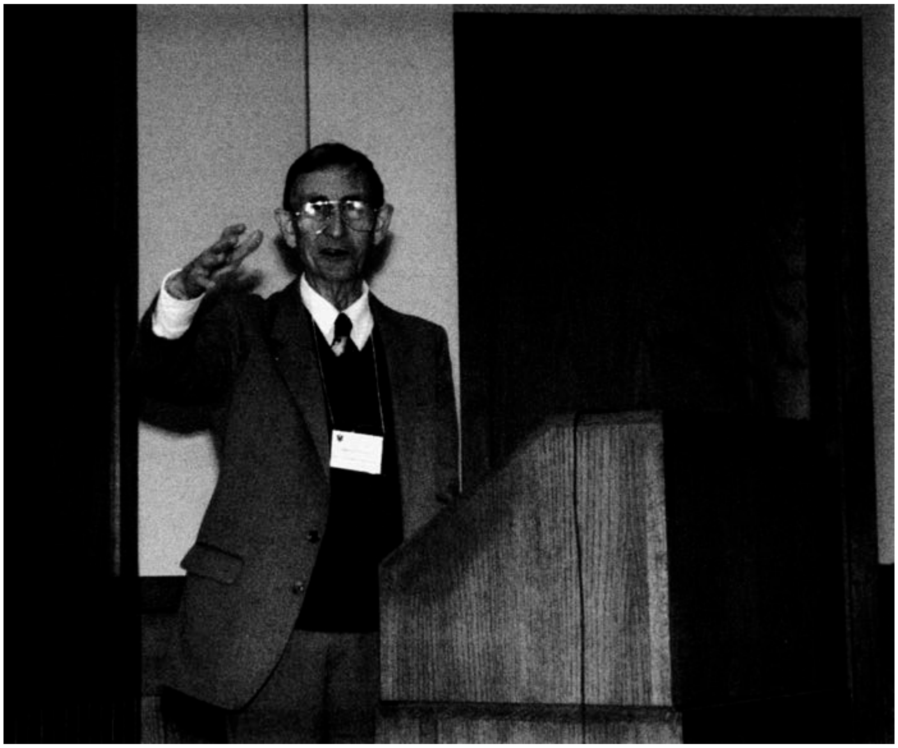

KEYNOTE ADDRESS:

Freeze-dried Fish and Warm-blooded Plants

Freeman S. Dyson

Today I want to look one hundred years ahead into the future of space. Many of the people in the audience know much more about the next twenty years. Many of you are actively engaged in designing hardware and planning missions for the next two decades so it would be idiotic for me to talk about the next twenty years where there are so many people in the room who are more confident and at home in the next twenty years than I am. When we talk about the more distant future, we're all equally ignorant. I don't pretend to predict what our grandchildren will be doing fifty years from now. They will be in charge and they will decide what they want to do. My purpose is to give them a menu of things to choose from, the possible ways in which space exploring might go ahead. My only qualification for speaking about the future is that I've done it before. When you make a habit of talking about the future you acquire a reputation as a prophet. Even when the things you predict never happen.

So here is a wish list. A list of things we need to do in order to open the Solar System to mankind. It's important to keep a clear distinction between wishes and facts. I'm not saying that the things on my 1 wish list are sure to happen. They're goals to be striven for; not facts to be taken for granted. If you want to have a decent future you have to work hard and also be lucky. With that understood, here is my list of four wishes.

Wish number one. Space exploring will get steadily cheaper as time goes on. If you're clever, any exploring that's worth doing can be done for less than a billion dollars. I'm not interested in grandiose projects that require substantial fractions of the G.N.P. to complete. Our grandchildren might decide to embark on grandiose projects, but projects of that kind should be funded as international sporting events and not as exploring. Space projects should always be cheap enough so that they can afford to fail. If a venture cannot afford to fail, it's not a genuine venture.

Wish number two. Large and expensive infrastructures will be built by commercial interests and by governments for purposes other than exploring. The most important infrastructure is launch systems to lift payloads from the Earth into space. Examples of advanced launch systems which should be in place by mid-century are: laser propulsion, ram accelerators, and slingatrons. I'll talk a bit about them later. Each of these systems keeps the power source on the ground so that the vehicle that is launched can be simple and cheap. The main cost is the capital cost of the infrastructure on the ground. Once the capital investment is made, the incremental cost of a launch is small.

