Chapter Eight

Where Do We Go from Here?

Have we reached the end of the story? We've certainly covered a lot of ground. We began with our early primate ancestors leaping through the trees sixty million years ago, raced forward to the dawn of apes, and then followed one ape lineage as its members began to walk upright. Much later our hominid ancestors began to craft stone tools and then embarked on the first of many journeys out of Africa. Forests retreated, deserts expanded, glaciers rose and melted back. Hominid brains grew in fits and starts, hominid tools became more elaborate, and finally our ancestors had acquired all of the fundamental ingredients of modern human existence by about 50,000 years ago.

Our species has not undergone any awesome evolutionary transition since then. An extra pair of eyes has not evolved on our foreheads. We have not sprouted wings. Our lives may be very different today from those of the first *Homo sapiens*, but our anatomy—including the size and shape of our brains—is practically identical. It may seem strange that natural selection, which has produced so many impressive adaptations, would slack off this way. But natural selection is not some sort of conscious engineer, forever creating designs from scratch. It merely tinkers with genes and the bodies made by genes, sometimes generating new innovations and sometimes leaving well enough alone.

A skull of a modern human.

Natural selection has not done away with the many vestiges of past adaptations that were already obsolete millions of years before our species emerged. Our backs, for example, were originally adapted for supporting a four-legged body. They have not adapted very well to our upright existence, leaving us hobbled by slipped disks and pinched nerves. As we've seen, the human brain has been the subject of natural selection as well. Many psychologists now wonder if they can get a deeper understanding of the mind by investigating how it has evolved. The human brain expanded enormously over the past two million years, but our ancestors spent the vast majority of that time not in cities or on farms but in wandering bands of foragers, scavengers and hunters. Our brains may have become finely tuned to that sort of life, and we may still inherit those adaptations.

A new breed of scientists who call themselves evolutionary psychologists are now searching for signs of our hominid heritage in the modern mind. Many of them focus on how men and women behave toward one another. In many cultures, for example, men tend to be attracted to women with large breasts, narrow waists and wide hips. Evolutionary psychologists argue that this is not merely the product of how men are raised, but an evolutionary adaptation. A 2004 study offered some support for this idea, finding that women with large breasts and narrow waists had hormone levels indicating they were more fertile than other women. Men may have evolved an attraction to these features because it brought them more reproductive success.

Emotions may have been shaped by natural selection as well. Evolutionary psychologists have proposed, for example, that jealousy emerged out of the long-term bonds that eventually emerged among hominid parents. They had to invest many years together to raise their children, which made the prospect of being

The human skeleton, like the rest of the human body, is the product of natural selection tinkering with an ancient anatomy. As a result, our bodies are full of oddities and imperfections.

abandoned by one's partner a potential disaster. Hominids may have become very sensitive to signs that might foretell abandonment—a sensitivity we now call jealousy.

Evolution has not only shaped human emotion, evolutionary psychologists argue, but human reasoning as well. They point out that people do badly on certain kinds of logic puzzles if the puzzles are presented abstractly. Here's an example of one of these tough puzzles: a psychologist presents you with four cards, each with a number on one side and a letter on the other. The cards are marked D, F, 3 and 5 respectively. The psychologist then says that if a card has a D on one side, then the other side should be marked with a 3. Which cards do you have to turn over to see if the rule actually holds? The answer is D and 5.

This puzzle becomes much easier if it is expressed in terms of people and social rules. For example, the cards might have information about four people drinking in a bar. One side of a card would be the age of a drinker and the other side would show their drink. Imagine that you are shown four cards that show beer, soda, 25 and 17 respectively. Which cards do you need to turn over to make sure that no one under 21 is drinking alcohol?

Many people get the right answer (in this case, beer and 17). Evolutionary psychologists argue that we do much better with social puzzles because they tap into a faculty that evolved in our hominid ancestors. They lived in small groups that had to share meat and other food. If cheaters broke the rules of a group, the effects could be devastating. As a result, hominids evolved a keen instinct for detecting cheaters.

While our minds may still be attuned to an ancient way of life, we have not stopped evolving. As *Homo sapiens* spread across the planet, new mutations continued to emerge, spread and disappear. Humans carried some of these mutations with them across continents and oceans. Deciphering this genetic

history isn't easy, because all living humans descend from only a few thousand Africans. Even smaller groups made the initial migrations out of Africa, becoming the earliest ancestors of Asians and Europeans. These tiny groups gave rise to the six billion people living on Earth today, and did so in only a few thousand generations. That hasn't been long enough for our species to accrue many genetic differences. The wildebeest in Kenya alone have twice as much genetic variation as our entire species. Yet despite this genetic similarity, our species is not just a collection of six billion clones. People vary. They have different skin colors and body shapes. A drug can have a different effect on your body depending on your ancestry.

