

cluded that Leonardo himself painted over the necklace, but that a later art restorer removed the mountain range, perhaps to make foreground mountains more prominent.

The computer, coupled to a scanning microdensitometer normally used on photographs sent back from space, allowed Asmus to look through the layers of discolored brown varnish and extensive aging cracks to simulate the painting's original appearance and reveal faint or lost detail. "After more than 450 years of deterioration, the image of the lady is barely a soiled caricature of the original," said Asmus.

—*Washington Post*

MOTHER EVE

IF FAMILY TREES were charted indefinitely backward, they would converge on a small group of ancients who were ancestors of us all. Now biochemists from the University of California at Berkeley think a single female living 200,000 years ago was an ancestor of everyone on Earth today. Inevitably, many scientists call her "Eve."

The biochemists—Rebecca Cann, Mark Stoneking and Allan Wilson—point out that other females reproducing at the time have modern descendants. But "Eve" is the only one who appears in everyone's genealogy, a conclusion they reached by studying mitochondrial DNA (mtDNA).

Most of the DNA in human cells is in the cell nucleus, in the form of chromosomes. But there is also DNA outside the nucleus—in mitochondria—that is inherited solely through the mother. The scientists believe that descendants of the other females alive during Eve's time eventually included generations that produced no children

or only males, thus halting transmission of their mtDNA.

Prior studies have shown that, over the generations, mtDNA changes at a steady, known rate of mutation in humans and other primates. To measure this change, the biochemists examined mtDNA from 147 individuals representing five broad geographic regions. Analyzing the differences in the mtDNA samples, the scientists constructed a "family tree" showing a common ancestral mtDNA. Then they extrapolated backward to calculate when that mtDNA existed—when Eve lived.

Examining the relationships and geographic origins among the 147 people, the biochemists also determined Eve's home: sub-Saharan Africa.

—*Time*

GARDENER'S DELIGHT

IT SOUNDS TOO GOOD to be true: a lawn that repels weeds, resists disease, stays green late in the season—and doesn't need regular mowing. Geneticist Jan Weijer of the University of Alberta, Canada, has produced 38 varieties of grass, of which eight are "super grasses" that will surely interest lawn growers. Native to the eastern slopes of the Canadian Rockies, where the climate is harsh and the soil poor, the grasses grow only two to eight inches a year. They exude substances that keep other plants, like weeds, from invading their territory, and their tough waxy coating protects against fungus attack. Their short blades produce a lawn resilient to traffic. These grasses come up in early spring and are greener than current varieties.

Weijer estimates that it will take at least four years to produce sufficient seed for the commercial market.

—*International Wildlife*

IN SEARCH OF EVE

A DNA Trail Leads to a Single African Woman, 200,000 Years Old

by REBECCA L. CANN

THE EXPEDITION that led to the recovery of the fossil skeleton Lucy was an adventure equal to its scientific achievement. For four years, beginning in the fall of 1973, Donald C. Johanson and his team of fossil hunters dug in the desert sand of central Ethiopia, as armed Afar tribesmen protected them from rebels and thieves. When the first hominid bone, a knee joint, was unearthed, Johanson became so eager to compare it with a modern bone, he robbed a nearby grave of a human femur. And after the first season, he was forced into bitter argument with a disgruntled colleague, who accused Johanson of incompetence and of stealing fossils, and nearly persuaded Ethiopian officials to end the digging. Of these exploits, Johanson later said, "Not every expedition is like *Raiders of the Lost Ark*, but they have their moments." Surely, the greatest of these was the discovery of Lucy, a forty-percent complete skeleton of *Australopithecus afarensis*, the best-preserved evidence ever found of the earliest human ancestor to diverge from apes. Lucy's bones eventually settled the question of whether hominids developed the ability to walk upright before or after they evolved large brains; her skeletal shape proved she was an accomplished biped, though her cranial capacity was not drastically larger than that of an ape.

Important as Lucy was, however, she could illuminate only one phase of human evolution, and Johanson expected much more than that from his Ethiopian site. He was convinced the region eventually would yield the bones of *Homo erectus*, the ancestor thought to stand between Lucy and modern humans on the evolutionary tree. Finding *erectus* in the same vicinity as Lucy would substantially reinforce the notion that the genus *Homo* evolved in eastern Africa. "I'll bet you . . . they're there," Johanson told Timothy White, his collaborator at the University of California at Berkeley. "They've got to be. And if they are, we'll find them."

