Reflections on Project Orion

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As the reader will learn, my friendship with Freeman Dyson goes back well over half a century. I never stopped marveling at his genius. He simply could not help seeing things in a unique way. The last communication I had with Freeman not long before he passed away had to do with climate change. He was concerned about the next ice age, which he thought was long overdue, and about which he was certain that no one really understood the science. Only Freeman would worry about a forthcoming ice age. As part of this essay, we are fortunate to be able to publish something he wrote about space travel and which is typical Freeman.

In the fall of 1957, I arrived at the Institute for Advanced Study (IAS) in Princeton to begin what turned out to be a two-year stay. I had spent that summer as an intern in the Theoretical Division at Los Alamos. Everyone who worked in the Theoretical Division was required to obtain a Q clearance, the highest level of security clearance in use at the Department of Energy and the Atomic Energy Commission. It was a prerequisite for anyone working in close proximity to nuclear weapons and was only granted after an elaborate FBI background check.[1] Q clearance holders were also authorized to receive classified information on a need-to-know basis. When I arrived at the IAS, I still held an active Q clearance. Despite having interned at Los Alamos, my knowledge of nuclear weapons was limited. None of the projects I had been involved with had any connections to the weapons program. At the end of the summer, I had been able to observe a couple of nuclear tests in Nevada, but I had no detailed knowledge of how the devices themselves actually worked.

At the Institute that fall, I became good friends with another physicist who was about the same age. Michael Cohen had obtained his degree at Caltech under the supervision of Richard Feynman, a rare distinction. Cohen was both very smart and very self-confident, two qualities he would have needed to succeed at Caltech. He later told me that, while he was getting his degree, he had consulted for the RAND Corporation in Los Angeles, a think tank that worked on nuclear strategy, among other topics, but that also did physics. Cohen suggested that he might be able to get me a summer job there. I took up his offer, and in June 1958, I found myself in Santa Monica, not far from the beaches of the Pacific Ocean. At first glance, the structure that housed RAND's research facility in Santa Monica looked a bit like a small college campus. It had a tennis court and people ate lunch on tables outside. It was only when you got inside that you began to realize that its entire mission seemed to be devoted to nuclear war.

The security at RAND was even tighter than at Los Alamos. A pass had to be shown to gain access to the offices of the theory group, and an armed guard would frequently inspect the area to make sure that classified documents had not been left unattended. In one of the offices, a small seismograph was used to observe the tremors induced by hydrogen bomb tests in the Pacific. The nuclear theorist Herman Kahn was a notable presence at the facility. A larger-than-life figure in more ways than one, Kahn appeared to spend much of his time trying to convince anyone within earshot that the US could win a nuclear war. Kahn once loaned me the manuscript of a book he was working on. When I read it, I thought he must surely be joking. It was perhaps fitting that Kahn became one of the main sources of inspiration for the eponymous Dr. Strangelove in Stanley Kubrick's film.

The longer I spent at RAND, the more obvious it became that there was not really anything much for me to do. The only work of any consequence that I was involved in during my time at the facility involved adding up a long column of numbers that apparently had some relevance to a nuclear test proposal. It did not take long before I began to feel that I was wasting my time.

Freeman Dyson had been a hero of mine since graduate school. When I was first trying to understand quantum electrodynamics, I had attempted to read Feynman's papers. I found them incomprehensible. I then tried to read Julian Schwinger's papers. I found them incomprehensible too. It was only when I read Dyson's paper, "The Radiation Theories of Tomonaga, Schwinger, and Feynman,"[2] and the notes from his course on advanced quantum mechanics at Cornell that I finally began to understand what was going on.[3] Dyson became a permanent member of the IAS in 1953 and was resident when

I arrived there. He was always friendly, but, for the most part, kept to himself. He had lunch with us from time to time but did not say all that much. I once went into his office to ask a question and found him reading the Bible in Russian. He had been studying the language since high school.

My relationship with Dyson was forever changed by the sort of happy accident that occurs all too rarely. I had been in New York and was traveling back to Princeton on the train late at night. By coincidence, Dyson was on the same train. We spoke a little during the trip, and when we arrived in Princeton I offered to give him a lift home in my car. He invited me in, and we had a long talk over a couple of drinks. I was curious about his first mathematical experiences. Dyson told me that when he was still young enough to be put down for naps he began adding in his mind the sequence 1 + 1/2 + 1/4 + 1/16 + … and realized that the sum was converging to 2. He had invented the notion of the convergent infinite series.

