



## CHAPTER 2

### ALL AFRICA AND HER PROGENIES

It is often thought clever to say that science is no more than our modern origin myth. The Jews had their Adam and Eve, the Sumerians their Marduk and Gilgamesh, the Greeks Zeus and the Olympians, the Norsemen their Valhalla. What is evolution, some smart people say, but our modern equivalent of gods and epic heroes, neither better nor worse, neither truer nor falsier? There is a fashionable salon philosophy called cultural relativism which holds, in its extreme form, that science has no more claim to truth than tribal myth: science is just the mythology favored by our modern Western tribe. I once was provoked by an anthropologist colleague into putting the point starkly, as follows: Suppose there is a tribe, I said, who believe that the moon is an old calabash tossed into the sky, hanging only just out of reach above the treetops. Do you really claim that our scientific truth—that the moon is about a quarter of a million miles away and a quarter the diameter of the Earth—is no more true than the tribe's calabash? "Yes," the anthropologist said. "We are just brought up in a culture that sees the world in a scientific way. They are brought up to see the world in another way. Neither way is more true than the other."

Show me a cultural relativist at thirty thousand feet and

I'll show you a hypocrite. Airplanes built according to scientific principles work. They stay aloft, and they get you to a chosen destination. Airplanes built to tribal or mythological specifications, such as the dummy planes of the cargo cults in jungle clearings or the beeswaxed wings of Icarus, don't.\* If you are flying to an international congress of anthropologists or literary critics, the reason you will probably get there—the reason you don't plummet into a ploughed field—is that a lot of Western scientifically trained engineers have got their sums right. Western science, acting on good evidence that the moon orbits the Earth a quarter of a million miles away, using Western-designed computers and rockets, has succeeded in placing people on its surface. Tribal science, believing that the moon is just above the treetops, will never touch it outside of dreams.

I seldom give a public lecture without a member of the audience brightly coming up with something along the same lines as my anthropologist colleague, and it usually elicits a murmur of approving nods. No doubt the nodders feel good and liberal and unracist. An even more reliable nod-provoker is "Fundamentally, your belief in evolution comes down to faith, and therefore it's no better than somebody else's belief in the Garden of Eden."

\*This is not the first time I have used this knock-down argument, and I must stress that it is aimed strictly at people who think like my colleague of the calabash. There are others who, confusingly, also call themselves cultural relativists although their views are completely different and perfectly sensible. To them, cultural relativism just means that you cannot understand a culture if you try to interpret its beliefs in terms of your own culture. You have to see each of the culture's beliefs in the context of the culture's other beliefs. I suspect that this sensible form of cultural relativism is the original one, and that the one I have criticized is an extremist, though alarmingly common, perversion of it. Sensible relativists should work harder at distancing themselves from the fatuous kind.

Every tribe has had its origin myth—its story to account for the universe, life and humanity. There is a sense in which science does indeed provide the equivalent of this, at least for the educated section of our modern society. Science may even be described as a religion, and I have, not entirely facetiously, published a brief case for science as an appropriate subject for religious-education classes.\* (In Britain, religious education is a compulsory part of the school curriculum, unlike in the United States, where it is banned for fear of offending any of the plethora of mutually incompatible faiths.) Science shares with religion the claim that it answers deep questions about origins, the nature of life, and the cosmos. But there the resemblance ends. Scientific beliefs are supported by evidence, and they get results. Myths and faiths are not and do not.

Of all origin myths, the Jewish story of the Garden of Eden is so pervasive in our culture that it has bequeathed its name to an important scientific theory about our ancestry, the theory of "African Eve." I am devoting this chapter to African Eve partly because it will enable me to develop the analogy of the river of DNA but also because I want to contrast her, as a scientific hypothesis, with the legendary matriarch of the Garden of Eden. If I succeed, you will find the truth more interesting, maybe even more poetically moving, than the myth. We begin with an exercise in pure reasoning. Its relevance will become clear soon.

You have two parents, four grandparents, eight great-grandparents and so on. With every generation, the number of ancestors doubles. Go back  $g$  generations and the number of

\**The Spectator* (London), August 6, 1994.

ancestors is 2 multiplied by itself  $g$  times: 2 to the power  $g$ . Except that, without leaving our armchair, we can quickly see that it cannot be so. To convince ourselves of this, we have only to go back a little way—say, to the time of Jesus, almost exactly two thousand years ago. If we assume, conservatively, four generations per century—that is, that people breed on average at the age of twenty-five—two thousand years amounts to a mere eighty generations. The real figure is probably more than this (until recent times, many women bred extremely young), but this is only an armchair calculation, and the point is made regardless of such details. Two multiplied by itself 80 times is a formidable number, a 1 followed by 24 noughts, a trillion American trillions. You had a million million million million ancestors who were contemporaries of Jesus, and so did I! But the total population of the world at that time was a fraction of a negligible fraction of the number of ancestors we have just calculated.

