Davide Sivolella

Space Mining and Manufacturing

Off-World Resources and Revolutionary Engineering Techniques

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Davide Sivolella
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Space Exploration: What For?

WHAT FOR?

What is the purpose of space exploration? Why spend prodigious amounts of money to enable a few highly trained individuals to travel in space months for at a time in an inherently dangerous environment? Why devote taxpayer money just to send a small robot to snap pictures at the edge of the Solar System? Are not there more pressing, urgent conditions affecting human society that would benefit from such investments? You, or somebody you know – a family member, a colleague, an acquaintance – might have similar questions. They all hinge on determining whether space exploration is a worthy endeavor. If you are an advocate for space exploration, you might find these questions annoying. Why cannot people understand the importance of spaceflight, you might ask yourself? Why must they question it?

However, if we take an objective look at some numbers we might concur that these questions, and the detractors, might be onto something. Consider that, on average, a mission by the Space Shuttle cost some US$450 million; support and handling of the International Space Station costs between $3 and $4 billion per year; the New Horizons spacecraft that in 2016 showed us the jaw-dropping landscape of Pluto cost some $700 million; the car-sized Curiosity rover on Mars required some $2.5 billion to build, and more money is poured annually to continue its adventures on the Red Planet. Space exploration is clearly expensive, and perhaps the money could be put to better use in building hospitals and schools in developing countries, in eradicating cancer, and in obliterating plagues such as AIDS. Advocates of space do have an obligation to answer to these questions. Let us start therefore by analyzing the main rationales attributed to space exploration.

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Then we will weigh their value against our present reality and assess whether space exploration has any place in our society.

Rationales of Space Exploration: Geopolitics, Prestige, National Security

Ever since the Soviet Union orbited Sputnik on October 4, 1957, space exploration in general, and human spaceflight in particular, have portrayed a country's technological strength and manifesto for way of living. The race to the Moon is the perfect example. In the midst of the Cold War, President John F. Kennedy's call to reach our natural satellite was motivated more by a need to demonstrate that America was superior, in every way, to its rival on the other side of the "Iron Curtain".

In his Special Message on Urgent National Needs delivered to a joint session of Congress on May 25, 1961, shortly after the Russians flew Yuri Gagarin in orbit and America responded by sending Alan Shepard on a ballistic mission, Kennedy made this explicit: "If we are to win the battle that is now going on around the world between freedom and tyranny, the dramatic achievements in space which occurred in recent weeks should have made clear to us all, as did the Sputnik in 1957, the impact of this adventure on the minds of men everywhere, who are attempting to make a determination of which road they should take." He presented space exploration and its achievements as the yardstick to gauge the success of a nation's way of living. The "road" he referred to was the choice between freedom and tyranny, and that decision was to be based, among the other things, on the quality of a nation's space exploration program.

Kennedy continued: "Recognizing the head start obtained by the Soviets with their large rocket engines, which gives them many months of lead-time, … we nevertheless are required to make new efforts on our own. For while we cannot guarantee that we shall one day be first, we can guarantee that any failure to make this effort will make us last. … We go into space because whatever mankind must undertake, free men must fully share." Considering that there were only two contenders in the space exploration arena, the United States had better not be last, because that was what free men had to undertake. Nothing less than freedom was at stake.

Having charged his audience with pride, and appealed to the ideology of freedom so dear to any American citizen, Kennedy was now ready to deliver the final blow: "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth." How could anybody refuse such a commitment now that it was linked to everything that American society stood for! On July 20, 1969, Neil Armstrong, an American citizen, became the first man to set foot upon the Moon.

The example set by Kennedy would be followed by a number of his successors. For instance, despite an ever decaying public and political support for human-crewed spaceflight which curtailed the Apollo program and ended NASA's dreams of lunar exploration, President Richard M. Nixon made sure that approval for the Space Shuttle would be given. In fact, in August 1971, Caspar W. Weinberger, Director of the Office of Management and Budget, wrote a memorandum to Nixon expressing his concern "that our best years are behind us, that we are turning inward, reducing our defense commitments, and voluntarily starting to give up our super-power status, and our desire to maintain world superiority" and that hence "America should be able to afford something besides increased welfare, programs to repair our cities, or Appalachian relief, and the like." And the Space Shuttle was expected to enable America to reassert its superiority among nations and surge ahead in the exploration of space.

When NASA Administrator James M. Beggs met with President Ronald Reagan on December 1, 1983, he showed him a photo of a Soviet Salyut space station against the backdrop of the USA. At the State of the Union Address delivered before a joint session of Congress on January 25, 1984, another Kennedy moment was about to take place. The words would be different but the structure of the script remained the same. Reagan first appealed to the greatness of his nation: "Nowhere do we so effectively demonstrate our technological leadership. ... Our progress in space, taking giant steps for all mankind, is a tribute to American teamwork and excellence." There was a nod to the values of the Free World relative to the closed communist Soviet Union: "And we can be proud to say: We are first. We are the best. And we are so because we are free." With his audience prepped for the next commitment in space, he said: "We can reach for greatness again. ... Tonight, I am directing NASA to develop a permanently manned space station and to do it within a decade." Once again, national pride was a potent ally in initiating a complex and rather contested space program.

However, it would be more than 20 years before the assembly of the space station would start. And when on November 20, 1998, the first component was orbited it was not American but a Made-in-Russia module named Zarya. The political climate was profoundly different. The Soviet Union had ceased to exist in December 1991, and the need to demonstrate the superiority of the Free World over communism was irrelevant. With the fall of the USSR, the Russian space program was plunged into an existential financial crisis and the concern in America was that the cash-strapped engineers would offer their undoubted talents and capabilities to countries hateful of the United States. With the space station program running way over budget and teetering on the brink of cancelation, in his State of the Union Address on January 25, 1994, President Bill Clinton tackled the need to keep the Russian space workforce busy: "Russian scientists will help us build the International Space Station." Therefore, it is not surprising that since its inception the ISS has been criticized for being primarily a tool to maintain the post-Cold War détente and to showcase goodwill in international relations. Indeed, it is not uncommon at times of crisis for this multi-billion dollar collaboration at 400 km altitude to be hailed as evidence the two superpowers *can* still cooperate.