With luck the incremental cost of the launch could be 100 times less than present day launch costs. The system operates like a public highway. The user brings the payload to the launch site, pays the toll, and off she goes. Large commercial operations generate a large volume of traffic that makes the system economic. Exploring is only a small user, but takes advantage of the economies of scale to get space missions cheaply off the ground.

Wish number three. Biotechnology will be roaring ahead and will allow us to breed plants and animals adapted to the space environment. The most important biotechnology will be plant breeding, based on a complete understanding of the language of DNA, so that we can grow plants with any required structure and function. The plants suitable for growing on Mars, or on any of the small objects in the outer Solar System, should have the ability to grow a greenhouse around themselves. The greenhouse must be gas-tight and thoroughly insulated so that warm blooded plants can survive through the nights without freezing. Colonies of such plants will be programmed to build large structures like the polyps in the ocean that cooperate to build coral reefs. The individual greenhouses will be connected together to form habitats for other species of plants and animals. Habitats for humans can be grown in the same way. The problems of construction of industrial facilities or colonies in space can be solved far more cheaply by biotechnology than by conventional construction.

Wish number four. The next century will see a profitable merger of the space science enterprise with the business of protecting our planet from extraterrestrial objects. The public has recently become aware that we need a system for detecting and deflecting asteroids and comets that might collide with the Earth. Since we saw this happen to Jupiter three years ago, it's clear that it could also happen here. It turns out that the cost of deflection is modest provided that the warning time is as long as 100 years. To give us a 100-year warning time, the detection system must include an array of powerful wide field telescopes. To build and operate these telescopes will cost about as much as the Mission to Planet Earth which NASA is now implementing to monitor the ecology of our planet on a global scale. The cost of these telescopes could reasonably be justified as an insurance premium paid to protect us from astronomical catastrophes. It's reasonable to spend about as much to look outward as to look inward. The telescopes would then give us - as an additional bonus - a magnificent tool for exploring the Universe outside the danger zone. So this happy marriage of astronomy with life insurance would bring lasting benefits to both parties.

So that's the end of my wish list. Whether my wishes come true or not, we're now at the beginning of a revolution in space technology, when, for the first time, cheapness will be mandatory. Missions that are not cheap will not fly. This is bad news for space explorers in the short run, good news in the long run. The good news is that cheapness now has a chance. The coming era of cheap space operations will begin with unmanned missions. Cheap manned missions will come later after unmanned missions have tested and debugged the new technologies of propulsion and operations. Cheap unmanned missions only require new engineering and new styles of management. Cheap manned missions require new biotechnology. For a manned mission, the chief problem isn't getting there, but learning how to survive after you've got there. To survive and make yourself at home away from Earth is a problem of biology rather than a problem of engineering. It's easy to predict that cheap missions both unmanned and manned will in the end be possible. There's no law of physics or biology that forbids cheap travel and cheap settlement all over the Solar System and beyond. But I cannot predict how long that will take. Predictions of the dates of future achievements are notoriously fallible. My guess is that the next fifty years will be the era of cheap unmanned missions and that the era of cheap manned missions will start sometime later in the Twenty-first Century. The time that these things will take will depend on unforeseeable accidents of history. My date for the beginning of cheap manned exploration and settlement is based on a historical analogy. From Columbus's first voyage to the settlement of the Pilgrims in Massachusetts was 128 years. So I'm guessing that in 2085, 128 years after the launch of the first Sputnik, private settlements of Pilgrims all over the Solar System will be beginning. But that may be a very conservative view. I think it could happen a lot sooner than that. I hope so.

So the two essential requirements for cheap manned missions are cheap launch systems and warm blooded plants. The three new launch systems that I mentioned earlier are laser propulsion, ram accelerators and slingatrons. Laser propulsion was invented and promoted by Arthur Kantrowitz 30 years ago. The laser sits on top of a mountain, the beam points up into the sky. The spacecraft rides up the beam with an acceleration of 3 g's, reaching escape velocity in six minutes at the slant range of 2,000 kilometers. The mass of the spacecraft that is launched is 2 tons with a crew of two. The propellant is one ton of water contained in a one cubic meter tank. The final mass of the spacecraft with payload is one ton. The power of the laser beam is one giga-watt, that's a thousand megawatts, converted into thrust with an overall efficiency of 15%. At the end of the six minutes of powered flight, the spacecraft is in an escape orbit and the laser is ready for the next launch. If the launcher is in use for 60% of the time, it can launch half a million spacecraft per year. The launch system is operated like a public highway - available to anybody who turns up at the launcher. You pay a toll to cover the capital and operating costs, you provide your own spacecraft and, most important, you travel at your own risk.