Soon after our talk, Dyson left Princeton for his summer job in California. He was working in La Jolla as a consultant for General Atomics, a division of the General Dynamics Corporation. The previous summer in California had been an eventful one for Dyson. On the one hand, he led the design team that developed a class of nuclear research reactors, known as TRIGA (Training, Research, Isotopes, General Atomics), that are still in use to this day.[4] On the other hand, during a day trip to Tijuana at summer's end, he had been bitten by a dog that was thought to be rabid and had been forced to endure all manner of vaccinations as a result. I had no idea what he was working on in the summer of 1958.

All the occupants of our building at the IAS, myself and Dyson included, shared the services of a secretary, Jane Kane. Once a week, she would forward any mail that had arrived and pass on any gossip she had heard. I received a note from her that summer with news of Dyson. He was in La Jolla, as expected, but had recently returned to Tijuana to see a bullfight and was currently working on a design for a spaceship. I immediately wrote to Dyson saying that if either of these things were true, he was certainly having a much better time than I was. A few days later, much to my surprise, Dyson called me. He confirmed that he was indeed working on a spaceship, but quickly added that he could not tell me about it over the phone. Instead, he suggested that I visit him to see the work for myself. This was how I came to join the Orion project.

I still had my Q clearance when I arrived in La Jolla, so Dyson was able to give me a general outline of the project. The following account draws on both my own experiences and a wonderful book written by Freeman's son George, entitled *Project Orion*, that was published in 2002.[5] The majority of the key figures in the project were still alive when George was researching the book, and his account includes interviews with many of the participants. At the time of writing, nearly twenty years later, there were, as far as I knew, only two surviving members of the project—Freeman and myself.

After Freeman's passing on February 28, 2020, I may be the only one left.

STANISŁAW ULAM arrived in Los Alamos in the winter of 1943. He had been recruited to the Manhattan Project by John von Neumann and Hans Bethe. Before traveling to New Mexico, Ulam had been working as an assistant professor at the University of Wisconsin in Madison. He was not told what he would be working on; his instructions were simply to report to Lamy—the railway depot for Santa Fe. Ulam had never heard of Lamy and knew little, if anything, about New Mexico. He later recalled:

> I went to the library and borrowed the Federal Writer's Project Guide to New Mexico. At the back of the book, on the slip of paper on which borrowers signed their names, I read the names of Joan Hinton, David Frisch, Joseph McKibben, and all the other people who had been mysteriously disappearing to hush-hush war jobs without saying where.[6]

After the war, Ulam continued working at Los Alamos. In 1946, he began thinking about how the energy released by the detonation of a nuclear bomb might be used to propel a spaceship.[7] In *Project Orion*, George Dyson quotes one of Ulam's colleagues, Harris Mayer:

> I heard Stan talk about this in—maybe it was 1948. … We knew a lot about nuclear bombs. At that time we didn't know about hydrogen bombs. But his idea was very simple. If you threw a nuclear bomb out the back of a rocket ship, it exploded and gave it a kick. Now he was thinking of a rocket ship of the conventional size and class, something like the Atlas; the whole ship is maybe 100 tons. We were just brainstorming, that was the level of it, and recognized immediately that this was not a manned ship. The accelerations would crush a person into a blot. So we didn't worry about all the other things, radioactivity and so on. And nobody did anything about it.[8]

It was not until 1955 that Ulam, with the assistance of Cornelius Everett, produced a detailed proposal.9 As part of their design, the bombs would be detonated at a rate of one per second at a distance of about fifty meters below the ship. At the same time, a rocket-borne propellant would be ejected and land ten meters below the ship. The extremely high temperatures produced by the bombs would heat the propellant, causing it to expand. When the expanding propellant came into contact with the bottom of the ship it would be propelled forward. Ulam and Everett had in mind a ship that would carry about fifty bombs, each with a yield of around one kiloton. The pair believed that the accelerations would be so violent that human passengers were out of the question.

Only one person at Los Alamos appeared to take all this seriously.