Consider the events involving the Russian annexation of Crimea in 2014. Despite the condemnation by the US and the European Union, and the economic sanctions that they then applied, Russia remains a partner in the ISS and routinely delivers supplies and personnel.[1]

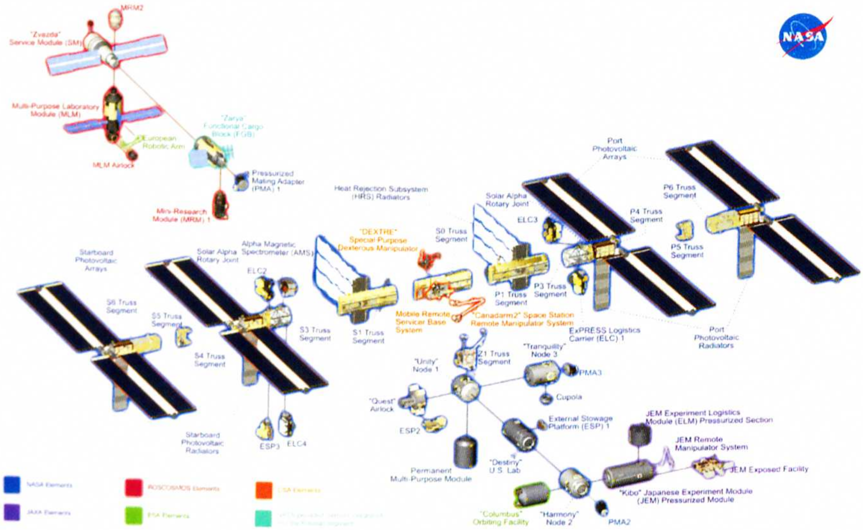

Figure 1.1 An exploded view of the International Space Station showing the individual components color coded by national contribution. The international cooperation in this venture is evident.

The umbrella of geopolitics has enabled defense and national security to become effective motivators for activities in space. Civilizations of any type, place, and time have recognized the benefit of being able to observe the movements of an approaching enemy. In fact, castles and villages, whenever possible, were built on cliffs, high hills, and mountains tops. And as soon as we began to master the art of flight, balloons and airplanes were used for reconnaissance of the enemy lines, and indeed far beyond. And in addition to determining the next defensive or offensive maneuver, an elevated point also allows the delivery of bombs, missiles and the like for a greater destructive impact. It is therefore easy to appreciate how space became the ultimate "high ground" for the observation of the enemy and formulating offensive actions. As early as 1951, Werner von Braun proposed a bomb-dropping space station, saying that a nation orbiting such a platform "might be in a position virtually to control the Earth". Perhaps he struck a chord with the US military, as on 16 March 1955 the United States Air Force officially ordered the development of an advanced reconnaissance satellite to

[1] With the advent of commercial service providers such as SpaceX and Boeing, which are both developing spacecraft for crew transportation, the status quo might change radically.

provide continuous surveillance of "preselected areas" "to determine the status of a potential enemy's war-making capability". Not surprisingly, when Sputnik was launched 2 years later, the US military, as well as the general public, were swift to grasp the implications of that tiny sphere emitting a faint radio signal; namely that the Soviet Union might now have the unhindered capability to drop weapons, possibly nuclear, anywhere on Earth without warning.

Luckily, bombs have not yet been dropped from space, and no satellite has carried weapons.[2] However, flotillas of so-called spy satellites have been launched with ever-increasing capabilities in photo surveillance, early warning of missile launch, detection of nuclear explosions, electronic reconnaissance, and radar imaging. Such skills are no longer exclusive to the United States and Russia. These capabilities have proved their worth in conflicts or situations involving national security for the past six decades.

Rationales of Space Exploration: The Frontier

Throughout history, "the frontier" has been a potent lure motivating people to explore what lies beyond their comfort zone. This spirit has been present everywhere, from the mythological account of Ulysses, to the Far West, to the exploration of the poles just a century ago. As the acclaimed astronomer and science communicator Carl Sagan wrote: "We're the kind of species that needs a frontier – for fundamental biological reasons."

The online Oxford Dictionary defines "frontier" as "a line or border separating two countries" and also as "the extreme limit of settled land beyond which lies wilderness". With this explanation, it is easy to appreciate how space can be considered a frontier. It is the opposite of a life-laden settled planet. It is vast, lifeless, and wild. As the most difficult to reach and subject to our own will, space is the *ultimate* frontier. It is not by accident that in the 1950s, and for some time after that, you would hear and read about "the conquest of space". Compared to the more politically-correct "space exploration" a conquest did indeed instill feelings of dominating the harshest of the frontiers in the same manner that the western part of the United States was colonized.

The iconography of the frontier goes well beyond physical places, and penetrates deeper into the human psyche. The same Oxford Dictionary offers an additional telling interpretation: "the extreme limit of understanding or achievement in a particular area". Space exploration has furthered our comprehension of the most disparate mysteries of the Solar System and the Universe. For instance, it was the American-born physicist Lyman Spitzer who first proposed the carrying out of astronomical observations from orbit when in 1946 he published an intriguing

[2] An interesting exception are the Soviet Almaz space stations designed for reconnaissance-gathering missions. They even had a small, fixed cannon that the cosmonauts would have used in the case of being approached by an enemy spacecraft.

scientific article entitled 'Astronomical Advantages of an Extra-Terrestrial Observatory'. He explained how the atmosphere hinders astronomical observation by absorbing most of the electromagnetic spectrum apart from that to which our eyes are sensitive. Furthermore, even the quality of optical observations is drastically affected by the daily and local changes of the atmosphere's physical properties, referred to by astronomers as 'seeing' conditions. The scheme that Spitzer concocted was to put a telescope in orbit around Earth to perceive the Universe at never-before-seen wavelengths. Sure enough, the first satellite applications, by both superpowers, were for astronomy. Since then, there have been a steady stream of ever-sophisticated space-borne telescopes.

At the same time, robotic probes have been posted to every major body of the Solar System, revealing alien vistas that had previously only been imagined in the pages of science fiction publications. In some cases, robots have even provided an up-close in-situ studies of such landscapes. However, the only celestial body to have been visited by humans is the Moon, by the Apollo astronauts. Thus far, all efforts to renew human exploration have failed the funding hurdle. Since the tragic loss of the Space Shuttle Columbia in February 2003, every major space agency has been trying to initiate plans for either a return to the Moon or to achieve the first boot prints on Mars. Among the top reasons presented to justify such ventures is the need to improve our understanding of these alien worlds.

There is another area of the frontier definition that we must reflect on: "the extreme limit of … achievement in a particular area". This is a frontier in what we, as a species, can do. Humans have always striven to accomplish ever grander projects and we have used them as yardsticks in demonstrating our ability to tame nature to our goals. The same attitude is also experienced on an individual scale, as most of us feel the need to embark on projects or hobbies that give us a sense of accomplishment and provide the confidence that we are capable of doing even better. It is not surprising that President Kennedy said: "We choose to the go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because the goal will serve to organize and measure the best of our energies and skills." The exploration of space is difficult and challenging. It does require an extraordinary effort to concoct complex machinery to harness in a controlled manner the equivalent energy of an atomic bomb, or to precisely arrange for a space probe to rendezvous with a small body billions of kilometers away after a journey lasting years. Consider the fly-by of Pluto by NASA's New Horizons spacecraft, the European Space Agency's Rosetta mission's encounter with the 67P/Churyumov-Gerasimenko comet, and more recently the Japanese Space Agency's Hayabusa 2 probe which landed two small hopping rovers on the surface of the asteroid 162173 Ryugu. Another good example is the intricate sky-crane apparatus devised to safely and precisely land NASA's Curiosity rover on Mars, something never previously attempted, difficult to test on Earth, and had only one chance to work upon reaching its target. Even for the layman such accomplishments raise awe, marvel, and a sense of pride at what humans can achieve.