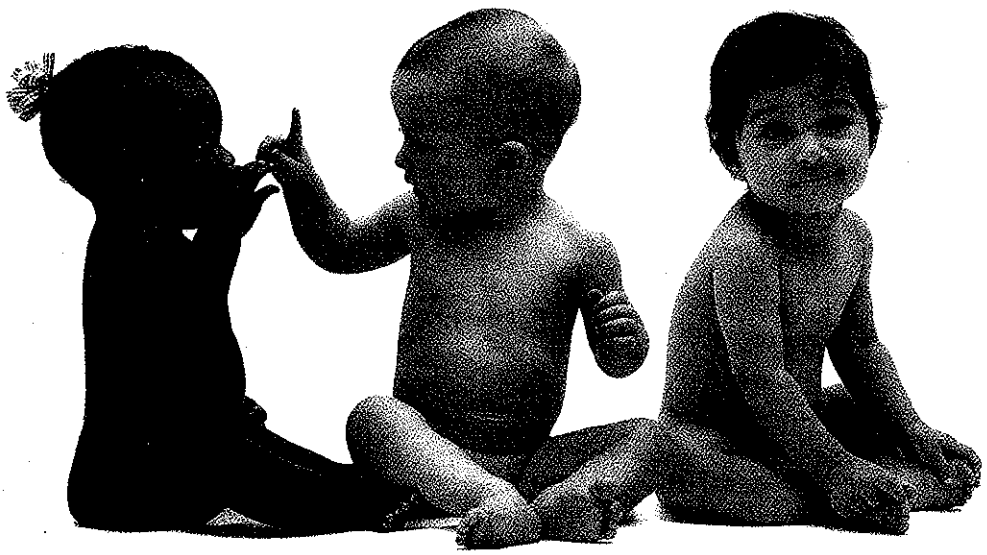
When most people think of human variations, they think of race. But it's important to bear in mind that the concept of human races was created in the 1700s and 1800s, long before it was possible to look at human variation at the genetic level. It was built instead of a crude mix of observation and chauvinism. The eighteenth-century naturalist Carolus Linnaeus, for example, divided humans into seven races, including *Homo sapiens europeanus* and *Homo sapiens afer* (Africans). He claimed that *Homo sapiens europeanus*'s distinguishing traits included not just white skin but also long flowing hair, blue eyes, a muscular body and a capacity for invention and for governing by laws. The distinguishing traits of *Homo sapiens afer*, by contrast, were black skin, as well as cunning and a personality ruled by impulse. This sort of racism, which has no real basis in biology or behavior, has provided justification for slavery, Nazi genocide and many other great evils over the past 200 years.

Despite this dubious history, scientists today are keenly interested in human genetic variation. It can not only tell us about human history but also shed light on how different genes predispose people to cancer and other diseases. One important measure of diversity is the amount of genetic variation

found within a population and between populations. According to the latest studies on the DNA of Africans, Europeans and Asians, only about 15 percent of genetic variation exists between these groups, while 85 percent can be found within them.

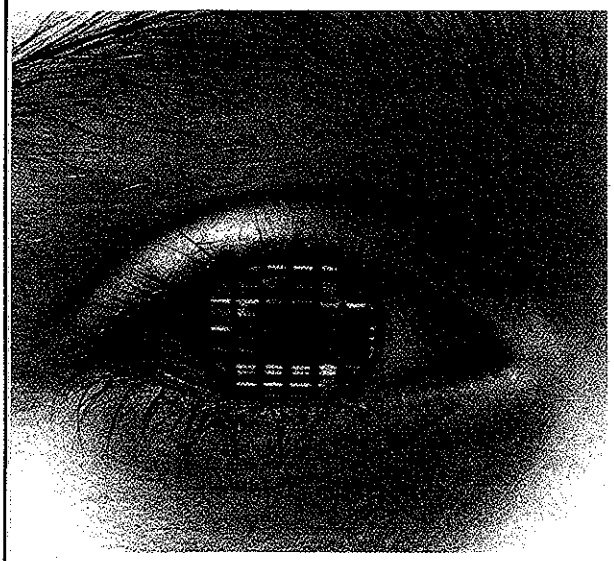
While the differences between populations may be small, that doesn't mean they are insignificant. Human populations vary enough, for example, to let geneticists determine where a person's ancestors are from. In 2003, University of Utah geneticists proved this by scanning the human genome for short sequences that tend to vary a lot between people. These stretches of DNA, known as Alu sequences, are prone to harmless mutations, which means that natural selection doesn't remove them from our species. The scientists identi-

