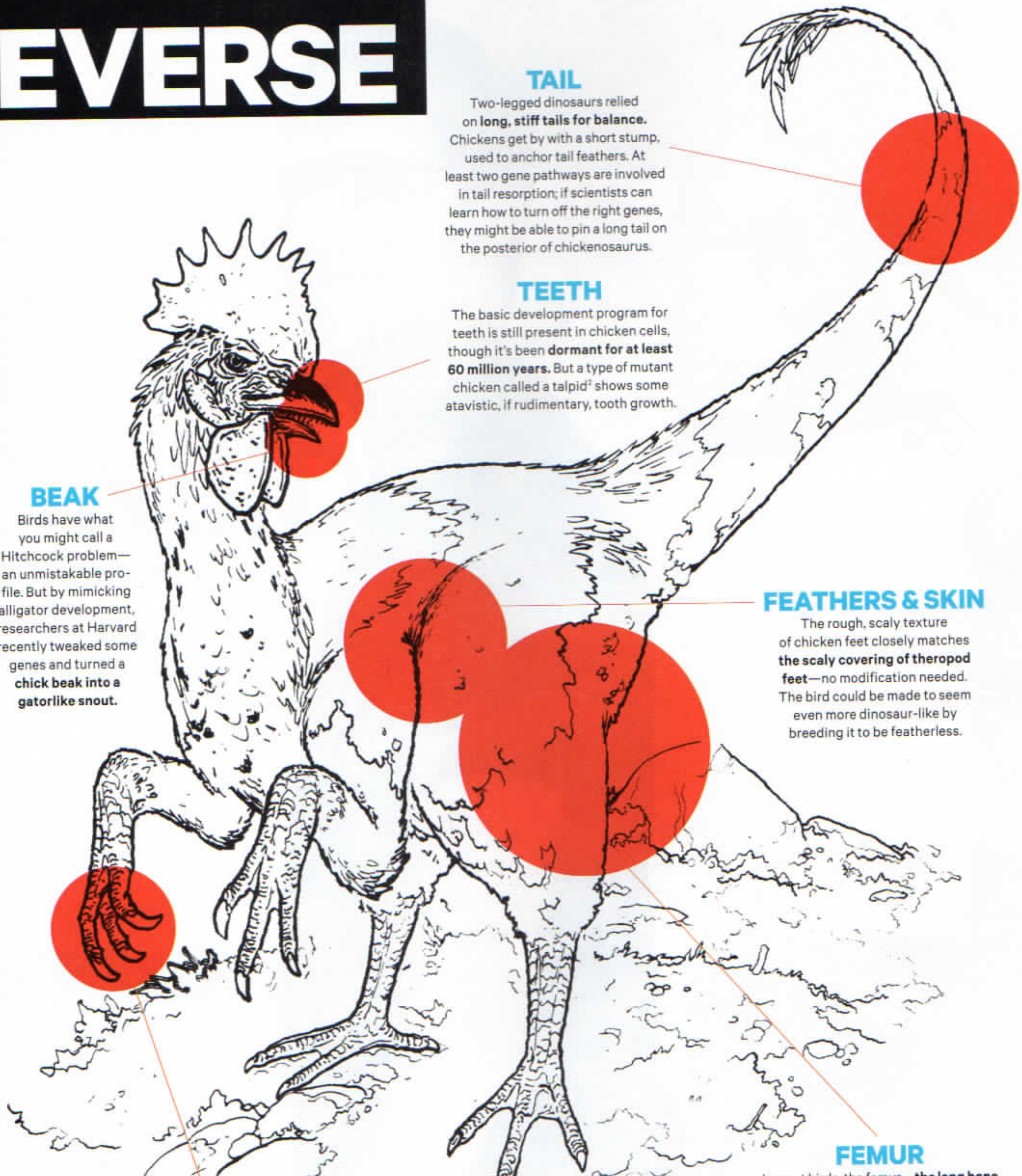


TAIL
Two-legged dinosaurs relied on **long, stiff tails for balance.** Chickens get by with a short stump, used to anchor tail feathers. At least two gene pathways are involved in tail resorption; if scientists can learn how to turn off the right genes, they might be able to pin a long tail on the posterior of chickenosaurus.

TEETH
The basic development program for teeth is still present in chicken cells, though it's been **dormant for at least 60 million years.** But a type of mutant chicken called a talpid[2] shows some atavistic, if rudimentary, tooth growth.

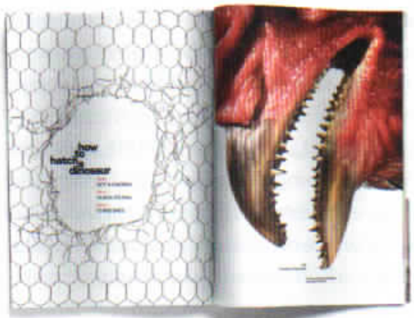
BEAK
Birds have what you might call a Hitchcock problem—an unmistakable profile. But by mimicking alligator development, researchers at Harvard recently tweaked some genes and turned a **chick beak into a gatorlike snout.**

FEATHERS & SKIN
The rough, scaly texture of chicken feet closely matches **the scaly covering of theropod feet**—no modification needed. The bird could be made to seem even more dinosaur-like by breeding it to be featherless.

HAND
Most theropods had **three-fingered hands with sharp claws** for climbing, grasping, and slashing. Birds still have the finger bones, but they're fused together in the wing. By arresting the fusion process inside the egg, scientists could induce a chicken to hatch with fearsome hands.