At times, it can inspire action. It frequently gives us confidence that we can resolve thorny and demanding problems. It is not unusual to hear expressions such as "if they were able to go to the Moon then they can also [substitute a problem familiar to you]". Time and again, the public relations departments of the national space agencies levy heavily on our natural desire to seek a grand challenge as a reason for a return to the Moon or to send people to Mars. Quotations from Werner von Braun such as: "I have learned to use the word 'impossible' with the greatest caution" or Robert H. Goddard's "It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow" really do nurture such spirit.[3]

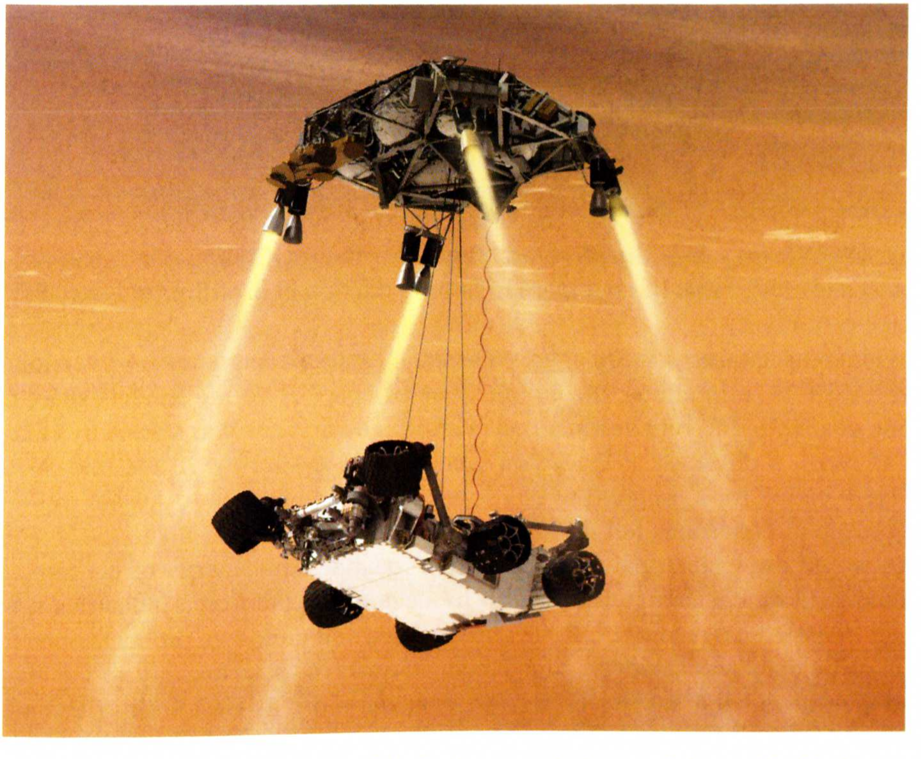

Figure 1.2 An artist's impression of the final moment before touchdown of the Curiosity rover on Mars. The so-called sky-crane consisted of a platform that was stabilized by four clusters of small rocket thrusters which fired just above the surface, while a winch lowered the rover gently to the surface at the end of a rope.

[3] It is worth recalling that both men are considered the fathers of modern rocketry in Germany and the United States, respectively.

The need to explore and advance the frontier has repeatedly protected our species from events that might otherwise have placed its survival at risk. There is abundant archaeological evidence of how large and small groups have undertaken migrations beyond their frontiers to find better places to settle. Often it was in response to natural events or human-made circumstances, such as war or overexploitation of resources as a result of runaway population growth (more on this at the end of the chapter).

The same rationale applies to space exploration, particularly in terms of a human presence in space. The renowned sci-fi writer Larry Niven once said: "The dinosaurs became extinct because they didn't have a space program. And if we become extinct because we don't have a space program, it will serve us right!" This might sound like a joke, but the demise of these giant reptiles has been attributed to an asteroid striking our planet. As we track more and more such rocks passing by, the risk of another such cataclysmic event is no laughing matter. Recall the 2,000 square kilometers of Eastern Siberia where some 80 million trees were razed on June 30, 1908, by either an asteroid or a comet exploding with the force of a large nuclear bomb over the Stony Tunguska River area. On February 15, 2013, another space rock detonated with a much smaller blast over the Chelyabinsk area in the Southern Urals of Russia. Although neither event produced human casualties, the destruction they unleashed are stark reminders that we cannot dismiss such threats. It is therefore not surprising that expanding our capability to detect and chase what lies out there is gaining traction both within and beyond the space community.

Others have taken a more aggressive stand by proposing a modern version of our ancestors' migrations: the colonization of space. Two movements share the same goal with different destinations in mind. The first one was started by Gerard K. O'Neill, a physicist at Princeton University, New Jersey. In the mid-1970s, O'Neill called for a program to build vast cylinders in space to sustain millions of people in conditions not dissimilar to a typical American suburb. Such colonies would draw electrical power from the inexhaustible energy of the Sun and would gain independence from Earth by developing their own industries using lunar or asteroidal resources. In fact, they would sell their own products once full self-sufficiency was achieved. Since then, colonies in space in every sort of shape and size have been subject to serious consideration, at least from a technical perspective.

The alternative is to create an artificial habitat on the surface of a celestial body. Although the Moon is the closest, and we have already shown that we can reach it, the destination that space agencies, individuals, and space advocacy societies yearn for is Mars. For example, one of the most prominent individuals actively championing Mars is Elon Musk. He has used his personal fortune to create SpaceX, a rocket company whose stated purpose is to make humankind a