Living humans vary in color, shape and size. Yet compared to other primates, human genetic variation is minor.



fied 100 Alu markers and then gathered them from the DNA of 107 sub-Saharan Africans, 67 East Asians and 81 Western Europeans. The individuals in each group shared an almost identical set of markers. The differences between the groups were so clear that the researchers could predict an individual's ancestry with nearly 100 percent accuracy.

Some of the genetic differences between ethnic groups are little more than statistical flukes. To understand why, imagine a country in which people have all sorts of eye colors—brown, blue, hazel, green, grey, pink, purple. Fifty of them board a ship to colonize a distant island. As a random sample of their country's population, they bring with them the full spectrum of eye colors. A few miles from the island shore, the ship sinks in a storm, and only three people make it ashore. By pure luck, they all have purple eyes. The survivors manage to make a life for themselves, and their descendants quickly fill up the entire island. When visitors come to the island, they are shocked to find that the residents all have



Traits such as eye color are determined by genes. But that doesn't mean that a particular person's eye color must be the product of natural selection.

purple eyes. They might speculate on what sort of advantage purple eyes offered the islanders so that natural selection favored them so strongly. But the real cause was the random hand of fate at work in the shipwreck. The random hand of fate—technically called genetic drift—is a powerful force in recent human history. Humans have migrated around the entire world, often in small numbers. Those small numbers boost some genes at random and eliminate others.

On the other hand, recent research has indicated that some differences between groups of people are not the random hand of fate, but the result of natural selection. In some cases, natural selection may alter the DNA of an enclave of people who live in a small region. In others, it operates across an entire continent.

The most obvious example of natural selection is skin color. The earliest hominids were probably covered mostly in hair, as living apes are. This hair covering became a liability when hominids began walking upright through open landscapes, because it trapped too much heat. Natural selection favored a hairless body instead, along with extra sweat glands to help cool the skin.

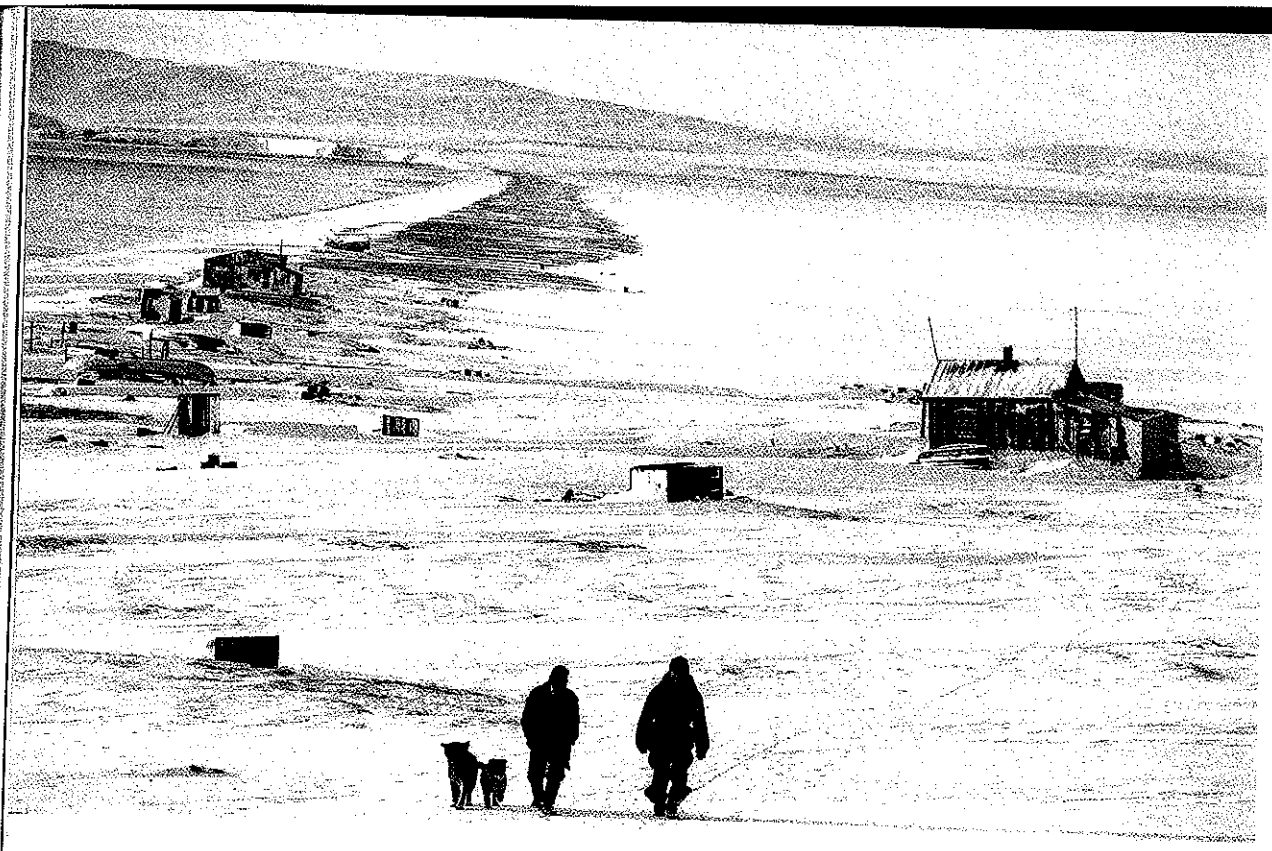
But a hairless body brought its own hazards. Underneath the dark coat of an ape, its skin is actually quite pale. Hairless hominids would have become vulnerable to ultraviolet radiation from the high tropical sun. In addition to causing skin cancer, intense ultraviolet light can break down an essential nutrient in the

