ARCHAEOPTERYX LOOKS UP

Speculations on the Future of Human Evolution

By Frank Wilczek

Archaeopteryx could fly—but not very well. Human beings today can penetrate outside Earth's airy envelope—but not very well. Our minds can penetrate into realms of thought far beyond the domain they were evolved to inhabit—but not very well.

It seems clear that the present form of humanity is, like *archaeopteryx*, a transitional stage. What will come next? I don't know, of course, but it's an entertaining, inspiring—and maybe important—question to think about.

QUALITATIVE EVOLUTION BASED ON BIOLOGY

In the past, evolution has been based on natural selection. Its results are impressive. Yet from an engineering perspective, natural selection is both haphazard and crude—haphazard because no meaningful goal is explicit; crude because it gathers feedback slowly and with much noise.

What we might call its "goal" is simply to keep going. Its "performance criterion" is production of fertile offspring: what Darwin called the struggle for existence. That "goal" is, of course, not a mindful goal, nor is the "performance criterion" a performance criterion in the conventional sense, where we judge how well some concrete task has been accomplished. Yet natural selection, by allowing information to flow from the environment to the replicating unit—the genes—results in effective adaptation and creative response to opportunities. Famously, it leads to what seems to be inspired designs to achieve what appear (to us) to be concrete goals.

Viewed analytically, evolution's design methods look terribly inefficient. Feedback arrives once a generation, and its information content is just a few bits, to wit the number and genetic types of surviving offspring. Furthermore, that information content is dominated by unrelated noise, all the complex accidents that impact survival. By way of comparison, we routinely gather gigabytes of useful information every hour by using our eyes and brain to look out at the world. Evolution by natural selection produces impressive feats of creative engineering only because it plays out over very long spans of time (many generations) on a very large stage (many individuals).

In the past, eugenics—encouraging certain individuals to reproduce while discouraging others—has been proposed as a path to human improvement. Even leaving moral issues aside, classical

eugenics was doomed to failure. Selecting human parents on the basis of a few superficial characteristics is inherently crude and inefficient, with the same drawbacks as natural selection.

Only recently, with increased understanding of genetics, development, and physiology at the molecular level, have truly powerful possibilities for directing evolution begun to arise.

Screening against catastrophic genetic diseases is widely practiced and accepted. But where are the boundaries between disease, substandard performance, and suboptimal performance? Is deafness a disease? Is tone deafness? Is lack of perfect pitch? Any boundary is artificial, and arbitrary boundaries will be breached. What's in store for the future? Some, if not all, parents will seek to produce the best children they can, according to their own view of "best." Parental (or governmental?) selection will replace natural selection as an engine of human evolution. Selection by genetic screening will be much more efficient.

What goals will parents pursue? (Note: I say *will*, not *should*.)

The most obvious goal is improved health, broadly defined to include both physical vitality and longevity. The popularity of performance-enhancing drugs for athletes, of diets and food supplements, and, of course, our vast investment in medical research, attest to our powerful drive toward that goal. In this area, the most fundamental issue is aging. After a long exile at the fringes of biology, the question of why we age, and what can be done to combat that process, has now firmly entered the realm of molecular investigation. Decisive progress may or may not come within a few years, but in a few decades it is likely, and in a century almost certain. Future humans will be healthier and live much longer than we do. They may be effectively immortal—and they'll all have perfect pitch.

A second goal is more powerful intelligence. It may not be obvious, especially if you pay attention to the American political scene, but the evidence of nature is that there is intense pressure toward the evolution of increased intelligence. In the six million years or so since protohumans separated from chimpanzees, even bumbling natural selection has systematically upgraded our brains and enlarged our skulls, despite the steep costs of difficult childbirth and prolonged infancy. I suspect an important part of the pressure for intelligence comes from sexual selection: finding a mate is a complicated business, and women in particular tend to be choosy.

The salient facts here are: first, that it was possible to come so far so fast (on an evolutionary timescale!), and second, that the limiting factor is plausibly the mechanics of childbirth. Together, these facts suggest that tuning up production of bigger and better brains may be simple, once we find the tuning mechanism. More generally, better understanding of the molecular mechanisms behind development and learning gives new hope for improving mental vitality, just as understanding molecular genetics and physiology does for physical vitality.