Obviously we have gone wrong somewhere, but where? We did the calculation right. The only thing we got wrong was our assumption about doubling up in every generation. In effect, we forgot that cousins marry. I assumed that we each have eight great-grandparents. But any child of a first-cousin marriage has only six great-grandparents, because the cousins' shared grandparents are in two separate ways great-grandparents to the children. "So what?" you may ask. People occasionally marry their cousins (Charles Darwin's wife, Emma Wedgwood, was his first cousin), but surely it doesn't happen often enough to make a difference? Yes it does, because "cousin" for our purposes includes second cousins, fifth cousins, sixteenth cousins and so forth. When you count

cousins as distant as that, every marriage is a marriage between cousins. You sometimes hear people boasting of being a distant cousin of the Queen, but it is rather pompous of them, because we are *all* distant cousins of the Queen, and of everybody else, in more ways than can ever be traced. The only thing special about royalty and aristocrats is that they can do the tracing explicitly. As the fourteenth Earl of Home said when taunted about his title by his political opponent, "I suppose Mr. Wilson, when you come to think of it, is the fourteenth Mr. Wilson."

The upshot of all this is that we are much closer cousins of one another than we normally realize, and we have many fewer ancestors than simple calculations suggest. Seeking to get her reasoning along these lines, I once asked a student to make an educated guess as to how long ago her most recent common ancestor with me might have lived. Looking hard at my face, she unhesitatingly replied, in a slow, rural accent, "Back to the apes." An excusable intuitive leap, but it is approximately 10,000 percent wrong. It would suggest a separation measured in millions of years. The truth is that the most recent ancestor she and I shared would possibly have lived no more than a couple of centuries ago, possibly well after William the Conqueror. Moreover, we were certainly cousins in many different ways simultaneously.

The model of ancestry that led to our erroneously inflated calculation of ancestral numbers was an ever-branching tree, branching and branching again. Turned the other way up, and equally wrong, is a tree model of descent. A typical individual has two children, four grandchildren, eight great-grandchildren and so on down to impossible trillions of

descendants a few centuries hence. A far more realistic model of ancestry and descent is the flowing river of genes, which we introduced in the previous chapter. Within its banks, the genes are an ever-rolling stream through time. Currents swirl apart and join again as the genes crisscross down the river of time. Draw out a bucketful at intervals from points spaced out down the length of the river. Pairs of molecules in a bucket will have been companions before, at intervals during their progress down the river, and they will be companions once more. They have also been widely separated in the past, and they will be widely separated again. It is hard to trace the points of contact, but we can be mathematically certain that the contacts happen—mathematically certain that if two genes are out of contact at a particular point, we won't have to travel far in either direction along the river until they touch again.

You may not know that you are a cousin of your husband, but it is statistically likely that you won't have to go far back in your ancestry until you meet a junction with his lineage. Looking in the other direction, toward the future, it might seem obvious that you have a good chance of sharing descendants with your husband or wife. But here is a much more arresting thought. Next time you are with a large group of people—say, in a concert hall or at a football match—look around at the audience and reflect upon the following: if you have any descendants at all in the distant future, there are probably people at the same concert whose hands you could shake as coancestors of your future descendants. Cograndparents of the same children usually know they are coancestors, and this must give them a certain feeling of affinity whether or not they get on person-

ally. They can look at each other and say, "Well, I may not like him much, but his DNA is mingled with mine in our shared grandchild, and we can hope to share descendants into the future, long after we're gone. Surely this creates a bond between us." But my point is that, if you are blessed with distant descendants at all, some of the perfect strangers at the concert hall will probably be your coancestors. You can survey the auditorium and speculate about which individuals, male or female, are destined to share your descendants and which are not. You and I, whoever you are and whatever your color and sex, may well be coancestors. Your DNA may be destined to mingle with mine. Salutations!

Now suppose we travel back in a time machine, perhaps to a crowd in the Colosseum, or farther back, to market day in Ur, or even farther still. Survey the crowd, just as we imagined for our modern concert audience. Realize that you can divide these long-dead individuals into two and only two categories: those who are your ancestors and those who are not. That is obvious enough, but now we come to a remarkable truth. If your time machine has taken you sufficiently far back, you can divide the individuals you meet into those who are ancestors of every human alive in 1995 and those who are the ancestors of nobody alive in 1995. There are no intermediates. Every individual you set eyes on when you step outside your time machine is either a universal human ancestor or not an ancestor of anybody at all.