The key to the cheap space launch system, whatever system it might be, is to have a high volume of traffic. The energy cost of a laser launch is about $10 per kilogram of payload or $5 a pound. If the launcher is kept busy, launching half a million payloads per year, each paying a toll of $20 per kilogram or $10 a pound, the gross income is 10 billion dollars a year, certainly enough to cover capital repayment and maintenance in addition to energy costs and probably a handsome profit. If the traffic is only a few launches a day, the tolls will have to set at several thousand dollars a kilogram and the system will be an economic disaster like the Space Shuttle - a prestige project too expensive to be used for ordinary commercial activities. On no account should the laser launch system be built until the demand exists to keep it active for a fair fraction of the time.

The second radically new launch system is the ram accelerator. It was invented by Abraham Hertzberg at the University of Washington in Seattle. The ram accelerator is an inside out ram jet engine. You can also think of it as a very efficient version of a gas gun, accelerating a projectile inside a steel pipe. The pipe is filled with a combustible mixture of gases. The projectile travels down the pipe propelled by the steady pressure of the gas igniting behind it. The gas does not move with the projectile but stays in place as the projectile passes by. The nose of the projectile is pointed sharply so that the bow shock is not strong enough to ignite the gas. The reflected shock at the stern is much stronger and causes the gas to ignite. I saw a toy model of the ram accelerator in action in the cellar of the engineering department at the University of Washington. That was some years ago, I don't know whether it's still there. The model was built and operated by two students with Hertzberg telling them how to do it. The pipe was 10 centimeters in diameter and 10 meters long. the gas was a mixture of methane and air at 25 atmospheres pressure. The projectile was a pointed cone with fins to keep it in the center of the pipe. At the beginning of the run the gas behind the projectile was ignited with a spark and for the rest of the run the gas burned smoothly and the projectile accelerated with a steady acceleration of 30,000 g's. It came out of the end of the pipe at 2.5 kilometers per second and was stopped in a tank full of scraps of oriental rugs. When I visited the cellar and saw the operation, the model had already been fired 500 times, and the inside of the pipe didn't show a single scratch. The projectile automatically centers itself in the pipe as it flies along. 30,000 g's would not be healthy for human passengers, but it would be tolerable for bulk freight or electronic machinery if it was carefully packed and loaded.

Hertzberg proposes to extrapolate his toy accelerator into a full-scale launch system. The launcher is built on the side of a mountain pointing up into space. To escape from the Earth, the payload needs to reach a speed of 12.5 kilometers per second, five times the speed of the toy model To reach five times the speed with the same acceleration, the pipe would be 250 meters inside of 10 meters long. All things considered, 250 meters is not a very long distance. It's much shorter than an average airport runway. The payload would be long and slender so that it could force its way through the atmosphere without losing a significant fraction of its momentum to drag. The main difficulty in extending the accelerator to the hypersonic domain is that the mixture of gases in the pipe has to change as the speed increases from one end to the other. The speed of sound in the gas must increase with the speed of the projectile. So the gas mixture must change by stages from methane and air to hydrogen and oxygen. Hertzberg envisions five stages, all at the same pressure, with thin diaphragms separating them in the pipe. So as the projectile flies along the pipe, the diaphragms rupture without impeding its passage. The pattern of gas flow changes from one stage to another. At the highest speed you get an oblique detonation wave. So you have five stages of flow patterns, but the acceleration remains roughly the same all the way down. In point of fact, you probably would compromise a bit: you probably would make the pipe a bit longer and the acceleration a bit lower in order to reduce the stresses on the payload. All the details will be worked out when the thing is finally built.