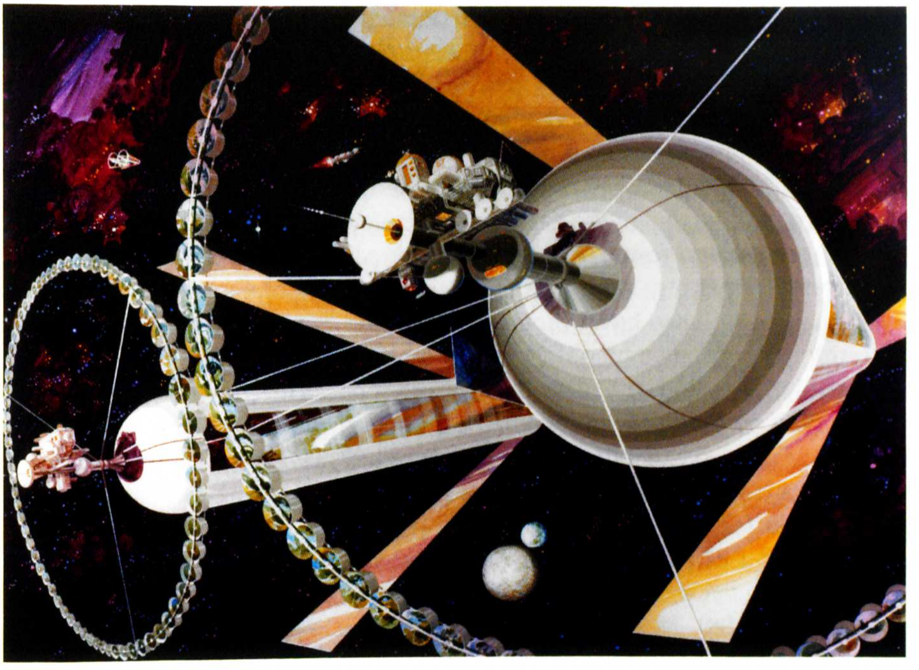

Figure 1.3 An artist's depiction of a pair of O'Neill cylinders, each capable of housing millions of people.

multi-planetary species. As of writing, SpaceX has already begun construction of a massive rocket ship with the objective of sending the first humans to Mars. Robert Zubrin, the founder of the Mars Society, has been strongly advocating for a Mars mission for several decades now. The work of the Mars Society to experiment with available technology in order to make a Mars mission feasible is both admirable and inspiring.

A major asteroid impact is not the only extinction risk facing the human species. A nuclear war, use of biological weapons, dwindling of resources due to overpopulation, societal collapse, and so on, are all reasons for a human migration into space. And in a few billion years our Sun will evolve into a 'red giant' star. Its inflated surface will swallow up the inner planets and the resulting conditions on Earth will render all life impossible. Thus, irrespective of the type of threat, the human colonization of space is heralded as an insurance policy against extinction. Furthermore, it can also provide the opportunity to give humankind a chance to develop a better society, opportunities for experiments in cultural diversity, even Utopian, as envisioned by science author T. A. Heppenheimer. As he wrote in his book *Colonies in Space*: "Some of these people will form specialized communities and will develop (or bring with them from Earth) their own characteristic ideas of how life should be lived, how a community should be organized. On Earth it is difficult for these people to form new nations or regions for themselves. ... But in space it will become easy for ethnic or religious groups, and for many others as well, to set up their own colonies. ... Those who wish to found experimental communities, to try new social forms and practices, will have the opportunity to strike out into the wilderness and establish their ideals in cities in space. This, in the long run, will be one of the most valuable results from space colonization: the new social or cultural forms people will develop."

Such possibilities also occurred to O'Neill in his masterpiece *The High Frontier*: "What chances will we have, though, here on an Earth ever more crowded and hungrier for energy and materials, to allow for diversity, for experiment, for groups to try in isolation to find better lifestyles? What chances for rare talented individuals to create their own small words, of home and family, as was so easy a century ago in our America as it expanded into a new frontier? ... The most chilling prospect that I see for a planet-bound human race is that many of these dreams would be forever cut off for us."

This comes full circle with the human need to reach and tame the frontier. Reaching and settling the frontier is what Robert Zubrin describes as "humanity's greatest social need. Nothing is more important ... Without a frontier to grow in ... the entire global civilization based upon values of humanism, science, and progress will ultimately die."

Answering the urge to conquer the frontier, an insurance policy for humankind, a chance to create a better society that has learned from the past, and infusing confidence in our ability to engage in seemingly impossible endeavors, are all tightly intertwined in bestowing a strong rationale for space exploration.

Rationales of Space Exploration: Searching for ET

"But where is everybody?" Italian physicist Enrico Fermi asked at a luncheon in Los Alamos in the summer of 1950. As recalled by his colleagues, Fermi was questioning the lack of evidence for extraterrestrial civilizations. Known as the Fermi Paradox, this has spurred many a debate about the existence of other intelligent forms of life in the galaxy. The Search for Extraterrestrial Intelligence Institute (SETI) was established in 1984. Far from being a laughable excuse to look for little green aliens, the institute is a serious "private, nonprofit organization dedicated to scientific research, education, and public outreach" with the mission "to explore, understand, and explain the origin and nature of life in the universe, and to apply the knowledge gained to inspire and guide present and future generations".

Among the original board of trustees was Dr. Frank Drake, a radio astronomer at the National Radio Astronomy Observatory in Green Bank, West Virginia. In 1961 he published an equation, known as the Drake Equation, which grouped those factors that should be appraised in estimating the number of civilizations in our galaxy capable of radio communications. As explained by the SETI Institute, the Drake Equation "is a simple, effective tool for stimulating intellectual curiosity about the universe around us, for helping us to understand that life as we know it is the end product of a natural, cosmic evolution, and for making us realize how much we are a part of that universe".

There is no doubt that we have become obsessed with the search for extraterrestrial life, be it intelligent or not. For instance, robotic exploration of Mars is predominantly focused on this topic. The two Viking probes landed on the Red Planet in the summer of 1975 and not only snapped panoramic vistas and close-up pictures of the soil, but also "conducted three biology experiments designed to look for possible signs of life". The Spirit and Opportunity rovers landed on Mars in early 2003 to carry out extensive soil sampling. In doing so, they unearthed "evidence of ancient Martian environments where intermittently wet and habitable conditions existed". These are circumstances considered suitable for the development of life. The small Phoenix lander spent three months on Vastitas Borealis, an arctic plains near the north pole, digging into a near-surface ice-rich layer looking for evidence "about whether the site was ever hospitable to life". The car-sized Curiosity rover is currently surveying Gale Crater to answer one question: "Did Mars ever have the right environmental conditions to support small life forms called microbes?" In 2020, a twin of Curiosity is scheduled for launch, and with additional tools such as a drill it will take "the next step by not only seeking signs of habitable conditions on Mars in the ancient past but also searching for signs of past microbial life itself".

The search for life has extended well beyond the confines of the Solar System, and is actively pursued both on the ground and in space. Most notably, the Kepler Space Telescope has discovered thousands of extra-solar planets. Thus far, no planets have been found to host all the conditions deemed necessary for life to occur or survive, but the search for a "second Earth" continues. There is no doubt that the search for another civilization, the quest for another Earth, and the desire to find out whether life on Earth is unique, all play major roles in assigning considerable human and financial resources to space exploration.