This is an arresting thought, but it is trivially easy to prove. All you have to do is move your mental time machine back to a ludicrously long time ago: say, to three hundred fifty

million years ago, when our ancestors were lobe-finned fishes with lungs, emerging from the water and becoming amphibians. If a particular fish is my ancestor, it is inconceivable that he is not your ancestor too. If he were not, this would imply that the lineage leading to you and the lineage leading to me had independently, without cross-reference, evolved from fish through amphibian, reptile, mammal, primate, ape and hominid, ending up so similar that we can talk to each other and, if we are of opposite sex, mate with each other. What is true of you and me is true of any pair of humans.

We have proved that if we travel sufficiently far back in time, every individual we encounter must be the ancestor either of all of us or of none of us. But how far is sufficiently far? We clearly don't need to go back to lobe-finned fishes—that was the *reductio ad absurdum*—but how far do we have to go back until we come to a universal ancestor of every human alive in 1995? That's a much more difficult question, and it is the one to which I next want to turn. This one cannot be answered from the armchair. We need real information, measurements from the hard world of particular facts.

Sir Ronald Fisher, the formidable English geneticist and mathematician, who could be regarded as Darwin's greatest twentieth-century successor as well as the father of modern statistics, had this to say in 1930:

It is only the geographical and other barriers to sexual intercourse between different races . . . which prevent the whole of mankind from having had, apart from the last thousand years, a practically identical ancestry. The ancestry of members of the same nation can differ little beyond the last 500 years; at 2000 years the only differences that would seem to remain would be

those between distinct ethnographic races; these . . . may indeed be extremely ancient; but this could only be the case if for long ages the diffusion of blood between the separated groups was almost non-existent.

In the terms of our river analogy, Fisher is, in effect, making use of the fact that the genes of all the members of one geographically united race are flowing down the same river. But when it came to his actual figures—five hundred years, two thousand years, the antiquity of the separation of different races—Fisher had to have been making educated guesses. The relevant facts were not available in his time. Now, with the molecular-biology revolution, there is an embarrassment of riches. It is molecular biology that has given us the charismatic African Eve.

The digital river is not the only metaphor that has been used. It is tempting to liken the DNA in each one of us to a family Bible. DNA is a very long piece of text, written, as we saw in the previous chapter, in a four-letter alphabet. The letters have been scrupulously copied from our ancestors, and only from our ancestors, with remarkable fidelity even in the case of very remote ancestors. It should be possible, by comparing the texts preserved in different people, to reconstruct their cousinship and work back to a common ancestor. Distant cousins, whose DNA has had more time to diverge—say, Norwegians and Australian aborigines—should differ in a larger number of words. Scholars do this kind of thing with different versions of biblical documents. Unfortunately, in the case of DNA archives, there is a snag. Sex.

Sex is an archivist's nightmare. Instead of leaving ancestral texts intact but for an occasional inevitable error, sex

wantonly and energetically wades in and destroys the evidence. No bull ever abused a china shop as sex abuses the DNA archives. There is nothing like it in biblical scholarship. Admittedly, a scholar seeking to trace the origins of, say, the Song of Solomon is aware that it is not quite what it seems. The Song has oddly disjointed passages, suggesting that it is really fragments of several different poems, only some of them erotic, stitched together. It contains errors—mutations—especially in translation. “Take us the foxes, the little foxes, that spoil the vines” is a mistranslation, even though a lifetime’s repetition has given it a haunting appeal of its own, which is unlikely to be matched by the more correct “Catch for us the fruit bats, the little fruit bats . . .”:

For lo, the winter is past, the rain is over and gone. The flowers appear on the earth; the time of the singing of birds is come, and the voice of the turtle is heard in our land.

The poetry is so ravishing that I am reluctant to spoil it by noting that here, too, is an undoubted mutation. Reinsert “dove” after “turtle,” as the modern translations correctly but leadenly do, and hear the cadence collapse. But these are minor errors, the inevitable, slight degradations we have to expect when documents are not printed in thousands or etched on high-fidelity computer disks but copied and recopied by mortal scribes from scarce and vulnerable papyri.