The third possibility for a cheap launch space system is the slingatron recently invented by Derek Tidman. I'm happy to see that Tidman is here and will talk about the slingatron at the meeting. And since he's here I don't have to say much about it. I believe he demonstrated his tabletop model at the SSI meeting two years ago. The slingatron is a ring-shaped track with a payload free to roll around inside. Electric motors cause each point on the track to move around in a small horizontal circle, the size and the orientation of the track remaining fixed. The position of the payload on the track is monitored and the motion of the track is programmed to remain always 90 degrees ahead of the payload so that the track pumps energy into the payload and the payload is continuously accelerated. I'll leave that to Tidman to describe. I think it's a beautiful system and it is very likely that it is actually economic compared to the others. The slingatron payload would have to withstand a peak acceleration of about 1,000 g's, far larger than the laser launch payload but smaller than the ram accelerator payload. It's likely that the slingatron will find a niche of economic viability between the gentle laser launch which is for humans and the brutal ram acceleration which is for bulk freight.

Those three launch systems have one common feature which will be of great economic importance if any of them turns out to be practical. All of them launch payloads into escape orbits or high-Earth orbits as cheaply as into low Earth orbits. In this respect they differ radically from chemical rocket launchers. The economics of high volume traffic and industry in space will require warehouses and refueling centers and factories and offices and hotels. If the cheap launch systems are going directly to high-Earth orbit, that's where the hub facilities for space industry and transport will be. Low-Earth orbit will remain a good place for observing the Earth and for rapid point to point communication networks. But for access to the rest of the Solar System, high-Earth orbit is the place to be. It's lucky that high-Earth orbit is also a good place to put astronomical instruments so they can see the whole sky without the Earth getting in the way.

Now I leave the subject of future launch systems and talk about Mars rocks. About twelve years ago, I was visiting the Johnson Space flight Center in Houston, and climbing around in the Space Shuttle that they keep there for visitors. That was before the Challenger disaster when the Shuttle was advertised as a safe ride for Congressmen and school teachers. What impressed me about the Shuttle was the immense quantity of stuff they had on board for the care and comfort of human passengers. It felt more like a hospital or a hotel than a rocket ship. I made rough calculations of how many tons of stuff they were flying to keep seven passengers alive and well for a couple of weeks. I was thinking, "Why don't we rip out all this stuff, leave the astronauts on the ground and fly the thing by remote control." The Shuttle takeoff and flight into orbit were already ground-controlled. Only the landing was done by a human pilot. And it would be easy to use remote control for the landing too. At that time most of the Shuttle missions were carrying unmanned satellites into orbit for various purposes, some of them scientific, some of them commercial and some of them military. Those launching jobs could just as well have been done automatically. Only a few of the Shuttle missions really need to have people on board to do experiments or repair the Hubble Space Telescope. It would have made sense to reserve two Shuttle ships with the hotel equipment for missions in which people were essential and to use the other two Shuttles for satellite launching jobs with the hotel stuff ripped out. The owners of railroad companies discovered long ago that it makes sense to use separate trains for passengers and freight. Passenger trains are expensive and passengers are fussy. Freight trains are cheaper and carry many more tons of payload. If we'd run the Shuttle program like a railroad we could have saved a huge amount of money and of course we still could. The freight-only version of the Shuttle could have carried bigger payloads for less money than the passenger version without risking any lives.

Unfortunately the authorities at Houston did not think that was a good idea. Their whole existence was centered on the training of astronauts and the operation of manned missions. So after failing to eviscerate the Shuttle, I wandered into the museum at the Johnson Spaceflight Center where there was a collection of rocks that the astronauts brought back from the Moon. Scientists who are interested in Moon rocks are usually also interested in meteorites. So the scientists have put into their museum a fine collection of meteorites which sit in glass cases next to the Moon rocks. They also organize expeditions to collect meteorites that have accumulated on the ice in Antarctica. Among their collection of meteorites were two identified as having come from Mars. And they also had in their collection, although they didn't know it, the meteorite ALH84001 which afterwards became famous. That one was collected by Roberta Score in 1984 and brought back to Houston but it was not identified as a Mars rock when I visited the museum. David Mittlefehldt identified it three years later. The Mars rocks looked different from the other meteorites. They are lighter in color and sandier in texture. But the difference in appearance doesn't prove that they came from a different place in the sky. We know for sure that they came from Mars because one of them contains tiny bubbles full of gas which has the exactly the same composition as the atmosphere of Mars. The composition of the Mars atmosphere was measured by the instruments which were landed on Mars by Viking in 1976. It's quite different from the atmosphere of Earth. The gas with the composition found in that Mars rock couldn't have come from anywhere except from Mars. The Mars rock must have been splashed off the surface of Mars by a big impact when an asteroid or comet collided with the planet. It then orbited around the sun for a few million years until it happened to land on the Earth. Besides the two that I saw in Houston, there are a dozen more in various other museums. It's surprising that so many of them survived the initial impact on Mars and the journey to Earth and also had the good luck to be picked up by meteorite hunters. Since so many have been found in a few years on the Earth, there must be millions more Mars rocks floating in orbit around the Sun waiting to be discovered.