skin called folic acid. Without enough folic acid, men may become infertile and women may give birth to babies with fatal neurological defects. Nina Jablonski and George Chaplin at the California Academy of Sciences have argued that once hominids became hairless, natural selection favored ultraviolet-absorbing pigments that turned their skin dark.

But when dark-skinned humans began migrating away from equatorial Africa, the evolutionary balance shifted. While too much ultraviolet light is dangerous, too little ultraviolet light is also bad for you. That's because it helps our bodies produce vitamin D. Without enough ultraviolet exposure, vitamin D levels fall, which can lead to devastating bone deformities. In regions of the world with low levels of ultraviolet rays, black skin might do its job too well.

Jablonksi and Chaplin argue that the balance between protecting folic acid and synthesizing vitamin D favored darker skins where ultraviolet exposure is high, and paler skins closer to the poles. They've found that the worldwide pattern of skin color matches pretty well with their predictions. There are exceptions, but most seem to prove the rule rather than undermine it. People with the "wrong" skin color tend to belong to groups who have migrated long distances within the past few thousand years. The light-brown Khoisan people of Southern Africa have lived there for tens of thousands of years; darker Zulu people came from tropical Africa much more recently. Eskimos ought to be as pale as Scandinavians, but they arrived in the Arctic only a few thousand years ago, and because they get an unusually rich supply of vitamin D from a diet heavy in fish, natural selection may not create as much of an advantage for pale-skinned Eskimos.

Natural selection has produced other differences between peoples that are less obvious, but no less significant. In 2004, Douglas Wallace of the University of California at Irvine and his colleagues reported signs of natural selection in



Evidence from DNA suggests that humans adapted to the harsh, cold climate of Siberia by evolving the ability to produce more heat from the food they eat.

human mitochondria—the fuel-generating factories of the cell. Mitochondria convert the glucose in food into a compound called adenosine triphosphate (ATP), which the cell can then use as fuel as it crawls around, produces hormones or performs some other task. The production of ATP releases heat as a byproduct, which can help keep our bodies warm.

Studying over 1,000 people, Wallace and his colleagues discovered that people in Europe and northeastern Siberia have inherited unusual mutations

in their mitochondrial DNA that can't be found in the genes of Africans. These mutations appear to make European and Siberian mitochondria produce more heat. Wallace and his colleagues suggest that these mutations brought benefits to humans as they moved into cold climates.

In these cases, humans have simply adapted to their physical surroundings just as other animals have. But some recent human adaptations are unusual, because they are the product of our own cultural evolution. As humans invented new ways of surviving, they altered the evolutionary landscape, encouraging the spread of genes that were previously rare. The best-documented example of culture driving biology this way occurred roughly 10,000 years ago, as humans in Europe, parts of Africa and a few other regions began to domesticate cows.