But a few years after the unearthing of Lucy, Ethiopian

officials forbade further digging, and Johanson's hopes were put on hold. Even if his adventures had been allowed to continue, there is no reason to expect he would have filled in the numerous gaps in the fossil record. Besides the likelihood that the most sought after bones never will materialize, there is the problem of properly identifying the fossils that *are* found. It is hard to know, by bone shape alone, whether a fossil represents a species already identified or whether it is different enough to represent a species of its own. Then there is the difficulty of knowing whether the fossil was left by a human ancestor or by a related primate that became extinct. All in all, it is too much to hope that the trickle of bones from the fossil beds of eastern Africa will, in itself, provide a clear picture of human evolution any time soon.

Fortunately, bones are no longer the only evolutionary clues available. In recent years, biochemists have learned to investigate human ancestry through living cells. By analyzing the DNA molecules of two animals and measuring the differences in the sequence of their components, they can gauge how long it has been since the two diverged from a common ancestor. Such investigations have proved, for example, that the most recent common ancestor of humans and the African apes (chimpanzees and gorillas) lived as recently as five million years ago, not fifteen million, as the fossil evidence was once thought to suggest. This new line of inquiry is much less glamorous than the movie-style exploits of desert paleoanthropologists, but as biochemical techniques have grown more sophisticated, DNA research has become the best hope for answering questions the bones have not.

Among the most compelling of these questions is, Where and when, exactly, did modern man evolve? On this issue the paleontological record is frustratingly silent. The fossils demonstrate that our most immediate ancestor, *Homo erectus*, who lived in Africa, Europe, Indonesia, and China, began developing some of the characteristics

of *Homo sapiens* between four hundred thousand and three hundred thousand years ago and that, by about forty thousand years ago, *erectus* was replaced, worldwide, by modern humans. But how did this transition take place? Biochemical techniques have uncovered, in our own cells, a significant chapter of the story, enabling us to pinpoint when and where a mother of all modern humans—our biological Eve—lived and how her descendants came to inhabit the globe.

THE FOSSIL RECORD has presented a much clearer picture of the divergence of apes and hominids than it has of the emergence of modern humans. Lucy's partial skeleton, and the pieces of some five hundred other individuals unearthed in Africa, show that members of her species lived between four million and three million years ago. The australopithecines were less than four feet tall, walked on two legs, and had long arms, massive jaws, protruding faces, low brows, and small brains. Although anthropologists do not agree on the details of australopithecine evolution (or of any other stage of hominid evolution, for that matter), there is general consent that, about three million years ago, Lucy's kind began to diverge into two lines of descent, one spawning other australopithecine species—*aethiopicus*, *robustus*, and *boisei*, which ultimately would become extinct—and the other giving rise, a million years later, to the genus *Homo*.

Bones found in Ethiopia, Kenya, Tanzania, and South Africa, dating to between two million and one and a half million years ago, indicate the size, shape, and physical abilities of the first hominid, *Homo habilis*—meaning handy man, a reflection of his ability to manufacture large quantities of regularly shaped stone tools. *Habilis* retained the short physique of his forebears but had a less protruding face and a higher, rounder, and significantly larger braincase, with a capacity of six hundred to seven hundred and fifty cubic centimeters (compared with four hundred to five hundred cubic centimeters for australopithecines and nearly fourteen hundred for modern man).

About one and a half million years ago, *habilis* evolved into the larger-brained *Homo erectus*, who had a cranial capacity of eight hundred to nine hundred cubic centimeters. *Erectus* had an even less protruding face and a more prominent brow ridge than *habilis*, as well as a sloping forehead and a sunken chin. He appears to have been the first hominid to migrate from Africa, setting up seasonal camps in southern Asia and later in northern Eurasia.

Fossils of the first human subspecies, archaic *Homo sapiens*, have been found throughout Europe, Asia, and Africa, so anthropologists assume that these early people descended from *erectus* in various parts of the world simultaneously. Their exact form varies from place to place, but, in general, their brains were about the size of ours, though their skulls were thicker-boned and their faces and bodies were comparatively husky.