But now let sex enter the picture. (No, in the sense I mean, sex does not enter the Song of Songs.) Sex, in the sense I mean, amounts to ripping out half of one document, in the form of randomly chosen fragments, and mixing it with the complementarily butchered half of another docu-

ment. Unbelievable—vandalistic, even—as it sounds, this is exactly what happens whenever a sex cell is made. For instance, when a man makes a sperm cell, the chromosomes that he inherited from his father pair off with the chromosomes that he inherited from his mother, and great chunks of them change places. A child’s chromosomes are an irretrievably scrambled mishmash of its grandparents’ chromosomes and so on back to distant ancestors. Of the would-be ancient texts, the letters, perhaps the words, may survive intact down the generations. But chapters, pages, even paragraphs are torn up and recombined with such ruthless efficiency that as a means of tracing history they are almost useless. Where ancestral history is concerned, sex is the great cover-up.

We can use DNA archives to reconstruct history wherever sex is safely out of the picture. I can think of two important examples. One is African Eve, and I’ll come to her. The other case is the reconstruction of more remote ancestry—looking at relationships among species rather than within species. As we saw in the previous chapter, sexual mixing takes place only within species. When a parental species buds off a daughter species, the river of genes splits into two branches. After they have diverged for a sufficient time, sexual mixing within each river, far from being a hindrance to the genetic archivist, actually helps in the reconstruction of ancestry and cousinships among species. It is only where within-species cousinships are concerned that sex messes up the evidence. Where between-species cousinships are concerned, sex helps because it tends automatically to ensure that each individual is a good genetic sample of the entire species. It doesn’t

matter which bucketful you haul out of a well-churned river; it will be representative of the water of that river.

DNA texts taken from representatives of different species have indeed been compared, with great success, letter by letter, to construct family trees of species. It is even possible, according to one influential school of thought, to put dates on the branchings. This opportunity follows from the albeit controversial notion of a “molecular clock”: the assumption that mutations in any one region of the genetic text occur at a constant rate per million years. We’ll return to the molecular-clock hypothesis in a moment.

The “paragraph” in our genes describing the protein called cytochrome *c* is 339 letters long. Twelve letter changes separate human cytochrome *c* from the cytochrome *c* of horses, our rather distant cousins. Only one cytochrome *c* letter change separates humans from monkeys (our fairly close cousins), one letter change separates horses from donkeys (their very close cousins) and three letter changes separate horses from pigs (their somewhat more distant cousins). Forty-five letter changes separate humans from yeast and the same number separates pigs from yeast. It is not surprising that these numbers should be the same, because as we follow back the river leading to humans, it joins with the river leading to pigs much more recently than their common river joins the river leading to yeast. There is a little slop in these numbers, however. The number of letter changes in cytochrome *c* separating horses from yeast is not forty-five but forty-six. This does not mean that pigs are closer cousins of yeast than horses are. They are exactly equally close to yeast, as are all vertebrates—and, indeed, all animals. Perhaps an extra change crept into the lineage leading to horses since the time

of the rather recent ancestor they share with pigs. That is not important. On the whole, the number of cytochrome *c* letter changes separating pairs of creatures is pretty much what we’d expect from previous ideas of the branching pattern of the evolutionary tree.

The molecular clock theory, as noted, holds that the rate of change of a given piece of text per million years is roughly fixed. Of the forty-six cytochrome *c* letter changes separating horses from yeast, it is assumed that about half of them occurred during evolution from the common ancestor to modern horses and about half of them occurred during evolution from the common ancestor to modern yeast (obviously, the two evolutionary pathways have taken exactly the same number of millions of years to accomplish). At first this seems a surprising thing to assume. After all, it is pretty likely that the common ancestor resembled yeast more than it resembled a horse. The reconciliation lies in the assumption, increasingly accepted since it was first championed by the eminent Japanese geneticist Motoo Kimura, that the greater part of genetic texts can change freely without the text’s meaning being affected.

A good analogy is varying the typeface in a printed sentence. “A **horse** is a **mammal**.” “A **yeast** is a **fungus**.” The meaning of these sentences comes through loud and clear, even though every word is printed in a different font. The molecular clock ticks away in the equivalent of meaningless font changes, as the millions of years go by. The changes that are subject to natural selection and that describe the difference between a horse and a yeast—the changes in *meaning* of the sentences—are the tip of the iceberg.

Some molecules have a higher clock rate than others.

Cytochrome *c* evolves relatively slowly: about one letter change every twenty-five million years. This is probably because cytochrome *c*'s vital importance to an organism's survival depends critically upon its detailed shape. Most changes in such a shape-critical molecule are not tolerated by natural selection. Other proteins, such as those called fibrinopeptides, although they are important, work equally well in lots of variant forms. The fibrinopeptides are used in blood clotting, and you can change most of their details without harming their clottability. The mutation rate in these proteins is about one change every six hundred thousand years, a rate more than forty times faster than that for cytochrome *c*. Fibrinopeptides, therefore, are no good for reconstructing ancient ancestry, although they are useful for reconstructing more recent ancestry—for example, within the mammals. There are hundreds of different proteins, each changing at its own characteristic rate per million years and each independently usable for reconstructing family trees. They all yield pretty much the same family tree—which, by the way, is rather good evidence, if evidence were needed, that the theory of evolution is true.