Cattle herding provided people with an immediate benefit in the form of a reliable supply of meat. Cows also produce milk, which is a good source of nutrition, but the first cattle herders probably couldn't drink much of it. As infants, most mammals digest their mothers' milk with the help of a protein they produce, called lactase. Acting as a set of molecular scissors, lactase snips apart a sugar found in milk, called lactose. Once it is cut into pieces, lactose can be absorbed into the bloodstream. But as mammals grow older, they stop producing lactase, with the result that they can no longer digest milk. Humans started out the same way, and many humans today remain lactose intolerant. They get indigestion when they try to drink milk or eat cheese.

But many people who descend from traditional cattle herders can still digest lactose. That's because they have inherited a mutation to a gene called LCT. Scientists are not yet sure how the mutant version of LCT works, but it shows clear signs of having undergone natural selection in the past few thousand years (in fact, it's the strongest selection yet measured in humans). It appears that thousands of years ago, the LCT mutation randomly emerged in cattle-herding people.

Genetic Engineering: A New Kind of Evolution?

Could genetic engineering alter the future of human evolution? Some observers of recent advances in biotechnology worry that it might. For years now, scientists have been inserting new genes into bacteria, turning them into factories to produce proteins. More recently, scientists have inserted genes into plants and animals. And they've begun to experiment with inserting genes into the cells of humans, in the hopes of curing disorders, such as cystic fibrosis, which are caused by defective genes. The typical procedure for this so-called gene therapy is to load a working copy of the gene in question into a harmless virus. Researchers then inject the virus into the part of the body where the gene is supposed to make proteins. The virus invades the patient's cells and inserts its code into the cell's genome, along with the engineered gene.

While gene therapy has yet to be proven safe and effective, it has already inspired some speculations about where this sort of science could go. For now, gene therapy is targeted at cells in the bodies of children or adults. If these people were to have children of their own, they might pass the same faulty copy of a gene that made them sick in the first place. Now imagine that a man with cystic fibrosis and his wife provide their egg and sperm to a doctor. The doctor lets the fertilized egg divide into four cells, and then transfers one of the eggs to another dish, where it multiplies into a colony. The doctor loads up viruses with working versions of the gene and sets them loose on the colony. She then searches the dish for a cell that has successfully absorbed the gene.

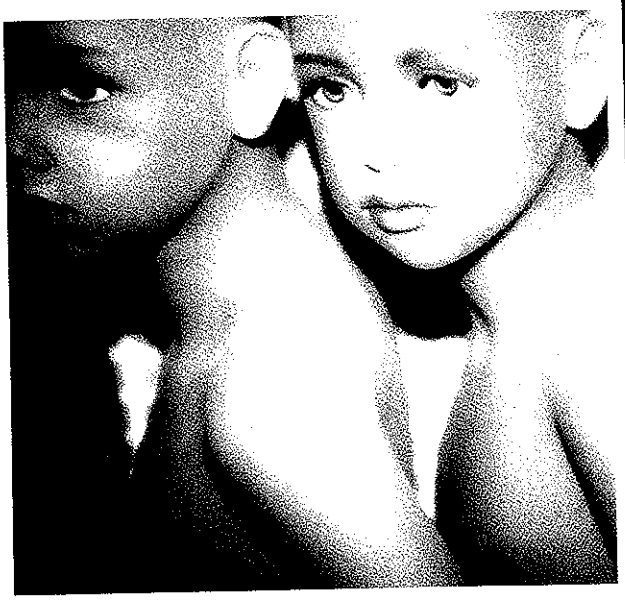
This cell can no longer give rise to an embryo, but its altered DNA can. The doctor simply has to take the DNA out of the cell. Next, she goes back to one of the three remaining cells from the original embryo, and replaces its DNA with the DNA from the altered cell. With the right combination of signals, this new cell will start dividing again and produce an embryo. When it grows into an adult, that person will carry working copies of the gene in every single cell, including his or her sex cells. Theoretically, his or her descendants will never have to worry about inheriting cystic fibrosis again.

This procedure—called germ line modification—might make it possible not only to repair defective genes but also to give children enhanced genes. Imagine two parents who are short, and are convinced that being tall will give their child an advantage in life. Rather than give their child injections of growth hormone, they might have a doctor install extra copies of the genes that produce the hormone. Intelligence is partly a result of the genes we inherit; if scientists manage to identify some of the most important genes associated with intelligence, it might be possible to engineer children with versions of those genes to make them smarter.