I could hardly believe it was true. Here I was in the museum in Houston twelve inches away from a piece of Mars with only a thin plate of glass to stop me from grabbing hold of it. In those days, NASA was talking seriously about grandiose missions to Mars costing many billions of dollars, hundreds of billions in fact. One of the reasons for going to Mars was to return samples of rock to Earth for scientists to analyze. And here were samples of Mars rocks already in Houston provided by nature free of charge. I found it odd that nobody seemed to be studying them. So far as I could tell, nobody in Houston seemed to be excited about the Mars rocks except for me. I stood and gazed at those rocks for a long time. Nobody else came to look to them. I remarked to the NASA people that they might usefully spend some time studying the Mars rocks they already had instead of planning billion dollar missions to collect more. But at that time the administrators in Houston did not seem to be interested in anything that didn't cost billions of dollars.

Things have changed since then. Last year some of the Mars rocks were studied more thoroughly than ever before. One of them, the famous rock, ALH84001, which was sitting in the museum in Houston when I visited, but not yet identified, contained chemical traces which might be interpreted as evidence of ancient life on Mars. Two groups of scientists found little worm-like structures that might be relics of ancient microbes. The evidence that these traces have anything to do with biology is highly dubious. On the basis of this evidence we can't say that life must have existed on Mars. The discovery of those traces is important for two other reasons. First, if we are seriously interested in finding evidence for life on Mars, we now know that the Mars rocks on the Earth are the most convenient place to look for it. Instead of waiting for many years for an expensive sample return mission to land on Mars and return a few small chips of rocks to Earth, we can find a supply of much bigger chips lying in Antarctica where meteorites accumulate on the ice and are free for us to take home. Second, these rocks show that if life was established on Mars at any time in the past, it was possible for it to be transported to Earth intact, so that life on Earth might be descended from life on Mars. And in fact, Joseph Kirschvink of Cal Tech just now did a careful mineralogical study of the Mars rock ALH84001 and concluded that the temperature inside the rock could never have risen above 110°C, in fact, probably not nearly that high. So if there had been a living microbe inside the rock, it could have survived the voyage. In the first billion years after the Solar System was formed, when Mars had a warm climate and abundant water, asteroid impacts were much more frequent than they are now. In those early times, Mars rocks were falling on the Earth in great numbers and many Earth rocks must also have been falling on Mars. We shouldn't be surprised if we find that life, wherever it originated spread, rapidly from one planet to another. Whatever creatures we may find on Mars will probably either be our ancestors or our cousins.

Another place where life might now be flourishing is in a deep ocean on Jupiter's satellite, Europa. Jupiter has four large satellites: Io, Europa, Ganymede and Callisto, arranged in order of increasing distance. Galileo gave them these names when he discovered them because Io, Europa and Callisto were girlfriends of Jupiter and Ganymede was a boyfriend. The Galileo spacecraft now orbiting around Jupiter is sending back splendid pictures of the satellites. The pictures of Europa show an icy surface with many low ridges and large cracks. I'm sure you've all seen those pictures. There are few craters and no mountains. It looks as if the ice were floating on a liquid ocean and being broken up from time to time by movements of the water underneath. The pictures are strikingly similar to some pictures of the ice that floats on the Arctic Ocean of the Earth. It wouldn't be surprising if Europa should have a warm ocean under the ice. We know that Io is blazing hot with active volcanoes on its surface. Ganymede has an icy surface like Europa but not so smooth, and Callisto looks like a solid ball of rock and ice covered with ancient craters. The three inner satellites are locked in an orbital resonance which causes them to be heated internally by the tidal effects of the huge mass of Jupiter. The orbits are non circular so they're always moving in and out and being squeezed by the tidal effects of Jupiter. The internal heating falls off rapidly with distance from Jupiter. We should expect that below the surface, Europa would be much cooler than Io and much warmer than Ganymede and Callisto. Since Io is hot enough to boil away all its water and Callisto is cold enough to freeze solid, Europa is the most likely place to find a warm liquid ocean. Ganymede might also have a liquid ocean, but it would be covered by a much thicker layer of ice.