These archaic humans eventually gave way, worldwide, to the modern subspecies, *Homo sapiens sapiens*, whose oldest remains—fragments of bone found in various sites south of the Sahara—date to about one hundred and twenty thousand years ago, eighty thousand years earlier than any found in Europe or Asia. This age difference—combined with evidence that Africans used sophisticated



Fernando Botero, Adam and Eve, 1979

blade tools (meticulously manufactured from fine-grained rock) ninety thousand to eighty thousand years ago, while flake tools (made less carefully from whatever rock was at hand) still were being used in Europe and Asia—suggests that truly modern humans evolved from a single, isolated population of archaic *Homo sapiens* in Africa and then fanned out to conquer the world.

More than one hundred thousand years ago, in Europe, archaic humans gave rise to *Homo sapiens neanderthalensis* (so named for the site where the bones were discovered, in the Neander Valley, near Düsseldorf). Neanderthal was a variant of archaic *Homo sapiens*, with high cheekbones,



prominent brow ridges, and a flattened skull crown that made him look more primitive than modern humans. Thus, he appears as a sort of bridge between the two subspecies of *Homo sapiens*. Even so, Neanderthal people are thought not to have been ancestors of modern humans, because they themselves are not as old as the earliest *Homo sapiens sapiens*. And even if they were, it would be difficult to explain how they kept essentially the same form for sixty thousand years, then, overnight, evolved into a new subspecies forty thousand years ago, when modern humans first appeared in Europe.

The same difficulty applies in Asia, where the fossils of

Homo sapiens sapiens are not much older than forty thousand years. Nonetheless, citing similarities between the bone structures of Asian *erectus* fossils and modern Asians, a few anthropologists have argued that *Homo sapiens sapiens* evolved in the Far East—and perhaps simultaneously in Africa. Most anthropologists reject this theory because of the great similarities in skeletal and cranial shapes that people throughout the world exhibit today. If modern humans had originated simultaneously in two such widely separated regions, adapting to two such different environments, we could expect that two distinct human forms would have evolved. Thus, the preponderance of paleontological evidence supports—though it does not prove—the theory that modern humans evolved in Africa and then emigrated to Europe and Asia, ultimately supplanting all their archaic cousins.

THE POSSIBILITY that molecular biology would one day be used to investigate this out-of-Africa hypothesis probably never occurred to the scientists who, some thirty years ago, began to study genetic material for clues to how life evolved. During the 1950s, biologists faced the more basic question of how minute changes in DNA molecules can lead to noticeable alterations in an animal's size, shape, and abilities. They discovered that genes, the sequences of nucleic acids strung together along the spiral staircase-shaped DNA molecule, provide recipes for making cellular proteins, with each sequence of three nucleic acid pairs specifying one amino acid in the protein chain. When DNA reproduces itself, some of the pairs, known as bases, are accidentally altered, which may cause changes in the protein produced. Of course, it is a long way from the coding of a single protein to the development of a new characteristic in an animal. Still, it is clear that most evolutionary change begins with mutations in genetic molecules.

In 1962, Linus Pauling and Emile Zuckerkandl, at the California Institute of Technology, in Pasadena, discovered a property of proteins that would become the foundation for later work in evolutionary biology. While studying the ways in which hemoglobin, the primary blood protein, differs from one primate species to another (in an attempt to learn why some primates never contract malaria or sickle-cell anemia), they found a correlation between the degree to which the hemoglobin molecules of two species differ and the evolutionary distance separating them. Specifically, the hemoglobin in two monkeys that shared a common ancestor ten million years ago would be twice as different as the hemoglobin in species that had diverged only five million years ago. This discovery led them to speculate that the same sort of correlation might hold true for other proteins and that those proteins might change at a constant rate over time, by accumulating a steady stream of accidental mutations. Thus, if it were possible to time the pace of protein change, a biologist could count the number of amino acid differences in two samples of the same protein (each from a different animal) and thereby pinpoint when the animals diverged from a common ancestor.