Rationales of Space Exploration: Spinoff and Satellite Applications

The use of space for applications directly affecting our daily lives is well documented, and perhaps the easiest to understand. Weather forecasting, telecommunications, and GPS-based services are among the most ubiquitous accomplishment of the Space Age, so much so that it is easy to forget they rely on multi-million dollar spacecraft orbiting Earth. Environmental monitoring conducted by satellites specialized in analyzing one or more peculiar aspects of our planet's environment are perhaps less popular in daily jargon, but they play a paramount role in understanding and better managing our world and its limited resources on behalf of future generations.

Satellite applications fulfill well-defined tasks, but the term "spinoff" is defined as "a by-product or incidental result of a larger project". In NASA parlance, a spinoff is "a commercialized product that incorporates NASA technology or expertise".[4] These include: products designed to NASA specifications initially for use by NASA and then commercialized; products that are developed as a result of a NASA-funded agreement or know-how acquired by collaboration with NASA; products that incorporate NASA technology in their manufacturing; products that receive significant contributions in design or testing from NASA personnel or facilities; products that are entrepreneurial endeavors by former NASA employees whose technical expertise was acquired while in the employ of the agency; and products that are developed using data or software made available by NASA. With this broad definition in mind, let us consider several examples of NASA spinoff.

In the 1960s, NASA JPL engineer Eugene Lally proposed the use of a mosaic of photosensors to digitize light signals and make still images. In the following decades, NASA toyed with this idea up to when the Charged Coupled Device (CCD) sensor was developed. This gave the scientific community the opportunity to equip detecting instruments with a small, lightweight, and robust image sensor suitable for the extreme environment of space, most notably for astronomical observations. In fact, with a CCD apparatus, high-resolution images can be recorded and held in a solid-state long-term storage ready for transmission to Earth at the next communications opportunity. The CCD enjoyed universal success from reconnaissance satellites to the Hubble Space Telescope, and once released into the commercial realm in the form of digital cameras it transformed the market. Generally speaking, an image sensor contains an array of photodetectors called "pixels" that collect photons.[5] The photons entering the pixel are converted to electrons, generating signals that a processor can assemble into a picture. CCD-based pixel arrays operate like a bucket brigade, with the light-generated charge from each pixel passing along the entire array of pixels to the corner of the chip, where it is first amplified and then recorded. But CCD sensors require a lot of power and an extremely high efficiency of charge transfer. These difficulties are compounded when the number of pixels increases for higher resolution or when video frame rates are sped up.

When in the early 1990s NASA adopted the banner of "faster, better, cheaper", JPL engineer and CCD-expert Eric Fossum recognized that it was time to improve the CCD sensor by using the Complementary Metal Oxide Semiconductor (CMOS) technology, a well-known process used since the 1960s in the manufacture of microprocessors of ever diminishing size and with an ever increasing number of transistors. Using this, he was able not only to produce a sensor that had the same performance as an equivalent CCD-based sensor, he was also able to integrate almost all of the associated electronics for timing and control systems, for analog-to-digital

[4] As a matter of fact, you can replaced NASA with any other national space organization.

[5] Pixel is a contraction of "picture element." Interestingly, the term was coined in 1965 by another NASA JPL engineer, Frederic Billingsley.

conversion, and signal processing. Thus was born the "camera on a chip" and with it the new term of CMOS Active Pixel Sensor (CMOS-APS). As Fossum explains, "active pixel means that the pixel's got an active transistor in it, an amplifier".

By allowing the integration of a complete imaging system onto a single piece of silicon, CMOS-APS technology has improved miniaturization, enhanced reliability, increased signal integrity, improved speed, and significantly cut power consumption to 1/100th of the equivalent CCD sensor. The fact that it shares the same manufacturing platform of microprocessors and memory chips means that crafting CMOS sensors is more cost-effective and simpler than CCDs. This facilitated smaller camera systems that included an architecture to protect the electronics from the radiation in the space environment.

Fossum soon recognized that this technology had the potential to address a wide range of non-space applications. In 1995 he and some coworkers founded Photobit for the commercial exploitation of the CMOS-APS technology. In the ensuing years, they designed specialized sensors and licensed them to colossi such as Kodak and Intel. The commercial breakthrough arose when cell phones became the "killer application" that drove manufacturers towards ever-smaller devices with longer battery lives. Soon, the CCD-based devices could no longer compete with the falling costs and the increasing quality, even when size and power were not priorities. Now, apart from niche markets, virtually all digital still and video cameras use Fossum's invention.

But CMOS-based imaging technology is not limited to our leisure activities, it has established itself in applications such as medical imaging with X-rays. In fact, X-ray radiography on film has a number of downsides, most notably the cost of film material, difficulties in storing the exposures because they degrade over time, disposing of the chemicals used in development, and, last but not least, subjecting the patient to a high dose of radiation.

To overcome these drawbacks, the medical community started to apply the NASA-developed CCD technology to digital imagers that combine a higher sensitivity with a lower dose of radiation. Because there is no need to develop a film, this eliminated the handling precautions for toxic chemicals. The fact that the turnaround is much faster meant that X-ray technicians and other medical staff did not have to wait for film to be processed. Furthermore, a digital image can be manipulated to improve the diagnosis and to communicate problems to the patient. There are, however, some nuisances. For instance, X-rays cannot be focused with lenses. And the array of pixels for a digital X-ray imager must have the size of the object being observed. That means a lot of pixels. A CCD-based array has to transfer each pixel's charge from pixel to pixel through the array with virtually no losses. The greater the number of pixels, the greater the overall potential for loss, with the risk of reducing the resolution that might lead to an error in characterizing vital details of a patient's health.

This prompted Schick Technologies to approach Photobit in 1995 and obtained an exclusive license to develop a CMOS-APS dental imager. Named Computed

Dental Radiography (CDR), this product employs an electronic sensor in place of X-ray film to generate sharp and clear images that appear on a computer screen within 3 seconds and can be enlarged and enhanced as necessary to identify problems. It is compatible with virtually all X-ray tubes, seamlessly integrates with existing practice management systems, and even permits the correction of underexposed radiographs. The low power requirements of CMOS sensors enabled the company to develop miniaturized battery-powered apparatus, for example intraoral X-ray sensors that fit inside the mouth and significantly improve a patient's comfort. CMOS imagers also allow the radiologist a low-resolution preview, or check for exposure, using a quick readout from a few pixels at minimal energy, whereas a CCD-based imager would have had to read out the entire array.