We came into this discussion from the realization that sexual mixing messes up the historical record. We distinguished two ways in which the effects of sex could be escaped. We've just dealt with one of them, following from the fact that sex does not mix genes between species. This opens up the possibility of using DNA sequences to reconstruct remotely ancient family trees of our ancestors that lived long before we became recognizably human. But we've already agreed that if we go back that far we humans are all definitely descended from the same single individ-

ual anyway. We wanted to find out how recently we could still claim common descent with all other humans. To discover that, we have to turn to a different kind of DNA evidence. This is where African Eve comes into the story.

African Eve is sometimes called Mitochondrial Eve. Mitochondria are tiny, lozenge-shaped bodies swarming by the thousands in each one of our cells. They are basically hollow but with a complicated interior structure of membranous baffles. The area afforded by these membranes is much larger than you'd think from the outside appearance of mitochondria, and it is used. The membranes are the production lines of a chemical factory—more precisely, a power station. A carefully controlled chain reaction is strung out along the membranes—a chain reaction involving more stages than those in any human chemical factory. The result is that energy, originating in food molecules, is released in controlled steps and stored in reusable form for burning later, wherever it is needed, anywhere in the body. Without our mitochondria, we'd die in a second.

That's what mitochondria do, but we are here more concerned with where they come from. Originally, in ancient evolutionary history, they were bacteria. This is the remarkable theory championed, by the redoubtable Lynn Margulis of the University of Massachusetts at Amherst, from heterodox origins through grudging interest to triumphant near-universal acceptance today. Two billion years ago, the remote ancestors of mitochondria were free-living bacteria. Together with other bacteria of different kinds, they took up residence inside larger cells. The resulting community of ("prokaryotic") bacteria became the large ("eukaryotic") cell we call our own. Each one of us is a community of a hundred million million

mutually dependent eukaryotic cells. Each one of those cells is a community of thousands of specially-tamed bacteria, entirely enclosed within the cell, where they multiply as bacteria will. It has been calculated that if all the mitochondria in a single human body were laid end to end, they would girdle the Earth not once but two thousand times. A single animal or plant is a vast community of communities packed in interacting layers, like a rain forest. As for a rain forest itself, it is a community seething with perhaps ten million species of organisms, every individual member of every species being itself a community of communities of domesticated bacteria. Not only is Dr. Margulis's theory of origins—the cell as an enclosed garden of bacteria—incomparably more inspiring, exciting and uplifting than the story of the Garden of Eden. It has the additional advantage of being almost certainly true.

Like most biologists, I now assume the truth of the Margulis theory, and in this chapter I mention it only to follow up a particular implication: mitochondria have their own DNA, which is confined to a single ring chromosome, as in other bacteria. And now for the point that this has all been leading up to. Mitochondrial DNA does not participate in any sexual mixing, either with the main “nuclear” DNA of the body or with the DNA of other mitochondria. Mitochondria, like many bacteria, reproduce simply by dividing. Whenever a mitochondrion divides into two daughter mitochondria, each daughter gets an identical copy—give or take the odd mutation—of the original chromosome. Now you see the beauty of this, from our point of view as long-distance genealogists. We found that where our ordinary DNA texts are concerned, in every generation sex scrambles the evidence, confusing the

contributions from paternal and maternal lines. Mitochondrial DNA is blessedly celibate.

We get our mitochondria from our mother only. Sperms are too small to contain more than a few mitochondria; they have just enough to provide the energy to power their tails as they swim toward the egg, and these mitochondria are cast away with the tail when the sperm head is absorbed in the egg at fertilization. The egg is massive by comparison, and its huge, fluid-filled interior contains a rich culture of mitochondria. This culture seeds the child's body. So whether you are female or male, your mitochondria are all descended from an initial inoculum of your mother's mitochondria. Whether you are male or female, your mitochondria are all descended from your maternal grandmother's mitochondria. None from your father, none from either grandfather, none from your paternal grandmother. The mitochondria constitute an independent record of the past, uncontaminated by the main nuclear DNA, which is equally likely to come from each of four grandparents, each of eight great-grandparents and so on back.