Five years later, Vincent M. Sarich and Allan C. Wilson, of the University of California at Berkeley, calibrated the "molecular clock" in albumin, a protein that transports nutrients through the bloodstream, by measuring

differences in the amino acid sequences of albumin taken from apes and Old World monkeys, which were then believed to have diverged thirty million years ago. Having established the pace at which albumin evolves (about one amino acid substitution every one and a quarter million years), they compared the protein in humans and African apes and found that humans diverged from chimpanzees and gorillas about five million years ago. Thus, the African apes are more closely related to humans than to the Asian apes (gibbons and orangutans), from which they diverged thirteen million to ten million years ago.

Initially, many paleoanthropologists rejected this finding, because they believed that *Ramapithecus*, a primate that lived at least fourteen million years ago, was an ancestor to humans but not to apes, which meant that humans and apes must have diverged before its time. But, in the twenty years since Sarich and Wilson's research, their conclusion has been corroborated again and again, and most anthropologists have come to accept the biochemical evidence—and to believe that *Ramapithecus* could not have been a hominid. In fact, many fossil experts now think *Ramapithecus* was an Asian ape and not an ancestor to either the African apes or humans.

BY THE EARLY 1970s, laboratory technology had made it possible to look beyond proteins and directly at the tinier and more intricate DNA molecules in the cell nuclei, to discern genetic differences between species in greater detail. A major advance was the discovery of bacterial enzymes known as restriction enzymes, because their natural function is to destroy, or restrict, any foreign DNA that might invade the cell. They accomplish this by cleaving the DNA molecule in each place along the chain where the enzyme identifies a particular sequence of four to six bases (called a restriction site).

To date, biologists have isolated more than two hundred restriction enzymes, each designed to identify a unique sequence of bases, and have used them to "map" DNA molecules. Once a strand of DNA has been cut apart, the pieces are placed into a synthetic gel and subjected to an electric current. This process, known as electrophoresis, causes the fragments, each of which carries a slight electric charge, to line up in order of size, longest to shortest. The result is a sort of signature, a visible arrangement of DNA segments whose lengths have been determined by the pattern of restriction sites on the original strand. This method does not identify every base along the DNA molecule, but by showing the sequence of restriction sites, it identifies a large share of them. Through comparison of the DNA signature of one animal with that of another, it is possible to tell how closely the two are related. Using this technique, biologists have verified the timetable for the divergence of apes and humans and have established when other groups of mammals, including horses and donkeys and lions and domestic cats, diverged from common ancestors.

Some ten years ago, biochemists discovered advantages to studying the separate set of DNA molecules found in mitochondria, outside the cell nuclei. Mitochondria, the tiny blob-shaped organelles that occur in all "higher" plants and animals (as opposed to such single-celled organisms as bacteria), are the cells' engines, metabolizing food and water into energy. They are thought to have

evolved early in the history of life (between three and a half billion and one billion years ago), when a new kind of bacterium somehow engulfed an older one, and the two remained joined in a symbiotic relationship, the internal organism metabolizing food for itself and its captor and ultimately becoming the mitochondrion. This theory would explain why, through the millennia, mitochondria have kept their own, distinctive DNA: to code for the proteins needed in metabolism, which the cell nucleus has never evolved the ability to carry out. Mitochondrial DNA, with only about sixteen thousand base pairs, is easier to analyze than nuclear DNA, which has several hundred million bases.

An even greater advantage of mitochondrial DNA to the biologist estimating evolutionary distances between animals is that it is inherited only from the mother. Some scientists believe that this is because, during fertilization, only the nucleus of the sperm makes its way into the egg (the other cellular material being destroyed), so only the egg's mitochondrial DNA is reproduced in the offspring. Thus, mitochondrial DNA is immune to change by sexual recombination of genes from each parent—change that confuses the biologist looking for evidence of random mutations. Because an animal's nuclear DNA is naturally quite different from either of its parents', it is difficult to discern changes due to the accidental substitution of base pairs. In mitochondrial DNA, on the other hand, mutation is the only kind of change that can occur.