NASA has also devoted considerable effort to developing software packages that accurately manipulate data received from planetary probes and space telescopes. In 1966 NASA set up the Image Processing Laboratory at JPL. Since then, evolution of the NASA-invented Video Image Communication and Retrieval (VICAR) software has laid the groundwork for understanding images ranging from the Voyager missions to New Horizons. This same software package is now playing a vital role in the early diagnosis of atherosclerosis in which a buildup of cholesterol and fatty substances in the arteries, along with arterial hardening, restricts the blood supply to the heart and hampers oxygen flow. Atherosclerosis is known as the "silent killer" because it does not display obvious symptoms prior to one or more of the major arteries becoming so congested that the problem arises. Often this results in death due to cardiac arrest with little time left for the medical personnel to reach and reanimate the victim. One clear sign of atherosclerosis is achieved by examining the thickness of the arteries, because this is the initial stage of the process. This is why Medical Technologies International (MTI) Inc., of Palm Desert, California, has patented ArterioVision, a software package based on the VICAR software. After an ultrasound inspection of the carotid arteries, ArterioVision gives an accurate measurement of the thickness of the inner two layers, the intima and media.[6] By knowing the real condition of their artery network, patients can appreciate the need to change their lifestyle with dietary modification and exercise. This technology is now being used worldwide.

In designing its first spacecraft at the beginning of the Space Age, NASA realized that the onboard electronics would be subject to either soaring or freezing temperatures if they were maintained facing either towards or away from the Sun. Electronics does not perform well when subjected to extreme temperatures. One remedy is to rotate a spacecraft in order to even out its internal temperature. But if the mission objectives require holding a given attitude, the spacecraft will have to endure an

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[6] The selection of the carotid arteries for this test stems from the fact that they are the largest blood vessels closest to the skin surface and are therefore easy to examine without requiring an invasive procedure.

extreme variation in temperature between its Sun-facing and the space-facing sides. One option is to use heat pipes. In its most basic form a heat pipe is a sealed tube with an internal porous wick distributed along its length and a volatile liquid in thermodynamic equilibrium with its vapor. As heat is applied to one end of the pipe, the liquid evaporates and is displaced to the cold end, where it recondenses. At this point, the liquid withdraws into the wick to produce a pressure gradient that transfers the liquid back to the warm end. If one end is kept warm and the other is kept cold this process will operate for as long as there is sufficient liquid. It is an elegant way of carrying heat away without involving moving parts and without drawing electrical power. Heat pipe technology comes in a variety of shapes and sizes. It is merely one part of the larger set of systems for passive thermal control.

In 1970 Thermacore was founded in order to apply this technology outside of the space industry. One field that welcomed it was electrosurgery in which an electrical current is used to cut, coagulate, desiccate, or fulgurate a biological tissue. It greatly benefits the patient because of a more precise localized cut and reduced blood losses. A common apparatus is the bipolar forceps, a two-pronged tool that uses electricity to cauterize or ablate tissue between its tips. The connection with space exploration is not obvious, but bipolar forceps share the same heat management issue that face a spacecraft's electronics. The problem is that the electricity that generates the heat in the forceps can damage the surrounding tissue, sometimes causing it to stick to the heated tips. For example, in working on a person's brain you definitely want to burn away as little gray matter as possible. By exploiting their work for the space industry, Thermacore decided to embed extremely thin heat pipes into the bipolar forceps tips. The challenge was to provide sufficient heat transport capability within such a small volume and retain the ability to operate against gravity.

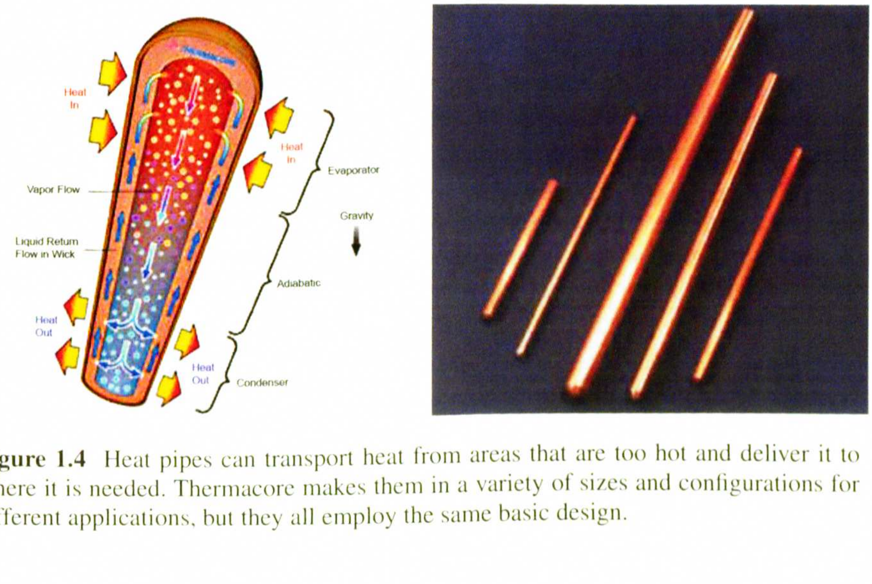

Figure 1.4 Heat pipes can transport heat from areas that are too hot and deliver it to where it is needed. Thermacore makes them in a variety of sizes and configurations for different applications, but they all employ the same basic design.

In addition to tools for brain surgery, Thermacore has improved robotic surgery systems which utilize lasers, PET-CT scanners, devices to ablate cancerous lesions, devices for DNA, blood analyzers, and many more applications.

A life-changing event can enable us to see things from a different perspective. It happened to NASA JPL engineer David Saucier, who suffered a heart attack in 1983 that resulted in a heart transplant the next year. He was lucky. Many people die while awaiting a suitable donor. Although Saucier and Dr. Michael DeBakery, the surgeon at Baylor College of Medicine that performed the transplant, worked in completely unrelated fields, they were both experts in fluid pumps. The former knew the inside-out workings of the propellant turbopump of the Space Shuttle Main Engine and the latter was an expert in the human heart that pumps blood around the body.

The two determined to combine their knowledge and develop a pump that would buy time for patients with congestive heart failure while a donor was sought. Saucier and DeBakery, along with others at their respective institutions, began working part-time. They developed a miniaturized battery-powered pump measuring 1 x 3 inches and weighing just 4 ounces. By assisting a critically ill patient's heart to pump blood until a heart became available for transplant, it forms a "bridge to transplant". There were already such Ventricular Assist Device (VAD) but they were cumbersome and weighed about 1 kg! The reduced size and weight of the NASA-designed VAD made it suitable for implantation into a patient's chest, even a child's. When it was realized that friction and pressure in the axial rotary impeller could damage the blood cells, it became necessary to optimize the pump. Help came from Cetin Kiris and Dochan Kwak at NASA's Advanced Supercomputing Division at the Ames Research Center in Moffett Field, California. Using the same computational fluid dynamic software that simulated the fluid flow through the Space Shuttle Main Engine's turbopumps, they were able to optimize the design of Saucier and DeBakery's VAD to eliminate its deficiencies and make it even better.