Ted Taylor had a somewhat erratic career prior to his arrival in New Mexico during the fall of 1949.[10] Born to American parents in Mexico City, Taylor had first become interested in physics in high school. After graduating in 1941, he moved to the US and enrolled at Caltech the following year. He was also enrolled in the Navy during the latter part of the war, but the bombs exploded over Hiroshima and Nagasaki and the fighting was over before he saw action. After the war, Taylor enrolled in the physics department at the University of California at Berkeley but failed his PhD qualifying exams twice. Robert Serber, a professor at Berkeley who had been J. Robert Oppenheimer's right-hand man during the war, helped him get a job in the Theoretical Division at Los Alamos. "Within a week," he later wrote, "I was deeply immersed in nuclear weaponry."[11] Taylor eventually obtained his PhD from Cornell in the mid-1950s. Freeman had been at Cornell just after the war, but had never bothered to get a PhD. "I'm very proud of not having a PhD," he once remarked, "I think the PhD system is an abomination."[12] Over the course of his long career, Freeman was awarded enough honorary degrees to paper a wall.

Taylor's attitude toward Project Orion—he had "picked the name out of the sky"[13]—was completely different from any of his predecessors. He was determined to make an atomic bomb propelled spaceship that actually flew. The great advantage of bomb propulsion is in relation to specific impulse, a measure of how efficiently a rocket generates thrust from a particular propellant. A bomb-powered rocket would have a much higher specific impulse than a chemical rocket—perhaps ten times greater. This would drastically lower the travel times for any interplanetary mission. Taylor wanted to make a ship that could journey to the planets, and Freeman wanted to be a passenger on the first journey. Together, they were a wonderful team. "When Freeman said he believed that Orion would work as Ted Taylor hoped," George notes in his book, "skeptics listened. They knew that Ted could design the bombs and that Freeman could calculate what would happen next."[14]

I knew nothing of all this when I made the drive south from Los Angeles to La Jolla. I had never heard of Taylor, and the only thing I knew about General Atomics was that its parent company, General Dynamics, made submarines. I remember being briefed on the project by Freeman and Taylor. This had to be done on a need-to-know basis, so I never learned how the bombs were actually designed. I knew they were small—around one kiloton in yield—and were designed to produce a shaped residue that could be directed toward the bottom of the ship, a huge flat disc that was known as the pusher. The payload was attached to the pusher by springs that absorbed the sudden violent accelerations and allowed the passengers—numbering in the dozens—to survive. Freeman took great pleasure in attempting to design the springs.

When the Orion spaceship design was first explained to me, I thought that it sounded completely mad. How could this ever work in practice? The detonations of the bombs would produce temperatures sufficient to melt anything in close proximity. I recall Freeman saying that when the internal combustion engine was described for the first time it sounded equally mad. The combustion of gasoline inside a car engine is accompanied by temperatures that far exceed the melting points of the internal components. In the case of car engines, the heat is dissipated before it can do any damage. For Orion, the challenge was to cool off the explosion detritus before it could ablate the pusher. The notion of opacity came to play a crucial role in our attempts to find solutions to these problems. It was sufficiently important that George devoted an entire chapter of his book to the topic.[15] It was also the only thing I worked on during my time as a consultant for the project.

An ordinary pane of glass is opaque to most, but not all, types of ultraviolet radiation. This is why it would be highly unusual to get sunburned sitting beside a window. To understand what causes this phenomenon at the atomic level, it is helpful to think of an atom as a tiny, positively charged nucleus surrounded by electrons in various quantum energy states. When a quantum of radiation strikes the atom, a number of things can happen. An electron can be detached from the atom, a transition known as bound-free absorption. Another type of transition, bound–bound absorption, occurs when an electron is induced to jump from one electron level to another. There are other possibilities too. In theoretical terms, measuring opacity involves calculating the probability for any of these things to occur using quantum mechanics. For a heavy nucleus, such as uranium, this is a huge job that requires an immense amount of computing power. The results of attempts to make these calculations for heavy elements remain classified.