Of course, none of this will happen tomorrow. Today scientists are still struggling to get gene therapy to work. But in twenty years, society may face the choice of altering its future genetic profile. Some people have argued that ethical concerns will keep germ line modification rare. But its attractions may convince many people that they should set their qualms aside. Consider, for example, the fact that scientists are now identifying the genes that produce longevity in animals. Imagine that a doctor offered to add these genes to your children's genomes to ensure that they were healthy and happy into their eighties. Would you say no?

Some skeptics have argued that even if germ line modification did prove successful, it would remain so expensive that only a handful of wealthy people would be able to afford it. Yet new technologies often have a way of becoming affordable. Consider how widespread in-vitro fertilization has become in just twenty-five years. During World War II, antibiotics were precious and rare—so much so that the United States government held onto the country's entire supply in order to treat wounded soldiers. Now, sixty years later, you can walk into a store in a city such as Lagos or Jakarta and buy antibiotics for a few dollars.

If genetic engineering did become widespread, its effects on the human gene pool would be carried forward from one generation to the next. It's an open question whether its effects would amount to short-lived ripples or major waves. The most likely people to use germ line modification at first—wealthy people—also tend to have small families. By definition then, their genes would not be favored by natural selection. What's more, genetic modification could turn out to have hidden dangers that emerge only after several generations, which would also make these genes grow rare. On the other hand, engineered genes could spread if natural selection strongly favors them. A lethal virus might emerge from a disturbed rain forest, and the only way to survive might be to carry a man-made resistance gene.



Will biotechnology alter our future evolution?

In the end, the only way to know would be to run an experiment. And given the advances in genetic engineering these days, it looks as if the experiment is about to begin.

It somehow disabled the off-switch for lactase production, and allowed people who carried it to drink milk into adulthood. The extra calories and protein from the milk ultimately translated into extra children for people who had the mutation. Mutations to LCT may have cropped up among people who did not herd cattle, but they offered no benefit because there was no cow's milk for them to drink.

Culture has shaped human evolution not only with the benefits it has brought, but also with new threats. The most common form of malaria, for example, has thrived since humans invented agriculture. This strain of malaria is caused by a single-celled mosquito-dwelling parasite called *Plasmodium falciparum*. Originally *Plasmodium*-carrying mosquitoes lived in African forests and drank the blood of forest animals. But over the past few thousand years they moved into the fields that African farmers began to clear for crops. They laid their eggs in the stagnant water that puddled in the fields, and feasted on the blood of farmers as they slept. The parasite's numbers exploded, and eventually it hitchhiked with mosquitoes into southern Europe and southern Asia. Finally humans brought it to the New World. Today malaria causes over a million deaths a year, mostly in Africa where it began.

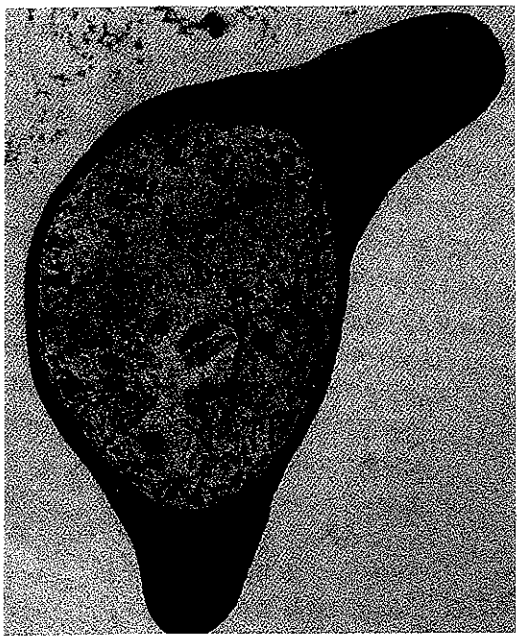
Nothing speeds up evolution faster than disease, because any mutation that can provide some resistance may save an animal from death. We humans are no exception. By unwittingly unleashing malaria, our ancestors triggered an explosion of evolution not only in *Plasmodium* but in our own species as well. Throughout malaria's range, human populations have acquired new defenses against the parasite, blocking its entry into blood cells to break its life cycle.

From defenses against diseases to protection from cold climates, the evolution of our species continued even after the dawn of modern human life 50,000 years ago. Is it possible to project forward and predict what evolution will do to *Homo sapiens* over the next 50,000 years?