In 1996 NASA patented the device and granted exclusive production license to MicroMed Technology Inc., in Houston, Texas. Mr. Dallas Anderson funded further development of the NASA invention to treat critically ill heart patients. In November 1998, a 56-year-old male was the first person to receive the device. Since then, this MicroMed DeBakery VAD has been implanted into hundreds of patients around the world, helping to keep them alive while they await a heart transplant. In 2002, the *Spinoff* magazine regularly published by NASA reported, "because of the pump's small size, less than five per cent of the patients implanted developed device-related infections, compared to an approximate 25 per cent infection rate for larger VADs. Additionally, MicroMed's VAD can operate up to eight hours on batteries, giving patients the mobility to do normal, everyday activities."

SPACE EXPLORATION: WHAT IS IT GOOD FOR?

Having briefly elaborated a number of rationales, can we say that space exploration is worthwhile?

Satellite applications have become an indispensable part of modern life. If denied them, even briefly, we become frustrated. We might even panic! The possibility of fast communications has made possible and accelerated globalization, making the world a smaller place. In the not so distance future, even more services will be available thanks to projects to create large satellite constellations in low-altitude orbits which will beam internet services sufficient to allow even rural areas in developing countries to benefit. Environmental monitoring from space has a large influence on a country's economy, allowing its institutions to obtain a synoptic view of the condition of the landscape and resources and hence plan for the most optimal exploitation and organization. Certainly there is no need to emphasize the benefits generated by weather monitoring, or analysis of the climate in terms of the main drivers in the sea, land, and atmosphere. Likewise, satellite reconnaissance for intelligence gathering purposes has proved an effective tool for national security, not only in fighting wars but also addressing the threats of global terrorism.

We cannot deny that exploration is a human trait, seemingly specifically coded into our DNA, that has driven our civilizations and societies for millennia. And nor can we resist the lure of the frontier, whether that be a location to reach or an achievement to accomplish. Surpassing in complexity and magnificence is a pure human trait that has served us well through the ages. The need to feel proud of our achievement is again as old as human history. You can think about the Egyptian obelisks, or the Assyrian relief panels, or any other civilization that recorded their successful battles and conquests. In the 20th century, the United States of America celebrated its existence by sending men to walk on the Moon and return with rock samples.

While it is undeniable that societies and civilizations of any complexity throughout history have expanded their territory, the urge to explore was actually the prerogative of a small number of individuals. That is to say, we may all have the explorer gene but it is active in only in a few of us.

As a point in case, consider that even the mighty Apollo program did not enjoy an unconditional endorsement, despite the monumental media and PR machine favoring it. In October 1965 a Harrison poll asked: "If you had to choose, do you think it more important or less important to spend 4 billion a year on the space program than to spend it on reducing the national debt?" Some 54% selected the latter option. Four years later, on the eve of the first lunar landing, the percentage who favored redirecting funding to recover the national debt rose to 56.4%. Such results are not surprising if we consider that the political nature of the whole endeavor had not escaped the American public's attention. For instance, in October 1964, in response to a survey asking "Do you think the U.S. should go all out to beat the Russians in a manned-flight to the Moon, or don't you think this is too important?", 66% replied that beating the Russians was "not too important" and 8% did not know how to answer. Another survey several months later asked "Does it matter a lot to you that the Russians have been ahead of us in our space program?" and a majority of 54% of respondents said it did not matter at all.

The same goes for breaking frontiers of knowledge regarding the mysteries of the Universe. It is enthralling to see close-up pictures of Pluto or discover the origin of a gamma ray burst, but again such scientific curiosity does not belong to everybody. And in any case, not all scientifically inclined people will necessarily possess an interest in astronomy. What about finding signs of present or past extraterrestrial life? In January 2004, after the successful landings of the Spirit and Opportunity rovers on Mars, a poll carried out by Gallup for CNN and *USA Today* asked "Do you think it is worthwhile for the United States to find out whether there were ever living creatures on Mars, or not?" A narrow majority (54.4%) felt it was not worthwhile. While discovering life on Mars would be remarkable from an academic and perhaps philosophical point of view, investing large human and financial resources exclusively for this purpose seems too weak a justification for space exploration and merely an excuse to gratify the scientific community that harbors such an interest.

Although there are other examples, it is evident that the real "elephant in the room" is the failure to capture support from a large section of the general populace. You may including yourself among the skeptics. It is the case that the exploration of space is too far removed from the everyday reality of normal people who have to struggle to make ends meet in our increasingly unstable economic and working environments. Rises in inequality and the technological displacement of work make living difficult for normal people. As a result, the rationale for sending a few selected individuals into space does not earn much support. Indeed, it can create resentment for what appears to be a useless expenditure that could be better employed to enhance life on Earth. The argument to colonize space or the surface of a celestial body as an insurance policy has merit, but the chance of being hit by an asteroid large enough to risk the extinction of the human race is so remote as to be readily dismissed from our minds. Our brain is wired to react to situations that pose an immediate danger, not to circumstances that might gradually develop into one. As an example, consider how great civilizations such as the Romans, the Maya, the Khmer Empire, to name but a few, flourished over a long period of time and then suddenly collapsed. The signs of collapse manifested themselves slowly, and when the point of no-return was reached it was too late to recover.

Furthermore, the usual rationales advanced for spaceflight are always presented in the context of developed countries. The vast majority of humankind live in conditions affected by poverty, malnutrition, violence. Spaceflight is the least of their concerns! How crucial could it be to a mother seeking food for her children to know that space could help our species to survive extinction? It is too far detached from her immediate needs. The "hierarchy of needs" theory proposed by psychologist Abraham Maslow in his 1943 paper 'A Theory of Human Motivation' places physiological necessities and safety as the foundation for any other demand in life, such as self-actualization deriving from, for instance, exploration and discovery. This is applicable to anybody, regardless of their upbringing or their country's gross domestic product. So, is space exploration worth the effort?

A SPACE PROGRAM WORTH UNDERTAKING

I have been an advocate for space exploration for as long as I can remember. At first, it was unalloyed admiration for the extraordinary feats of the brave astronauts and the talented engineers at prestigious national institutions, but then I began to wonder about the justification for space exploration. For sure, the motivations presented above have enabled six decades of continued accomplishments in the space arena, and continue to drive us in that direction. This is especially the case for satellite applications, national security intelligence, surveying the cosmos and visiting the bodies of our Solar System. But I believe we can do much more. In particular, we can convert space from being a mere destination to satisfy mere scientific curiosity, into a resource to facilitate human activities undertaken for the benefit of Earth, the only home we currently have that is capable of sustaining a biosphere and thereby our species.

In his *The High Frontier*, Gerard K. O'Neill wrote: "In my opinion, the long-term goals we should set relevant to space habitability should only be those with which nearly every rational human being, possessed of good will towards others, could agree. I think that the following goals satisfy that criterion and that they should be our most important goals not only for humanitarian reasons, but for our own self-interest.