When we began working on opacity as part of the Orion project, it was decided that calculations for any elements heavier than iron in the periodic table should be considered classified. As it turned out, we only needed to calculate the opacities of relatively light elements. This is reflected in the title of a General Atomic report that I co-authored with Freeman, "The Opacities and Equations of State of Some Mixtures of Light Elements."[16] The report is dated July 6, 1959, and was published during my second summer at General Atomic. In his book, George also lists a report that I wrote during the previous summer.[17] This report is a mystery to me; I have no recollection of it whatsoever. To understand why we were so focused on opacity, it is important to understand the role it played in the design and development of the hydrogen bomb.

The Teller–Ulam design for the hydrogen bomb is a two-stage affair. The first stage involves the detonation of a fission bomb, producing radiation that is channeled for the second stage. The target is a container made, at least in part, from uranium metal. Inside the container is deuterium, the fuel for the second stage. The deuteron is an isotope of hydrogen which has both a neutron and a proton in its nucleus. Under certain conditions, two deuterons can fuse, producing an isotope of helium and an energetic neutron. If this can be achieved, the result is two sources of energy. The fusion reaction produces energy due to the relation among the masses and Albert Einstein's equation, $E = mc^2$. The energetic neutrons can trigger the fission of uranium producing even more energy. A key consideration for a successful detonation is ensuring that the deuterium inside the container is not allowed to cool off before sufficient fusion reactions take place. For this reason, it is essential to know whether uranium is opaque enough to contain the radiation inside the container at these extreme temperatures. This explains the frenetic efforts to calculate the opacity of uranium at places such as Los Alamos and RAND, and why the results of these calculations are still classified. We were working with different elements in a different temperature regime for the Orion project.

In the Orion design, the exploding bombs produce a plasma of propellant that becomes more dense when squeezed against the pusher. At this point, the design has two contradictory objectives. On the one hand, any containing material should be opaque enough to allow intense thermal radiation to dissipate away from the pusher and avoid ablating it. On the other hand, the radiation produced inside the plasma needed to be confined so as to make use of its momentum to assist in propulsion. We were working in a temperature regime that had never been explored—cooler than a bomb, but hotter than the surface of a star. As part of this approach, it was essential that the probabilities for each kind of radiation-induced transition were computed and then added up. As part of my work on the project, I made an initial attempt at this task. The results were rather feeble, and it eventually fell to the astrophysicist John Stewart to do the job properly. He discovered that there were windows in which radiation of certain frequencies could get through. The precise location of these windows depended on the element involved. Closing the windows could be achieved by mixing elements. Freeman's contribution to the problem was completely original. He studied the weighted average over all the transitions and found that quantum mechanics provided an upper bound to the opacity. This result gave us a sense of whether the project might actually work. It also indicated that, if we needed a level of opacity above and beyond the upper bound Freeman identified, we were probably out of luck. Some forty years later, we published a joint paper on the topic.[18] I am pleased to see that it is still referred to from time to time with improvements noted.

After I finished working on the Orion project in 1959, a scale model was built that used high explosives as a means of propulsion. It flew beautifully. Some thought was subsequently given to constructing a Super-Orion, which would have been the size of a ten-story apartment building and been able to transport hundreds of people to the planets. Then the project collapsed.

When I was first briefed about Orion by Freeman and Taylor, I found myself wondering about radioactive fallout. The first part of the flight up through the earth's atmosphere would have produced a great deal of fallout. I remember asking whether they had considered using conventional explosives for the launch and only detonating bombs once the spaceship had traveled beyond the atmosphere. Freeman pointed out that such an approach would only have postponed the problem. Fission debris carries an electric charge that can be captured by the magnetic field lines emanating from the earth. These lines extend far above the atmosphere and could guide the particles back down to the earth's surface. Freeman estimated that a typical Orion flight would result in at least one death from cancer. This soured him on the project. There was also the problem that no one really wanted to fund it. NASA was committed to chemical rockets, and the military had no use for the technology. At the height of the project, Orion employed about fifty people and was eking out a budget of about $150,000 per month of government money. In February of 1965, the project was finally abandoned after the funding ran out.

Three years later, Kubrick's *2001: A Space Odyssey* included a nod to the project in the name of the *Orion Spaceplane*.[19] Arthur C. Clarke recalled:

> When we started work on *2001*, some of the Orion documents had just been declassified, and were passed on to us by scientists indignant about the demise of the project. It seemed an exciting idea to show a nuclear-pulse system in action, and a number of design studies were made of it; but after a week or so Stanley decided that putt-putting away from Earth at the rate of twenty atom bombs per minute was just a little too comic. Moreover—recalling the finale of *Dr. Strangelove*—it might seem to a good many people that he had started to live up to his own title and had really learned to Love the Bomb. So he dropped Orion, and the only trace of it that survives in both movie and novel is the name.[20]

In 2012, Freeman wrote the foreword for a new edition of George's book. As it turned out, the second edition of *Project Orion* was never published.

