A plant is a creature that uses the energy of sunlight to convert water and carbon dioxide and other simple chemicals into roots and leaves and flowers. To live, it needs to collect sunlight. But it uses sunlight with low efficiency. The most efficient crop plants, such as sugarcane or maize, convert about 1 percent of the sunlight that falls onto them into chemical energy. Artificial solar collectors made of silicon can do much better. Silicon solar cells can convert sunlight into electrical energy with 15 percent efficiency, and electrical energy can be converted into chemical energy without much loss. We can imagine that in the future, when we have mastered the art of genetically engineering plants, we may breed new crop plants that have leaves made of silicon, converting sunlight into chemical energy with ten times the efficiency of natural plants. These artificial crop plants would reduce the area of land needed for biomass production by a factor of ten. They would allow solar energy to be used on a massive scale without taking up too much land. They would look like natural plants except that their leaves would be black, the color of silicon, instead of green, the color of chlorophyll. The question I am asking is, how long will it take us to grow plants with silicon leaves?

If the natural evolution of plants had been driven by the need for high efficiency of utilization of sunlight, then the leaves of all plants would have been black. Black leaves would absorb sunlight more efficiently than leaves of any other color. Obviously plant evolution was driven by other needs, and in particular by the need for protection against overheating. For a plant growing in a hot climate, it is advantageous to reflect as much as possible of the sunlight that is not used for growth. There is plenty of sunlight, and it is not important to use it with maximum efficiency. The plants have evolved with chlorophyll in their leaves to absorb the useful red and blue components of sunlight and to reflect the green. That is why it is reasonable for plants in tropical climates to be green. But this logic does not explain why plants in cold climates where sunlight is scarce are also green. We could imagine that in a place like Iceland, overheating would not be a problem, and plants with black leaves using sunlight more efficiently would have an evolutionary advantage. For some reason which we do not understand, natural plants with black leaves never appeared. Why not? Perhaps we shall not understand why nature did not travel this route until we have traveled it ourselves.

After we have explored this route to the end, when we have created new forests of black-leaved plants that can use sunlight ten times more efficiently than natural plants, we shall be confronted by a new set of environmental problems. Who shall be allowed to grow the black-leaved plants? Will black-leaved plants remain an artificially maintained cultivar, or will they invade and permanently change the natural ecology? What shall we do with the silicon trash that these plants leave behind them? Shall we be able to design a whole ecology of silicon-eating microbes and fungi and earthworms to keep the black-leaved plants in balance with the rest of nature and to recycle their silicon? The twenty-first century will bring us powerful new tools of genetic engineering with which to manipulate our farms and forests. With the new tools will come new questions and new responsibilities.

Our Biotech Future (July 19, 2007) Freeman Dyson [The New York Review of Books]

To the Editors:

Freeman Dyson has written his usual insightful essay ["Our Biotech Future," NYR, July 19], but I differ on one important point regarding how evolution works. He points out that black leaves would be more efficient than green ones at capturing sunlight, and then tries to explain why leaves are not black. In doing so, he implicitly assumes that natural selection, left to itself after enough time, will always zero in on the most efficient means for improving adaptation. However, natural selection proceeds via a narrow point-to-point pathway, not a wide all-encompassing one. In solving any given problem it can make use of only what happens to be available at that particular time.

An anecdote illustrates this better than a discourse. Many years ago I was in a group of chemists making new antibiotics. One path taken was to synthesize cephalosporins with the ring sulfur atom replaced by oxygen, a chemically profound alteration. These oxy-cephs turned out to be orders of magnitude more potent than the natural ones. Why then did Nature not discover them, given so much time? Because the immediate precursors of cephalosporins on the synthetic pathway Nature had created to make them had a sulfur atom, not an oxygen atom, in the key position. The corresponding oxy precursor either did not then exist or was chemically unsuited to that pathway, and there was no going back a dozen steps to find a missing link that could go on to oxy-cephs, because every step in natural selection must be adaptive in its own right.

The basic premise is that every step in evolutionary change is stochastic and adaptive. No new structure that appears in this way persists unless it is immediately adaptive, even if just one more step might produce something very superior. Thus green leaves dominate because they happen to have come along before black ones, and also because chance uncovered no route from green to black that was adaptive at every new step.

Raymond A. Firestone

Stamford, Connecticut
Freeman Dyson replies:

Raymond Firestone correctly points out that evolution is constrained by the laws of chemistry and can only move one step at a time. His analogy between antibiotics and leaves is a good one. Evolution has failed to produce black leaves because they must be made of silicon, and the chemical reduction of silicate rock or sand to silicon cannot be done in one step. Although silicon is one of the most abundant elements, it occurs naturally in rock and sand in combination with oxygen, and no form of life has evolved a chemical pathway leading from silicon dioxide to pure silicon.

'Our Biotech Future' (October 11, 2007) Raymond A. Firestone, reply by Freeman Dyson [The New York Review of Books]