Of all the worlds that we have explored beyond the Earth, Mars and Europa are today the most promising places to look for life. To land a spacecraft on Europa with the heavy equipment needed to penetrate the ice and explore the ocean directly will be a formidable undertaking. The direct search for life in the Europa ocean would today be prohibitively expensive. But there's a much easier way. Just as asteroid and comet impacts gave us an easier way to look for evidence of life on Mars, impacts on Europa give us an easier way to look for life on Europa. We know that impacts on Europa must be at least as frequent as impacts on Callisto, the more distant satellite of Jupiter which is visibly covered with craters. Every time there is a major impact on Europa, a huge quantity of water will be splashed from the ocean into the space around Jupiter. The water will partly evaporate and partly condense into snow. Any creatures living in the water, not too close to the impact, will have a chance of being splashed intact into space with the water and quickly freeze-dried. Therefore the easy way to look for evidence of life in the Europa ocean is to look for freeze-dried fish orbiting around Jupiter. Jupiter already has a ring of space debris orbiting around it. It's likely that freeze-dried fish or any other garbage splashed out of the Europa ocean will accumulate in the ring. Bringing a spacecraft to visit and survey the Jupiter ring will be far less expensive than bringing a submarine to visit and survey the Europa ocean. We might find many unexpected surprises in the Jupiter ring, even if we don't find freeze dried fish. We might find freeze-dried seaweed or a freeze-dried sea monster of the kind that was originally suggested by Arthur Clarke.

Freeze-dried fish orbiting around Jupiter are a fanciful notion. But nature in the biological realm has a tendency to be fanciful. Nature is usually more imaginative than we are. Nobody in Europe ever imagined a bird of paradise or a duck-billed platypus before they were discovered by explorers. Even after the platypus was discovered and a specimen brought to London, several learned experts in London declared it to be a fake. Many of nature's most beautiful creations might be dismissed as wildly improbable if they were not known to exist. When we are exploring the Universe, and looking for evidence of life, we may either look for things that are probable but hard to detect, or we may look for things that are improbable but easy to detect. In deciding what to look for, detectability is as least as useful a criterion as probability. Primitive organisms such as bacteria and algae hidden underground may be more probable, but freeze-dried fish in orbit are more detectable. To have the best chance for success we should keep our eyes open for all possibilities.

A similar logic suggests warm-blooded plants as a reasonable target for a search for life on the surface of Mars. Any form of life that survived on Mars from the early warm and wet era to the present cold and dry era had a choice of two alternatives. Either it adopted an entirely subterranean life-style, retreating deep underground to places where liquid water can be found, or it remained on the surface and learned to protect itself against cold and dryness by growing around itself an insulating greenhouse, maintaining inside the greenhouse a warm and moist environment. The first alternative is more probable but much more difficult to detect. Organisms living deep underground without making use of sunlight would probably be microscopic like the bacteria that live deep in the Earth. To find such creatures would require deep drilling and heavy machinery.

The second alternative is less probable but more detectable. Many species of terrestrial plants, including the skunk-cabbage that sprouts in our Princeton woods in February and March, are warm-blooded to a limited extent. An article by Roger Seymour in the March 1997 issue of Scientific American describes these plants in detail. The skunk-cabbage maintains a warm temperature for about two weeks in the part of its anatomy know as the spadix, which contains the hidden flowers with their male and female structures. According to folklore, the spadix is warm enough to melt the snow around it. I actually have not seen this happen. If I'd gone out in the woods a little more frequently, maybe I would. Some of you might have seen that. The evolutionary advantage of warm-bloodedness to the plants is probably to attract small beetles that linger in the spadix and pollinate the flowers. The warm temperature is maintained by rapid metabolism of starch stored inside the spadix. The spadix is not a greenhouse, and the supply of starch is not sufficient to maintain a warm temperature all the year round. No terrestrial plants are able to stay warm during an Arctic winter. Certain Arctic flowers have learned to grow their petals in a parabolic shape so that they reflect sunlight onto the vital reproductive organs, the pistil and the ovaries, at the focus of the paraboloid. But that's only a small step toward true warm bloodedness. On the Earth, the extreme Arctic and Antarctic regions belong to animals alone. Polar bears and penguins flourish in colder climates than trees. It seems to be an accident of history that warm-blooded animals evolved on Earth to colonize cold climates while warm blooded plants did not. On Mars, because of the more severe pressure of natural selection, plants might have been pushed to more drastic adaptations. Plants that learned to grow greenhouses could keep warm by the light from a distant sun and conserve the oxygen that they produce by photosynthesis. Plants could grow greenhouses just as turtles grow shells and polar bears grow fur. The greenhouse would consist of a thick skin providing thermal insulation rather like the bark of a tree, with small transparent windows to admit sunlight. Inside the skin there would be shutters to cover the windows at night and during bad weather. Outside the skin, there'd be an array of simple lenses or mirrors focusing sunlight through the windows into the inside. The windows have to be small to limit the loss of heat by outward radiation and convection. To maintain a temperature difference of 100°C between inside and outside - that's roughly what you have on Mars - it would be necessary to limit the area of the windows to about a tenth of the surface area of the greenhouse. The lenses or mirrors would need to concentrate the incident sunlight by a factor of ten. That doesn't require high quality optics; it only requires that the lenses or mirrors track the sun as it moves across the sky. But the accuracy of tracking does not need to be greater than that already achieved by the common sunflower.