Here is what Freeman wrote.[21]

Ten years have passed since this book was published, and forty-seven since Project Orion ended. Interest in the project is still alive as memories of it are fading. I am still frequently asked whether I believe it has a future. I am asked whether I share a hope that some new version of Orion might take us to the stars. I am asked whether our dreams of fifty years ago are dead.

The answer to all three questions is no. Orion does not have a future, because the political and environmental concerns that caused the project to be ended in 1965 are still valid today and are likely to be permanent. No new version of Orion will take us to the stars, because the stars are too far away, and all versions of Orion travel too slowly and carry too much weight, crawling for hundreds of years to reach even the nearest stars. Our dreams of fifty years ago are not dead, because faster and more agile vehicles will avoid the political and environmental snags of Orion and will reach speeds that leave Orion far behind.

When we started the project in 1958, we could see clearly the promise and the limitations of Orion. The promise was a spaceship well matched in speed and size to the task of exploring the solar system within a human lifetime. The Orion ship would travel at speeds around twenty miles per second, which is the speed of the earth in its orbit around the sun. It would take about a year to travel to Jupiter, two years to Saturn, seven years to Neptune and Pluto. It would carry about a thousand tons of payload. We considered a thousand tons appropriate for a party of human adventurers with all the supplies and equipment that they would need for a thorough exploration of a planet or a satellite. We imagined the explorers to be like Charles Darwin, taking a leisurely tour around South America in the good ship *Beagle*, and not like Roald Amundsen racing to the South Pole and back with his provisions loaded on a dogsled. The payload of Orion would be larger than the payload of the *Beagle*, because Orion would not be buying supplies from friendly natives on Mars or Pluto. The promise of Orion was to explore the entire solar system within a century, as the planet Earth had been explored in previous centuries. The annual cost would be much less than we actually spent on the Apollo missions to explore the moon.

The most serious limitation of Orion was the lower limit on its size. Any efficient nuclear bomb must weigh a few hundred pounds, and any spaceship using bombs to accelerate to speeds of the order of twenty miles per second must carry about a thousand bombs. Consequently, any Orion mission making efficient use of bombs for propulsion must carry several hundred tons of bombs, and the weight of the structure required to handle the bombs and convert their energy into thrust will be several thousand tons. If the payload is a substantial fraction of the overall weight, the payload will also be on the order of a thousand tons. That is why we planned our first missions to carry thousand-ton payloads. To make them smaller would not have made them cheaper. But in the forty years since Project Orion and the Apollo missions ended, the style of space exploring has changed radically. Instruments can do the job far more economically than humans. The performance of cameras and computers and radio communication systems has improved by many orders of magnitude. The same survey of a planet, which an Orion mission could have done in 1965 with a thousand-ton payload, can now be done by a few modern unmanned spacecraft with payloads on the order of a ton. If we had today an Orion ship with a thousand-ton payload, we would not know what to do with it. In the context of modern technology, a single mission with a thousand-ton payload is preposterous. That is why the idea of reviving Orion makes no sense. Even if by some magic we were given a spaceship propelled by bombs that produced no radioactive fallout, we would not have any appropriate mission for it.

A second limitation of Orion is the upper limit on its speed set by the laws of nuclear physics. Even the most explosive nuclear reactions release less than one per cent of the mass-energy of the reacting atoms. When we dreamed of traveling to the stars on a mythical vehicle, which we called Super-Orion, we found that the speed limit set by the energy yield of bombs powered by fission or by fusion is about 2,000 miles per second. This is a hundred times as fast as we needed for exploring the solar system, but a hundred times slower than the speed of light. The nearest star is 4,000 times further away from us than Pluto. The Super-Orion could travel to Pluto in a month, but would take 400 years for a one-way trip to Proxima Centauri. In addition to being unreasonably slow, the Super-Orion would be unreasonably large. To reach a speed of 2,000 miles per second, it would need to carry a hundred thousand bombs and would weigh at least a million tons. Even for dreamers, a Super-Orion mission is absurdly slow and cumbersome. We could dream of interstellar voyages, but Super-Orion was not the magic carpet that would take us to the stars.