Evolution has acted on humans over just the past few thousand years. A number of cultures, such as the Maasai of East Africa, took up cattle herding. As a result, natural selection favored mutations in their genes that allowed them to digest milk.

Certainly not. Human culture now alters the rules by which biological evolution unfolds. The future of human culture will therefore help steer the course of evolution. In order to predict the future of our species, we have to predict the future of our society. That's no small task, when you consider that we can't predict what the stock market will do next week.

Still, scientists have indulged in some speculation about what the future will



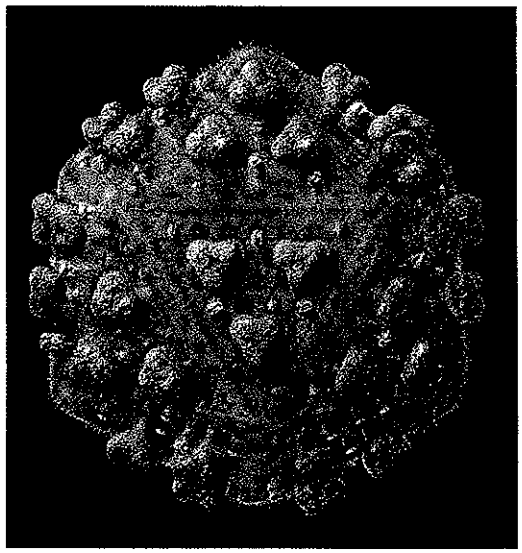
A human red blood cell plays host to *Plasmodium*, the parasite that causes malaria. Humans have been subject to malaria for thousands of years, and its deadliness has driven the evolution of many adaptations to fight the parasite.

bring. Some have looked at human evolution up close, on the generation-by-generation scale. They have pointed out that natural selection works fastest when there are big differences in the sizes of families. Some genes may allow some people to produce seven children, while alternate versions might leave them childless—or even dead before they have a chance to have children. Antibiotics, clean drinking water, steady supplies of food and other pleasures of modern life have blunted the knife that cleaves the species. Genes that leave people prone to juvenile diabetes or other potentially fatal disorders are no longer a guarantee against having children. Meanwhile, large families are becoming rarer as the rate of population growth slows. In fact, the world's population is now projected to level off at about nine billion by 2100. If the unconscious competition between genes is leading to much smaller payoffs for the winners, the race itself may be slowing down.

On the other hand, the world today is hardly free of diseases. In just the past thirty years, HIV has exploded into one of the worst epidemics in recorded history. It has killed over twenty million people and shows every sign of continuing its deadly march. Certain genes offer protection to HIV, just as certain genes offer protection to malaria. Unless we can stop the spread of HIV, the virus will shift the genetic profile of our species. It's likely that new diseases will continue to put

pressure on our genome. HIV is believed to have evolved from chimpanzee viruses, which hopped to our species as logging roads were cut into African forests, making it possible for hunters to slaughter more chimps and other primates. Many other viruses could colonize us by a similar route.

While parasites will continue to cause enormous suffering to our species, we probably don't have to worry about them causing complete extinction. Diseases can wipe out species with small ranges, but there's no evidence they can cause the extinction of widespread animals. But the history of life offers many warnings to us. An asteroid impact sixty-five million years ago may have wiped out the dinosaurs. A sudden surge in global warming 250 million years ago claimed 90 percent of all species on Earth.



Artist's rendition of HIV, the virus that causes AIDS. HIV has become a major cause of death in humans in just the past three decades. Unless its spread is stopped soon, the virus will probably influence the future evolution of our species.

While these gloomy possibilities can't be ignored, that doesn't mean that they are our destiny. Perhaps we will manage to bring diseases under control, ward off asteroids with interplanetary mines and find a way to keep our emissions of greenhouse gases from scorching us. But even in a sunnier, extinction-free future, our species would probably keep evolving. One particularly fascinating possibility is that our species will give rise to a new one.

It would be a most unusual birth, as species go. The best documented way for a new species to emerge is for a population to become physically isolated from

the rest of its species—cut off by a river, for example, or swept away to an island. The isolated population evolves for thousands of years, acquiring mutations that the rest of the species lacks. If the population can then mix with the rest of the species—if, for example, dropping sea levels turn its island into a peninsula—its new mutations may prevent any successful interbreeding. For many biologists, that's the hallmark of a new species.