Biochemists have calibrated the mitochondrial DNA clock by measuring the number of mutations that have taken place in the mitochondrial DNA of primates whose evolutionary divergence already was dated by fossil evidence. They have found that the mitochondrial DNA molecule mutates at the rate of two to four percent every million years. (If two monkeys diverged from a common ancestor five hundred thousand years ago—each accumulating five hundred thousand years' worth of mutations, for a total of one million years' worth of change between them—their mitochondrial DNA should show two to four differences in any given sequence of one hundred bases.) This is five to ten times faster than the rate of mutation in the nuclear genetic material, in part, perhaps, because mitochondrial DNA is not as well protected from poisons, temperature changes, and other mutagens as is the protein-coated DNA in the nucleus, and because its mutations are never repaired, as are many mutations in nuclear DNA. Because mitochondrial DNA undergoes significant change every few hundred thousand years, it is a particularly good gauge of short-term evolution, and the most precise clock available for measuring the time when modern humans diverged from a common ancestor.

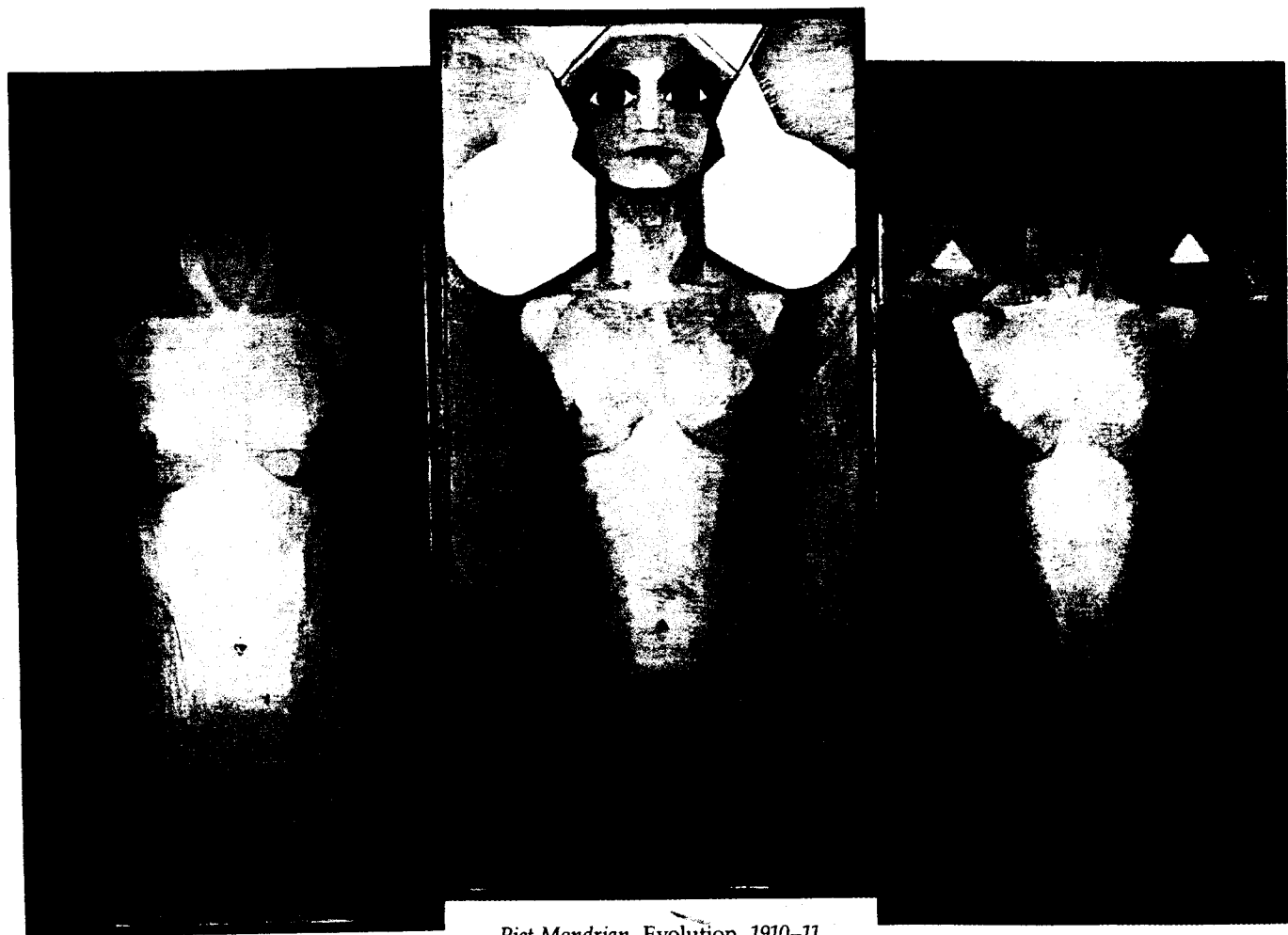
IN 1979, I began gathering samples of mitochondrial DNA from the placentas of newborn children (which contain the same genes as the children themselves). By last year, Allan C. Wilson, Mark Stoneking, and I had collected a total of one hundred and forty-seven samples from children whose ancestors lived in five parts of the world: Africa, Asia, Europe, Australia, and New Guinea. Then, using restriction enzymes, we divided each sample into more than three hundred fragments, which were arranged in distinctive patterns by gel electrophoresis. Finally, with a computer, we calculated the