After Project Orion ended, other dreamers appeared with better ideas. In 1966, George Marx, a Hungarian physicist writing from Budapest, published a proposal for an interstellar spaceship which became known as the laser-driven sail.[22] The essential new feature of this invention was to separate the vehicle from its source of energy. Orion and Super-Orion were speed limited because they carried their energy source with them in the nuclear cores of bombs. The laser-driven sail was powered by a massive laser that stayed at home, pointing its beam of light in the direction of the destination. The vehicle was attached to a wide, thin sail that sailed along the laser beam, picking up energy and momentum from the beam as it accelerated. With a powerful enough laser and a light enough sail, the vehicle could travel much faster than Super-Orion. The only absolute limit to its speed was the speed of light. With reasonable dimensions for the laser and the sail, the vehicle could travel at half–light speed. That would be fifty times the speed of Super-Orion, reaching Proxima Centauri in eight years and Sirius in sixteen. The vehicle traveling with the light sail would be small and agile. If Super-Orion were ever built, the light sail would overtake it and make it obsolete before it could reach its destination.

In 1985, Robert Forward proposed a project which he called Starwisp, replacing Marx's laser by a microwave radio transmitter and using a thin wire mesh for the sail.[23] A beam of microwave radiation replaces the laser beam. Starwisp is designed to be ultralight, so that the wire-mesh sail is also the payload, working as a collector and transmitter of information. The payload can be as small as a few grams, with the size of the energy-source reduced in proportion to the payload. Starwisp would not carry human passengers. It would explore neighboring stars and their planets with instruments, just as we are now sending instruments to explore our own solar system. Starwisp would be radically smaller and cheaper than super-Orion. If a payload of four grams is accelerated to one-fifth of the speed of light by sailing along a microwave beam for a week, the power of the microwave transmitter must be roughly ten gigawatts. This is more power than any existing transmitter can deliver, but it isn't absurd. The cost of it might seem reasonable when we have large-scale industrial operations in space using large quantities of solar energy. It is conceivable that we could build such a transmitter in space, powered by the sun, within a hundred years from now. After that, it would be another huge jump to go from small unmanned missions to human travel. But Starwisp has made it possible for us to dream again of interstellar voyages, as we did in the days of Orion. Starwisp could be the first step on our way to the stars.

In recent decades, our vision of the universe has been transformed by an avalanche of astronomical discoveries. Every discovery makes the vision richer and makes the universe more diverse. We met a spectacular surprise on Enceladus, one of the smaller satellites of Saturn. When we planned our missions for Orion, we chose Mars as the destination for the first mission and Enceladus for the second. We chose Mars and Enceladus because both had large quantities of ice or snow on their surfaces. Mars had a visible polar ice cap, and Enceladus had a measured density so low that it must be made mostly of ice rather than rock. We could land on Mars or on Enceladus and reliably find ample supplies of water. Water was our most essential need, to provide life-support for an extended stay, and to provide propellant for our return to Earth. At that time, we knew nothing about Enceladus except that it was a moon of Saturn with bright white surface and low density. We pictured it as a big cold snowball.

In 2004, the spacecraft Cassini arrived from Earth to explore Saturn and its rings and satellites. Cassini flew by Enceladus many times and took close-up pictures that show powerful jets of gas escaping from cracks near the South Pole. The jets form visible plumes extending far into space. Enceladus has a warm interior and is geologically active. The gas is probably a mixture of water vapor with other volatile organic gases such as methane or ammonia. We are amazed to discover that Enceladus, which we chose as our destination for its practical convenience, is also the most interesting world to study from the point of view of science. The warm, wet interior of Enceladus is the most promising place in the whole Saturnian system to look for traces of indigenous life.