QUALITATIVE EVOLUTION BASED ON TECHNOLOGY

Biological evolution, whether based on natural or parental selection, is intrinsically limited. Early design decisions, that may not be optimal, were locked in or forced by the physical nature of Earth-based life. Some of those decisions can be revisited through the addition of nonbiological enhancements (man-machine hybrids); others may require starting over from scratch.

The concept of a man-machine hybrid may sound exotic or even perverse, but the reality is commonplace. For example, humans do not have an accurate time sense, or absolute place sense,

Previous page: A cast of the Berlin specimen of *Archaeopteryx lithographica* shows its avian features (wings, wishbone, feathers) and its theropod features (tooth-filled head, lizardlike tail).

This page: A model of *Archaeopteryx lithographica* displays its large wings, but its lack of a bony breastbone would have made it a weak flier. *Photos by Ballista.*

or the ability to communicate over long distances or extremely rapidly, or the ability to record sensory input accurately. To relieve these deficiencies, they have already become man-machine hybrids: by wearing a watch, using a GPS system, and carrying a cell phone, a Blackberry, and a digital camera. Of these devices, only the watch was common ten years ago (and today's watches are more accurate and much cheaper). Many more capabilities, and more seamless integration of man and machine, are on the horizon. For better or worse, much of the cutting-edge research in this area is military.

In other cases, incremental addition of capability may not be feasible. To do justice to what is possible, radical breaks will be necessary. I'll mention three such cases.

The vast bulk of the universe is extremely hostile to human physiology. We need air to breathe, water to drink, a narrow range of temperatures to support our biochemistry; our genetic material is vulnerable to cosmic radiation; we do not thrive in a weightless environment. As a practical matter, our major ventures into space will be by proxy. Our proxies will be either humans so modified

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as to clearly constitute a different species; or, more likely, new species we design from scratch, that will contain a large nonbiological component.

The fundamental design of human brains, based on ionic conduction and chemical signaling, is hopelessly slower and less compact than modern semiconductor microelectronics. Its competitive advantages, based on three-dimensionality, self-assembly, and fault tolerance, will fade as we learn how to incorporate those ideas into engineering practice. Within a century, the most capable information processors will not be human brains, but something quite different.

Recently, a new concept has emerged that could outstrip even these developments. Physicists have realized that quantum mechanics offers qualitatively new possibilities for information processing, and even for logic itself. At the moment, quantum computers are purely a theoretical concept lacking a technological realization, but research in this area is intense, and the situation could change soon. Quantum minds would be very powerful, but profoundly alien. We—and this "we" includes even highly trained, Nobel-Prize-winning physicists—have a hard time understanding the subtleties of quantum mechanical entanglement; but exactly that phenomenon would be the foundation of the thought processes of quantum minds!

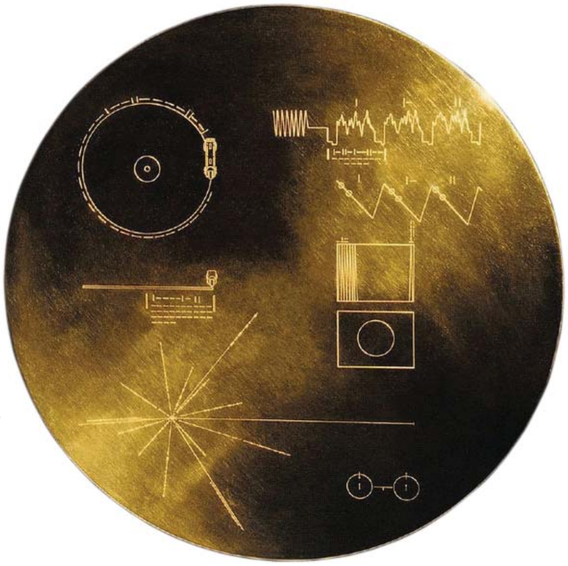
WHERE DOES IT LEAD?

A famous paradox led Enrico Fermi to ask, with genuine puzzlement, "Where are they?"