number of mutations that had taken place in each sample since it and the others evolved from a common ancestor. Fourteen of the samples had essentially the same base sequences as others in the survey, leaving one hundred and thirty-three distinct types of mitochondrial DNA. Within this group, some individuals were closely related in base sequences—presumably because they had diverged from a single female within the past few centuries—whereas others were connected only by a common grandmother who lived tens of thousands of years ago.

The computer then constructed an evolutionary tree, placing the one hundred and thirty-three mitochondrial DNA types at the tips of the branches. Those with the fewest differences in their base sequences (those most closely related) are grouped together in clusters of tiny branches, and each of these clusters is, in turn, linked to others at the points (further in the past and, thus, closer to the tree trunk) at which they diverged from common ancestors. All but seven mitochondrial DNA types are on limbs that converge on a single large branch, and descendants of people from the five areas are mixed throughout this branch. A second major branch, much thinner than the first, contains the seven remaining mitochondrial DNA types, all of them from people of African descent. These seven are as different from one another, in the composition of their mitochondrial DNA, as are any of those on the more widely radiating, multiracial branch.

Thus, their common ancestor is just as old as the common ancestor of the one hundred and twenty-six on the larger branch. The base of the tree, the point at which the two branches split apart, is the position of the common mother—Eve. It was her children who diverged and spawned the two lines of descent.

That modern man emerged from Africa is confirmed by two of the tree's characteristics: First, there are Africans who can trace their ancestry to the base of the tree without running into *any* non-African ancestors, while descendants of the other areas have at least one African ancestor. And second, the Africa-only branch contains more diverse types of mitochondrial DNA than any other geographic group, which demonstrates that more evolutionary change has occurred among Africans than among members of any other group. Since it appears unlikely that the African environment changed drastically enough to account for an aberrantly high rate of evolution there, it can be assumed that Africans accumulated the greatest number of mutations simply because their mitochondrial DNA is the oldest. (By contrast, anthropologists who argue that Asia was the birthplace of modern humans must explain why Asians living today show relatively little diversity in their mitochondrial gene pool.) Eve, then, as the fossil evidence suggests, was an African, and her descendants include both those who remained on her continent and others who struck out to populate the planet.



Piet Mondrian, *Evolution*, 1910-11

Assuming that mitochondrial DNA mutates at the rate of two to four percent every million years, and knowing that the greatest difference between mitochondrial DNA types in the survey (the difference between the two main branches) is nearly six-tenths of one percent, we can conclude that Eve nursed her babies between two hundred and eighty-five thousand and one hundred and forty-three thousand years ago. Hence, Eve is about two hundred thousand years old.

The mitochondrial evidence indicates that archaic *Homo sapiens* evolved into *Homo sapiens sapiens* about eighty thousand years earlier than the fossil evidence suggests. Yet it is also possible that Eve herself belonged to the archaic subspecies and contributed her mitochondrial DNA to those who, perhaps many generations later, evolved into *Homo sapiens sapiens*. This would require only that both branches of Eve's ancestors simultaneously evolved into *Homo sapiens sapiens* without intermixing. Given that they would have lived on the same continent and thus been subject to similar climate and other environmental pressures, it is entirely possible that such concurrent evolution took place. In fact, Eve's descendants could have maintained their archaic form for thousands of years before taking on fully modern characteristics. There is no evidence to suggest that people today have retained any of Eve's particular physical features. We know only that we have inherited her mitochondrial DNA; she might have contributed very little to the surviving pool of human nuclear DNA, which determines such characteristics as head and body shape, eye and skin pigmentation, hair color and thickness.