Enceladus is an example of a general rule that applies to all astronomical discoveries. When we first discover an object, we imagine it to be simple and boring. When we examine it in detail, we find it to be complicated and puzzling. The more we explore the universe, the more puzzling it becomes. Another example of the same rule is the space between the solar system and the stars. When we were working on Project Orion, we thought of only two kinds of space travel, either going to the planets or going to the stars. We thought of the space between as empty and uninteresting, containing only a dilute gas and an occasional grain of dust. Now we know that this space contains a great variety of other objects. There is the Kuiper belt of icy objects, the brightest and best known being Pluto, orbiting the sun in the space outside Neptune. There is the Oort cloud containing a bigger population of such objects at greater distances from the sun. There are orphan planets unattached to stars, probably outnumbering the stars in our galaxy. There is an even larger population of orphan comets drifting through the galaxy. All these objects will be there for us to explore on our way from the planets to the stars. The more we explore them, the more surprises we will find. The first voyage to the stars will not be a straight run through a featureless void. It will be a zigzag path from one oasis to another in the desert of space. Our destiny may be to become nomads rather than settlers.

Other visions which were out of sight in 1958 have grown out of spectacular discoveries in biology. During the last fifty years we have learned to read and write genomes, sequencing and synthesizing DNA with rapidly increasing speed and rapidly decreasing cost. We do not yet understand the language of the genome well enough to design new species of living creatures, but the power to create new species will soon be in our hands. This power will radically transform once more our visions of future space travel. Instead of trying laboriously to construct artificial Earth-like habitats in which creatures adapted to living on Earth can survive, we will bring to remote places creatures already adapted to live wild wherever we bring them. Wherever we wish to travel, we will bring a complete ecology of plants and animals and microbes, adapted to survive in the local environment and to supply us with food and fuel. We may also choose to modify our own physiology so that we can discard our spacesuits and live freely on alien worlds.

When we were dreaming fifty years ago, we thought mostly about traveling through space. We did not think much about how we would live when we arrived at the destination. The problems of travel are problems of engineering. The problems of how to live are problems of biology. For the last 500 years, engineering was the main driving force of change in human affairs. In future, as in the earlier time when we invented agriculture, biology will be the main driving force. This is true for our future in space as well as on Earth. Our dreams for the future of humanity will be less about space-ships and more about living greenhouses and warm-blooded plants, space butterflies and astrochickens, creatures of our imagination that make their homes in space and make it possible for us to make our homes there too.

Freeman Dyson
Institute for Advanced Study, Princeton, New Jersey
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1. These background checks included interviews with people who might have information about you going back a number of decades. Some years later, I was able to access my own clearance dossier. The version provided to me was so heavily redacted that it was essentially illegible.
2. Freeman Dyson, "The Radiation Theories of Tomonaga, Schwinger, and Feynman," *Physical Review* 75, no. 3 (1949): 486–502, doi:10.1103/physrev.75.486.
3. It was not until 2007 that the notes from Dyson's Cornell lectures were finally published. See Freeman Dyson, *Advanced Quantum Mechanics* (Singapore: World Scientific, 2007). For a discussion of this volume, along with Julian Schwinger's *Quantum Mechanics* and Steven Weinberg's *Lectures on Quantum Mechanics*, see my earlier essay, Jeremy Bernstein, "Recollections of Some Notable Texts," *Inference: International Review of Science* 3, no. 2 (2017).
4. "TRIGA Nuclear Reactors," *General Atomics*.
5. George Dyson, *Project Orion: The True Story of the Atomic Spaceship* (New York: Henry Holt, 2002).
6. Stanisław Ulam, *Adventures of a Mathematician* (Berkeley: University of California Press, 1991), 144. Hans Bethe, who had been working at the IAS before joining the Manhattan Project, recounted the following anecdote about the journey to New Mexico:

   > I went by train to a place called Lamy, New Mexico, which was the railroad station for Santa Fe. Later on, there was a story about some people who went to the railroad station in Princeton to buy tickets to Lamy, and the ticket seller told them, "Don't go there. Twenty people have already gone there, and not one of them has ever come back."

   Craig Nelson, *The Age of Radiance: The Epic Rise and Dramatic Fall of the Atomic Era* (New York: Scribner, 2014), 150.
7. Cornelius Everett and Stanisław Ulam, "On a Method of Propulsion of Projectiles by Means of External Nuclear Explosions. Part I," Los Alamos Scientific Laboratory (1955), 5.
8. Dyson, *Project Orion*, 23.
9. Everett and Ulam, "On a Method of Propulsion of Projectiles."
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