Mitochondrial DNA is uncontaminated, but it is not immune to mutation—to random errors in copying. Indeed, it mutates at a higher rate than our “own” DNA, because (as is the case with all bacteria) it lacks the sophisticated proofreading machinery our cells have evolved over the eons. There will be a few differences between your mitochondrial DNA and mine, and the number of differences will be a measure of how far back our ancestors diverged. Not *any* of our ancestors, but our ancestors in the female female female . . . line. If your mother happens to be a purebred native Australian, or a purebred Chinese, or a purebred !Kung San of the Kalahari, there

will be rather a lot of differences between your mitochondrial DNA and mine. It doesn't matter who your father is: he can be an English marquess or a Sioux chieftain, for all the difference it makes to your mitochondria. And the same goes for any of your male ancestors, ever.

So there is a separate mitochondrial Apocrypha, handed down alongside the main family Bible but with the great virtue of going down the female line only. This is not a sexist point; it would be just as good if it came down through the male line only. The virtue lies in its intactness, in its not being chopped and merged in every generation. Consistent descent via either sex but not both is what we, as DNA genealogists, need. The Y chromosome which, like a surname, is handed down the male line only, would in theory be just as good, but it contains too little information to be useful. The mitochondrial Apocrypha is ideal for dating common ancestors within one species.

Mitochondrial DNA has been exploited by a group of researchers associated with the late Allan Wilson in Berkeley, California. In the 1980s, Wilson and his colleagues sampled the sequences from 135 living women drawn from all around the world—Australian aborigines, New Guinea highlanders, Native Americans, Europeans, Chinese and representatives of various peoples in Africa. They looked at the numbers of letter differences separating each woman from each other woman. They gave these numbers to a computer and asked it to construct the most parsimonious family tree it could find. "Parsimonious" here means doing away as much as possible with the need to postulate coincidence. This requires some explaining.

Think back to our earlier discussion of horses, pigs and

yeast, and the analysis of cytochrome *c* letter sequences. You remember that horses differ from pigs in only three such letters, pigs differ from yeast in forty-five letters, and horses differ from yeast in forty-six letters. We made the point that, theoretically, since horses and pigs are connected to each other by a relatively recent common ancestor, they should be exactly the same distance from yeast. The difference between forty-five and forty-six is an anomaly, something that in an ideal world would not be there. It may be due to an additional mutation on the route to horses or a reverse mutation on the route to pigs.

Now, absurd as such an idea is in reality, it is theoretically conceivable that pigs are really closer to yeast than they are to horses. It is theoretically possible that pigs and horses have evolved their close resemblance to one another (their cytochrome *c* texts are only three letters apart, and their bodies are basically built to an almost identical mammalian pattern) by massive coincidence. The reason we don't believe this is that the ways in which pigs resemble horses vastly outnumber the ways in which pigs resemble yeast. Admittedly, there is a single DNA letter in which pigs appear closer to yeast than to horses, but this is swamped by millions of resemblances going the other way. The argument is one of parsimony. If we assume that pigs are close to horses, we need to accommodate only one coincidental resemblance. If we try to assume that pigs are close to yeast, we have to postulate a prodigiously unrealistic concatenation of independently acquired coincidental resemblances.

In the cases of horses, pigs and yeast, the parsimony argument is too overwhelming to be in doubt. But in the mitochondrial DNA of different human races there is noth-

ing overwhelming about the resemblances. Parsimony arguments still apply, but they are slight, quantitative arguments, not massive, knock-down arguments. Here's what the computer, in theory, has to do. It has to make a list of all possible family trees relating the 135 women. It then examines this set of possible trees and picks out the most parsimonious one—that is, the one that minimizes the number of coincidental resemblances. We must accept that even the best tree will probably force us to accept a few little coincidences, just as we were forced to accept the fact that, with regard to one DNA letter, yeasts are closer to pigs than to horses. But—in theory, at least—the computer should be able to take that in its stride and announce to us which of the many possible trees is the most parsimonious, the least coincidence-ridden.

That is in theory. In practice, there is a snag. The number of possible trees is greater than you, or I, or any mathematician, can possibly imagine. For horse, pig and yeast there are only three possible trees. The obviously correct one is *[[pig horse] yeast]*, with pig and horse nested together inside the innermost brackets and yeast as the unrelated “outgroup.” The other two theoretical trees are *[[pig yeast] horse]* and *[[horse yeast] pig]*. If we add a fourth creature—say, squid—the number of trees goes up to fifteen. I won't list all fifteen, but the true (most parsimonious) one is *[[[pig horse] squid] yeast]*. Again, pig and horse, as close relatives, are cosily nested together in the innermost brackets. Squid is the next to join the club, having a more recent ancestor with the pig/horse lineage than yeast does. Any of the fourteen other trees—for instance, *[[pig squid] [horse yeast]]*—is definitely less parsimonious. It is highly improbable that pig and horse could have independently evolved their numerous resemblances if pig

were really a closer cousin to squid and horse were really a closer cousin to yeast.