FEMUR
In most birds, the femur—**the long bone in the thigh**—is nearly horizontal. Some Asian fighting cocks walk tall and, like their dino ancestors, have a nearly vertical femur. Dinosaur-makers could start with that breed to create a dino-chicken whose gait can support the weight of its tail.

ILLUSTRATION BY **Ulises Farinas**



Chickenosaurus

CONTINUED FROM PAGE 156

tunately for Horner, Harris is among those who don't see the path quite as clearly. "I respect him and what he does," Harris says. "But I think what he's trying to sell is a little outlandish."

Those chick's teeth were evidence, Harris says, that evolution had preserved the basic developmental mechanisms for making teeth. But they were mere buds, with none of the design and material flourishes that make teeth into tearers of flesh and crushers of bone. "Development has the capacity to remake a lot of things," Harris says. "But what you lose are some of the last bits, like enamel and dentine, that are specific for teeth. You can't even find a gene for enamel in the chicken genome."

Carroll, the evo devo expert, shares that skepticism. He has done plenty of body-changing experiments on insects, manipulating the order and structure of development, and let's just say that the resulting bugs are never happy. "It's not like a Mr. Potato Head, where you just give it a tail and new hands and voilà: dinosaur," Carroll says. "That tail has got to work with the rest of the body. There's likely going to be some wiring problems, some coordination problems. Maybe some other body parts won't develop normally." He doesn't disparage the imagination behind the idea and thinks that with enough money and time Horner might get something done, but "even if you raised an adult chicken with teeth, you'd really end up with nothing more than Foghorn Leghorn with teeth," Carroll says. "And shitty teeth at that."

HORNER'S QUEST TO MAKE A DINOSAUR reflects what he sees as a broader problem in paleontology: Digging bones out of the ground has produced huge amounts of information about prehistoric life, but he has begun to think that scientists have learned just about everything they can from that method. "We'll get little chunks of DNA, and we'll figure out what colors they were," Horner says. "But the fossil record is pretty limited."

Having spent a career shaking up paleontology, Horner seems perfectly happy with the idea that even *considering* a chickenosaurus shakes up biologists. "Paleontology is ossified," says Nathan Myhrvold, the former Microsoft CTO who now dabbles in a bunch of different sciences and has worked extensively with Horner. "The methods haven't changed substantially in 100 years." Yes, researchers know more about dinosaurs and other extinct creatures now than they did a century ago—Myhrvold has been coauthor of several academic papers that contribute to that supply of knowledge. He sees Horner's work as the first real push to bring the tools and insights of molecular and developmental biology into the paleontological fold. "Normally, paleontologists go out and walk around until they find fossils," Myhrvold says. "But it turns out that there's a place to look that's just as good as the badlands of Montana, and that's the genome of living relatives."

And if Horner is right, do we get the joy of real dinosaurs menacing the San Diego suburbs? "A lot of people say, 'You worked on *Jurassic Park*, you should know better,'" Horner says with a laugh. "But contrary to Steven Spielberg's movies, animals don't want to get even with us. We actually could have dinosaurs running around and they wouldn't be any worse than grizzly bears and mountain lions." That might seem like scant reassurance to those who spend less time wandering the badlands than Horner does. But for now, Horner has no intention of letting any of his experiments hatch. (Just give him a few years and some funding.) And because he intends to tweak only development and not alter the DNA itself, any offspring of a chickenosaurus would just be a chicken. So what could possibly go wrong?

One project, if it ever happens, could give us an idea. In 2008, researchers at Penn State announced that they'd sequenced most of the genome of the woolly mammoth, extinct for 10,000 years, from samples of its hair. That prompted Harvard geneticist George Church to claim that for around $10 million he could resurrect the mammoth. He'd take a skin cell from an elephant, even more closely related to mammoths than humans are to chimps, and then reprogram the elephantine bits of its genome into something more mammothy. Convert that into an embryo and bring it to term in an elephant uterus. No problem.

If Church were to ever try it—and there are no signs he will—the project would have a few advantages over Horner's. DNA can last for around 100,000 years, so researchers actually have mostly intact genetic material from mammoths, avoiding the *Jurassic Park* degraded-DNA problem. And from a genetic perspective, elephants are practically mammoths already, whereas chickens have diverged pretty significantly from, say, a velociraptor. But the important part of all this is that the technology to do this kind of work didn't exist 10 years ago. It's now possible, for example, to make thousands of modifications to the genome in a single cell. Genomics has gone from an artisanal craft to something more akin to the mechanical looms of the early industrial revolution. Sure, to realize his reverse-evolution dream, Horner needs to take the technology even further. But the trend lines do seem to point in the right direction.

Back in his office, he picks up a heavy introductory developmental bio textbook from his desk. "All these books are about flies," Horner says, arching his eyebrows. "Flies are great. They're very interesting, and you can learn a lot by studying them. But ..." He tosses the book onto a chair and stands up, walks down a long hallway to his crammed collection room and a drawer filled with every imaginable sort of bird skull—a toucan with its giant orange proboscis, a parrot's hooklike mouth, the flattened beak of a spoonbill. "Birds are pretty amazing, too," he says.

Developmental biologists talk about the regulatory machinery they study as a biological toolkit, a small set of mechanisms and processes that evolution uses to construct new and wonderful bodies. "Well," Horner says, "they've found the toolkit. But what good is a toolkit if you don't use it to build something?"