Mars is not the only place where warm-blooded plants might be found. They might also flourish on the surface of Europa or anywhere else where sunlight falls onto a surface where the chemical elements required to sustain life are accessible. An atmosphere is not essential. I imagine that warm-blooded plants on Mars would absorb carbon dioxide from the atmosphere in the way plants do on Earth. They would have to have pores in the skin in order to absorb the CO_2, with some sort of cold trap to avoid losing water vapor. On Europa there's no atmosphere. If there's an ocean under the ice, warm-blooded plants on the surface would send roots down through the ice and extract their nutrients including carbon from the ocean. Or, more probably, creatures that originate in the ocean could send up shoots through cracks in the ice and grow greenhouses where the shoots emerge on the surface. So it's easy to imagine greenhouses being evolved in incremental fashion by creatures that first developed photosynthesis using sunlight percolating through thick ice and then gradually pushed shoots closer to the surface until they broke through into the vacuum of space. The design of a greenhouse to operate in a vacuum is in some ways simpler than the design of a greenhouse to operate in the atmosphere of Mars. The skin of a greenhouse on Europa would be totally impermeable without the complications introduced by pores. To keep the windows clean might be a severe problem on Mars where dust storms are frequent, but would not be a problem on Europa. The only factor which makes survival on Europa more difficult is the scarcity of sunlight. To keep a greenhouse warm on Europa, the lenses or mirrors must concentrate sunlight by a factor of 100 instead of 10. So the windows must be smaller and the lenses and mirrors larger. But that still would not require high quality optics. It would only require a rather more accurate tracking of the sun than would be needed on Mars.

The main lesson I draw from the history of space activities in this century is that we must clearly separate short term from long term aims. The dream of expanding the domain of life from Earth into the Universe makes sense as a long term goal, but not as a short term goal. The practical feasibility of cheap human voyages and settlement of the Solar System depends on fundamental advances in biology. Any affordable program of manned exploring must be centered on biology. So it will have a time-scale tied to the time-scale of biotechnology. The time-scale of fifty years is probably reasonable, roughly the time it will take us to learn how to grow warm-blooded plants. Warm-blooded plants will not by themselves solve all of our problems, they're necessary but not sufficient. They're only the first of the thousands of diverse new species that will be required to create viable ecologies in places where humans may wish to go. The biological technology mature enough to create warm-blooded plants will also be able to take care of other ecological problems - either on Mars or on Europa or even at home on the Earth.

If Gerry O'Neill were alive today, I think he'd understand that the rapid progress of biotechnology has totally changed the nature of space colonies. To adapt terrestrial life forms to space, so that they can live wild on planets or asteroids as they are, will be far easier than terraforming asteroids in the image of planet Earth. Instead of building huge artificial structures to live in, we shall teach warm-blooded plants to grow greenhouses as tall as trees and as wide as cathedrals. So when we arrive on Mars or on Europa or on our favorite asteroid, we shall find our habitats already growing there, waiting for us to move in. Just as SSI did the pioneering studies of O'Neill's artificial space colonies, SSI should now move ahead to pioneer the living space colonies of the future. Thank you.