If three creatures yield three possible trees, and four creatures yield fifteen possible trees, how many possible trees could be constructed for a hundred and thirty-five women? The answer is such a risibly large number that there is no point in writing it out. If the largest and fastest computer in the world were set to work listing all the possible trees, the end of the world would be upon us before the computer had made a perceptible dent in the task.

Nevertheless, the problem is not hopeless. We are used to taming impossibly large numbers by judicious sampling techniques. We can't count the number of insects in the Amazon Basin, but we can estimate the number by sampling small plots dotted at random through the forest and assuming that these plots are representative. Our computer can't examine all possible trees uniting the 135 women, but it can pull out random samples from the set of all possible trees. If, whenever you draw a sample from the gigabillions of possible trees, you notice that the most parsimonious members of the sample have certain features in common, you can conclude that probably the most parsimonious of all the trees has the same features.

This is what people have done. But it isn't necessarily obvious what is the best way to do it. Just as entomologists might disagree over the most representative way to sample the Brazilian rain forest, so DNA genealogists have used different sampling methods. And unfortunately the results don't always agree. Nevertheless, for what they are worth, I'll present the conclusions the Berkeley group reached in their original analysis of human mitochondrial DNA. Their conclusions

were extremely interesting and provocative. According to them, the most parsimonious tree turns out to be firmly rooted in Africa. What this means is that some Africans are more distantly related to other Africans than to anybody in the whole of the rest of the world. The whole of the rest of the world—Europeans, Native Americans, Australian aborigines, Chinese, New Guineans, Inuits, and all—form one relatively close group of cousins. Some Africans belong in this close group. But other Africans don't. According to this analysis, the most parsimonious tree looks like this: [some Africans [other Africans [yet other Africans [yet other Africans and everybody else]]]]. They therefore concluded that the grand ancestress of all of us lived in Africa: "African Eve." As I have said, this conclusion is controversial. Others have claimed that equally parsimonious trees can be found in which the outermost branches occur outside Africa. They also claim that the Berkeley group obtained the particular results they did partly because of the order in which their computer looked at the possible trees. Obviously, order of looking ought not to matter. Probably most experts would still put their money on Mitochondrial Eve's being African, but they wouldn't do so with any great confidence.

The second conclusion of the Berkeley group is less controversial. No matter where Mitochondrial Eve lived, they were able to estimate when. It is known how fast mitochondrial DNA evolves; you can therefore put an approximate date on each of the branch points on the tree of divergence of mitochondrial DNA. And the branch point that unites all womankind—the birth date of Mitochondrial Eve—is between a hundred fifty thousand and a quarter of a million years ago.

Whether Mitochondrial Eve was an African or not, it is important to avoid a possible confusion with another sense in which it is undoubtedly true that our ancestors came out of Africa. Mitochondrial Eve is a recent ancestor of all modern humans. She was a member of the species *Homo sapiens*. Fossils of much earlier hominids, *Homo erectus*, have been found outside as well as inside Africa. The fossils of ancestors even more remote than *Homo erectus*, such as *Homo habilis* and various species of *Australopithecus* (including a newly discovered one more than four million years old), have been found only in Africa. So if we are the descendants of an African diaspora within the last quarter of a million years, it is the second African diaspora. There was an earlier exodus, perhaps a million and a half years ago, when *Homo erectus* meandered out of Africa to colonize parts of the Middle East and Asia. The African Eve theory is claiming not that these earlier Asians didn't exist but that they leave no surviving descendants. Whichever way you look at it, we are all, if you go back two million years, Africans. The African Eve theory is claiming in addition that we surviving humans are all Africans if you go back only a few hundred thousand years. It would be possible, if new evidence supported it, to trace all modern mitochondrial DNA back to an ancestress outside Africa ("Asian Eve," say) while at the same time agreeing that our more remote ancestors are to be found only in Africa.

Let's assume, for the moment, that the Berkeley group is right, and examine what their conclusion does and does not mean. The "Eve" sobriquet has had unfortunate consequences. Some enthusiasts have run away with the idea that she must have been a lonely woman, the only woman on Earth, the ultimate genetic bottleneck, even a vindication of Genesis! This is

a complete misunderstanding. The correct claim is not that she was the only woman on Earth, nor even that the population was relatively small during her time. Her companions, of both sexes, may have been both numerous and fecund. They may still have numerous descendants alive today. But all descendants of their mitochondria have died out, because their link with us passes, at some point, through a male. In the same way, a noble surname (surnames are linked to Y chromosomes and pass down the male-only line in exact mirror image to mitochondria) can die out, but this doesn't mean that possessors of the surname have no descendants. They may have numerous descendants via pathways other than the male-only pathway. The correct claim is only that Mitochondrial Eve is the most recent woman of whom it can be said that all modern humans are descended from her in the female-only line. There *has* to be a woman of whom this claim can be made. The only argument is over whether she lived here rather than there, at this time rather than at that time. The fact that she did live, in some place and at some time, is certain.