Simple considerations strongly suggest that technological civilizations whose works are readily visible throughout our Galaxy (that is, given current or imminent observation technology) ought to be common. If they were, I'd base my speculations about future directions of evolution on case studies! But they aren't. Like Sherlock Holmes's dog that did not bark in the nighttime, the absence of such advanced technological civilizations speaks through silence.

Main-sequence stars like our Sun provide energy at a stable rate for several billions of years. There are billions of such stars in our Galaxy. Although our census of planets around other stars is still in its infancy, what we know already makes it highly probable that many millions of these stars host, within their so-called habitable zones, Earth-like planets. These bodies meet the minimal requirements for life in something close to the form we know it, notably including the possibility of liquid water.

On Earth, the first emergence of a species capable of technological civilization took place about one hundred thousand years ago. We can argue about defining the precise time when technological civilization itself emerged. Was it with the beginning of agriculture, of written language, or of modern science? But whatever definition we choose, the number will be significantly



Cover of the Voyager Golden Record, launched into space in 1977 on two Voyager spacecraft. Its sounds and images were selected to introduce Earth to extraterrestrials.

less than one hundred thousand years.

In any case, for Fermi's question the most relevant time is not ten thousand years, but closer to one hundred. This marks the period of technological "breakout," when our civilization began to release energies and radiations on a scale that may be visible throughout our Galaxy. Exactly what that visibility requires is an interesting and complicated question, whose answer depends on the means available to hypothetical observers. We might already be visible to a sophisticated extraterrestrial intelligence through our radio broadcasts or our effects on the atmosphere. The precise answer hardly matters, however, if anything like the current trend of technological growth continues. Whether we're barely visible to sophisticated though distant observers today, or not quite, after another hundred years of technological expansion we'll be easily visible.

A hundred years is less than a part in ten million of the billion-year span over which complex life has been evolving on Earth. The exact placement of breakout within the multi-billion-year timescale of evolution depends on historical accidents. With a different sequence of the impact events that lead to mass extinctions, or earlier occurrence of lucky symbioses and chromosome doublings, Earth's breakout might have occurred one billion years ago, instead of one hundred.

The same considerations apply to those other Earth-like planets. Indeed, many such planets, orbiting older stars, came out of the starting gate billions of years before we did. Among the millions of experiments in evolution in our Galaxy, we should expect that many achieved breakout much earlier, and thus became visible long ago. So, where are they?

Several answers to that paradoxical question have been proposed. Perhaps our simple estimate of the number of life-friendly planets is for some subtle reason wildly overoptimistic. Perhaps, even if life of some kind is widespread, technologically capable species are extremely rare. Perhaps breakout technology quickly ends in catastrophic warfare or exhaustion of resources. There are uncertainties at every stage of the argument. Even so, like Fermi, I remain perplexed.

The preceding discussion suggests another sort of possibility: they're out there, but they're hiding.

QUANTUM QUIET

If the ultimate information processing technology is deeply quantum-mechanical, it may not be energy-intensive. Excessive energy use brings heat in its wake, and heat is a deadly enemy of quantum coherence. More generally, quantum information processing is extremely delicate, and easily spoiled by outside disturbances. It is best done in the cold and the dark. Quantum minds might well be silent and isolated by necessity.

Silence and inner contemplation can also be a choice. The ultimate root of human drives remains what our selfish genes, in the struggle for existence, have imprinted. That root is apparent in many of our behavior's most obvious priorities, which include fending off threats from a hostile environment, finding and attracting desirable mates, and caring for the young. Those priorities involve active engagement with the external world. The products of deliberate biological or technological evolution, as opposed to natural selection, could have quite different motivations. They might, for example, seek to optimize their state according to some mathematical criterion (their utility function). Having found an optimum state, or several excellent ones, they could choose ever to relive selected moments of perfect bliss, perfectly reconstructed. This was the temptation of Faust:

If I say to the moment:
"Stay now! You are so beautiful!"
Then round my soul the fetters throw,
Then to perdition let me go!

Humans were not built to treasure a Magic Moment, nor could they reproduce such a moment reliably and in detail. For our evolutionary successors, that Faustian temptation will be much more realistic. ■

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