It's hard to imagine how humans could become physically isolated long enough somewhere on Earth to form a new species—as long as there are ships in the sea and planes in the air. But there may be one way that a new species of human might emerge on a peaceful, intermingled Earth. Geneticist Matt Hurles of the Sanger Center in England and his colleagues point out that as the human population approaches nine billion, some of evolution's rules may change in subtle but important ways.

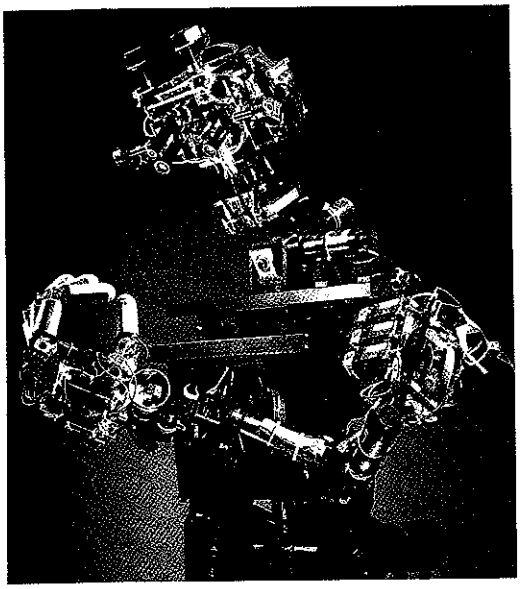
It helps to think back to the island of purple-eyed shipwreck survivors. The fatal shipwreck not only boosted the number of purple-eye genes on the island but completely eliminated the genes for other eye colors. If shipwrecks and other statistical flukes wiped out enough people with brown eyes, the gene for brown eyes would vanish from our species altogether. A species that is made up of small populations is prone to these sorts of statistical flukes, which can wipe out genes. As a result, it ends up with low levels of genetic diversity.

But in big populations—say, a population of nine billion humans—these statistical flukes have a much weaker effect. There are always enough brown-eyed people to spread the brown-eye gene to the next generation. Hurles and his colleagues suggest that in the future, the large size of the human population will foster a rise in mutations in the human genome. These mutations will for the most part be utterly harmless. But under some conditions, the researchers suggest, they can cause infertility.

People can become infertile because their sperm or eggs don't form properly. Normally, sex cells form from precursor cells equipped with the standard allotment of twenty-three pairs of chromosomes. As the precursor cells divide, so do the chromosome pairs, so that each sex cell winds up with only one chromosome from each pair. But before the chromosome pairs part ways, they have time for a final embrace. During this hug, they swap similar chunks of DNA. This embrace only occurs because the chromosomes are so similar that they can lock together. If their sequences are too different, they cannot line up properly. The dance of cell division is thrown off, and the sex cells that are produced as a result may wind up with an extra chromosome. These malformed cells will not be able to produce a fertilized egg.

Now imagine nine billion people with a vast number of mutations in their genomes. The mismatching of chromosomes becomes common, and widespread infertility follows. Hurles and his colleagues suggest that people whose parents had the same genetic background would have the lowest risk of infertility. That's because the chromosomes they inherited from their parents would tend to have the same mutations, and thus line up properly. Human genes would no longer get mixed together as much as they do today. Instead, people would begin to form populations that were reproductively isolated. If this isolation lasted for thousands of years, one of these populations might evolve into a separate species.

All of this speculation—and speculation is what it must remain—deals with the future of biological evolution, the sort that has driven life's history for some four billion years. But it may turn out that biology may not drive the next stage of human evolution. Humans have developed the cultural traditions of their ape ancestors into a high-speed evolutionary process of their own. Our ideas spread, change and give rise to new ideas. They don't need millions of years to transform. It's rare for a few months to go by without some new electronic device hitting the



Cog, a robot built by scientists at the Massachusetts Institute of Technology, is designed to experience the world in much the way a human being does. It raises the unsettling possibility that machines may carry on our evolution.

market. Those devices still need us to conceive of them, build them, program them and debug them. But perhaps not for long. It is possible that self-replicating artificial systems will emerge. If we program them with our culture, they could carry the ideas of our species into a new sort of existence—one that might even spread to other worlds. Some futurists have speculated that this is a common pattern for intelligent life throughout the universe. Once a species becomes intelligent enough to build tools, it's only a matter of time before it passes into a post-biological civilization. By this line of reasoning, our best chance of detecting signs of extraterrestrial life is not to search for habitable planets, but for self-replicating machines wandering through deep space.

If we find them, we might be looking at our future.

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Carl Zimmer

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