Here is a second misunderstanding—a more common one, which I have heard perpetrated even by leading scientists working in the field of mitochondrial DNA. This is the belief that Mitochondrial Eve is our most recent common ancestor. It is based on a confusion between “most recent common ancestor” and “most recent common ancestor in the purely female line.” Mitochondrial Eve is our most recent common ancestor in the purely female line, but there are lots of other ways of being descended from people than in the female line. Millions of other ways. Go back to our calculations of numbers of ancestors (forgetting the complication of cousin mar-

riage, which was the point of the argument before). You have eight great-grandparents but only one of them is in the purely female line. You have sixteen great-great-grandparents but only one of *them* is in the purely female line. Even allowing that cousin marriage reduces the number of ancestors in a given generation, it is still true that there are far, far, far more ways of being an ancestor than just in the female-only line. As we follow our genetic river back through remote antiquity, there were probably lots of Eves and lots of Adams—focal individuals, of whom it is possible to say that all 1995's people are descended from her, or him. Mitochondrial Eve is only one of these. There is no particular reason to think that of all these Eves and Adams, Mitochondrial Eve is the most recent. On the contrary. She is defined in a *particular* way: we are descended from her via a particular pathway through the river of descent. The number of possible pathways to set alongside the female-only pathway is so large that it is mathematically highly unlikely that Mitochondrial Eve is the most recent of these many Eves and Adams. It is special among pathways in one way (being female-only). It would be a remarkable coincidence if it were special among pathways in another way (being the most recent).

An additional point of mild interest is that our most recent common ancestor is somewhat more likely to have been an Adam than an Eve. Harems of females are more likely to occur than harems of males, if only because males are physically capable of having hundreds of children, even thousands. *The Guinness Book of Records* puts the record at over a thousand, achieved by Moulay Ishmael the Bloodthirsty. (Incidentally, Moulay Ishmael might well be adopted by feminists as a general symbol of macho unpleasantness. It is said that his

method of mounting a horse was to draw his sword and leap into the saddle, achieving quick release by simultaneously decapitating the slave who held the bridle. Implausible as this is, the fact that the legend comes down to us, together with his reputation for having killed ten thousand men with his own hand, perhaps gives an idea of the kinds of qualities that were admired among men of his type.) Females, even under ideal conditions, cannot have more than a couple of tens of children. A female is more likely than a male to have the average number of children. A few males may have a ludicrously greedy share of the children, which means that other males must have none. If anybody fails to reproduce altogether, it is more likely to be a male than a female. And if anybody garners a disproportionate posterity, it is also likely to be a male. This goes for the most recent common ancestor of all humanity, who is therefore more likely to have been an Adam than an Eve. To take an extreme example, who is more likely to be the ancestor of all present-day Moroccans, Moulay Ishmael the Bloodthirsty or any *one* woman in his unfortunate harem?

We may come to the following conclusions: First, it is necessarily certain that there existed one female, whom we may call Mitochondrial Eve, who is the most recent common ancestor of all modern humans down the female-only pathway. It is also certain that there existed one person, of unknown sex, whom we may call the Focal Ancestor, who is the most recent common ancestor of all modern humans down any pathway. Third, although it is possible that Mitochondrial Eve and the Focal Ancestor are one and the same, it is vanishingly unlikely that this is so. Fourth, it is somewhat more likely that the Focal Ancestor was a male than a female. Fifth, Mitochondrial Eve very probably lived less than a quar-

ter of a million years ago. Sixth, there is disagreement over where Mitochondrial Eve lived, but the balance of informed opinion still favors Africa. Only conclusions five and six depend upon inspection of scientific evidence. The first four can all be worked out by armchair reasoning from common knowledge.

But I said that ancestors hold the key to understanding life itself. The story of African Eve is a parochial, human microcosm of a grander and incomparably more ancient epic. We shall again have recourse to the metaphor of the river of genes, our river out of Eden. But we shall follow it back through a time scale incommensurably older than the legendary Eve's thousands of years and African Eve's hundreds of thousands. The river of DNA has been flowing through our ancestors in an unbroken line that spans not less than three thousand million years.