(It is important to note that, unlike her biblical namesake, mitochondrial Eve was not the only woman alive during her time. She merely is the only woman of her age whose descendants have included some females in every generation. Some of her contemporaries, no doubt, also have progeny alive today who carry traces of the ancestral nuclear DNA, but at some time along the course of descent, there were no female offspring to pass on their grandmothers' mitochondrial genes.)

THE EARLIEST that Eve's descendants could have left Africa for Europe, Asia, and Australia is indicated by the age of the oldest limb of the mitochondrial tree to contain no surviving African members, which dates to about one hundred and thirty-five thousand years ago. This does not mean that the migrations necessarily began then; the migrant population could have lived in isolation within Africa, developing its unique collection of mitochondrial DNA mutations, for thousands of years before leaving home. But it does, at least, raise the possibility that *Homo sapiens sapiens* took as long as one hundred thousand years to take over the world from archaic *Homo sapiens*. The fossil evidence indicates only that Asia, Europe, and Australia were fully colonized by modern humans forty thousand years ago; New Guinea, thirty thousand years ago; and the New World, twelve thousand years ago.

Surprisingly, the mitochondrial tree also indicates that *Homo sapiens sapiens* did not simply migrate to various parts of the world and immediately spawn distinct races—as anthropologists have assumed. If that were the case, each of the largest limbs radiating from the most populous

branch would contain only members of a single race—Asian, European, Australian, New Guinean, or African. If these groups had been isolated enough to develop racial traits so early, each race would have distinctive mitochondrial DNA. Instead, each limb on the tree, except the purely African one, holds an assortment of races. One New Guinean type, for example, has as its nearest relative an Asian, and the other twenty-five New Guineans in the survey are scattered among six other limbs. That the world's races evolved from multiple mitochondrial lineages implies that early modern humans moved back and forth around the world several times, intermixing with one another along the way, before they settled down in sufficient isolation to develop racial features. That one branch holds only Africans indicates that some of the original *Homo sapiens sapiens* remained in Africa. But thirteen of the twenty Africans in the survey are scattered along the branch that includes the four non-African races, which proves that some populations migrated out of Africa, mixed with European and Asian populations, and then returned.

The mitochondrial evidence also may lead to a reappraisal of assumptions about the ways in which particular parts of the world were settled. One theory of the founding of Australia, for example, holds that a small group of people struck out in boats from the southern coast of Asia forty thousand years ago, paddling their way from one island to another until, by chance, they landed on a new continent. The mitochondrial tree belies this theory, by demonstrating that members of not one but at least fifteen lineages must have made the long ocean crossing, because aboriginal Australians descend from that many limbs on the evolutionary tree. It is difficult to see how so many different peoples could have made the same accidental discovery; more likely, the migrants knew exactly where they were going.

The mitochondrial tree also indicates that the Australian gene pool is between eighty-five thousand and forty-three thousand years old, suggesting a somewhat earlier date for the founding of that continent. Larger and more geographically focused surveys of mitochondrial DNA can be expected to supply similar details about the settlement of Europe and Asia. And they may provide clues to such specific questions as how the Polynesians crossed the Pacific and when and how the aboriginal Americans populated the Western Hemisphere.

The relationships among various populations traced through mitochondrial DNA research can be verified through a check to see if those found to be most closely related also display the greatest similarity in nuclear genes. For just as the molecular evidence must be calibrated with the fossil evidence to create the clearest evolutionary picture, the various kinds of molecular evidence must be correlated with one another. Of particular interest are studies soon to begin of the DNA contained in the Y chromosome, which is passed only from father to son. Presumably, a comparison of mutations in the male sex chromosome could generate a genealogy leading back to Adam, and ultimately could determine whether he lived at the same time and in the same place as Eve. ●

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