1. Ending hunger and poverty for all human beings.
2. Finding high-quality living space for a world population.
3. Achieving population control without war, famine, dictatorship or coercion.
4. Increasing individual freedom and the range of options available to every human being."

He also made a case for "unlimited low-cost energy available to everyone" and "unlimited new materials sources, available without stealing or killing or polluting". Although this sounds like science fiction dreaming, it is my desire throughout the next chapters to demonstrate that a properly organized space program can transform, in part, such beliefs into reality, and furthermore that doing so is not beyond our present-day technological capabilities.

A great many problems affect our modern way of living, and our environment, on scales ranging from local to global. One goes under the name of Ecological Footprint. Developed by Mathis Wackernagel and William Rees at the University of British Columbia, Canada, in 1990, this is intended to compare actual human consumption of renewable resources and ecological services against nature's supply of such resources and services. It measures how fast we are consuming the resources of nature and are dumping waste relative to how fast nature can generate new resources and absorb our waste. In this sense, Ecological Footprint is an accounting system of our demands for natural resources versus what nature can effectively supply and produce (also known as biocapacity). More specifically, biocapacity is defined as a measure of the existing biologically productive area which is capable of regenerating natural resources in the form of food, fiber and timber, and of providing carbon sequestration. It is measured in relation to five categories of use, namely: cropland, grazing land, fishing grounds, forest land, and built-up land.

Both biocapacity and Ecological Footprint are expressed in a productivity-adjusted hectare-equivalent unit called a global hectare (gha). One gha represents a biologically productive hectare with world-average productivity. Conversion from actual land areas to global hectares is by means of country-specific yield factors and equivalence factors. This normalizes highly productive areas such as tropical forests and low productivity areas such as alpine deserts.

In layman's terms, you can also envisage Ecological Footprint as an indicator for a minimum condition of sustainability for our civilization and whether our consumption is sustainable by the biological threshold defined by the planet's biocapacity. For this reason, Ecological Footprint is widely applied in the monitoring of ecological resource use and degree of sustainable development. An insightful additional parameter is Earth Overshoot Day, which is the date in a given year when humanity's annual demand on nature exceeds what the ecosystems can regenerate in that year. For instance, in 2019, Earth Overshoot Day was July 29th. Rather alarmingly, this date is arriving earlier year by year.

Simply put, humans are consuming more than the Earth's ecosystem can tolerate. We are effectively borrowing biocapacity income production from future generations. This draining of Earth's savings account can continue only until the reserves are gone. According to calculations, as of 2019, humankind is currently using nature 1.75 times faster than the ecosystem can tolerate. It takes the biosphere one year and eight months to regenerate what we deplete in a year. To express this another way, we would require at least 1.75 Earths to maintain our present-day consumption and waste disposal.

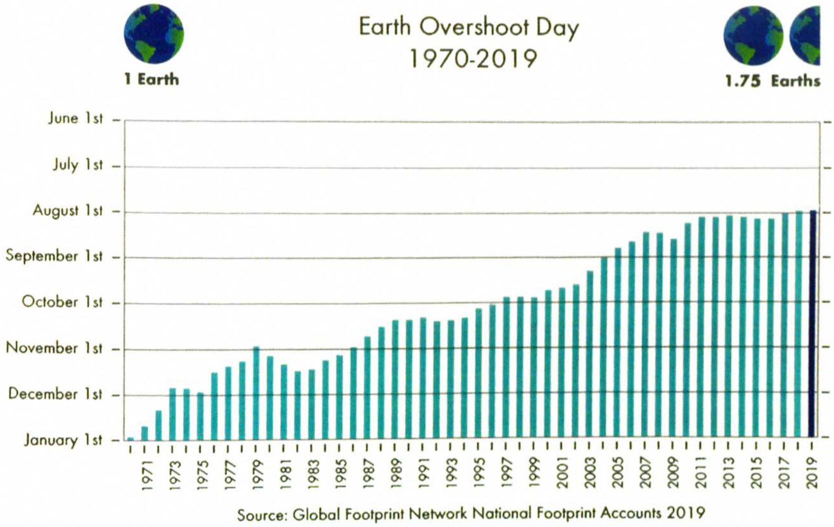

Figure 1.5 A plot of Earth Overshoot Day for the last 50 years. The few visible dips do not correspond to years in which intentional policies were activated to limit our impact on nature, they coincide with years of major economic crises, such as the 1973 oil crisis, the deep economic recession in the USA and many of the OECD countries during 1980-1982, and the global economic recession of 2008-2009.

It is not surprising that geoscientists and biologists argue that we have transitioned into a new geological epoch named the Anthropocene. This is because anthropogenic activities have profoundly changed every aspect of the environment, including loss of biodiversity, ocean acidification, soil erosion, deforestation, and other signs of climate change. It is the case that planetary modifications to the environment and climate have occurred throughout our planet's history, but they have never been concentrated in the human timescale. Instead of occurring slowly over millennia, if not millions of years, they are manifesting within decades as a result of the pressure imposed by one single species, namely humankind!

There are several drivers for these dramatic changes. One is the growing demand for mineral resources to feed the material-hungry manufacturing industries that satisfy our daily needs and wishes. Simply put, mining resources is akin to an invasive surgical procedure that leaves deep scars that are difficult to fully heal. Resource mining entails moving humungous amounts of soil, and makes use of heavily polluting chemicals and physical processes in separating the precious resource from the waste material. Mining areas are usually peppered with large pools of contaminated water awaiting treatment (if that is feasible, at all) and dumps of remaining residues. The landscape around any significant mining activity is profoundly changed, and not for the better. Similarly, the manufacturing industry that turns raw materials into goods and commodities invariably pollutes its surrounding environment. To borrow from acclaimed science fiction writer Robert A. Heinlein, the second law of thermodynamics is a harsh mistress. Matter and energy cannot be created, only transformed, and the process incorporates losses in the form of heat, incomplete reactions, waste, and so on. The environment, water, land and air accommodate the curse of the second law of thermodynamics. Collectively, such energy and material losses are labeled pollution. Earth's ecosystem is able to assimilate pollution. Every living organism and biological process contaminates its surroundings to some extent. And as the saying goes, one's trash is somebody else's treasure. Nature is smart, and its many forms of life are symbiotic, feeding on each other's wastes. For instance, animal poo is manipulated by the microorganisms that render soil fertile and allow fresh and nutritious vegetation to grow for herbivorous animals. One of the most essential wastes that nature produces is oxygen, emitted by the photosynthesis process of plants. Oxygen is vital to all animals having aerobic respiratory apparatus, including ourselves. Furthermore, the carbon dioxide that animals exhale from their lungs is the sustenance that plants require. In nature, things work in cycles of give and take, and an equilibrium state sustains the biosphere overall. The difficulty arises when something goes haywire.

The problem with human-induced pollution is that the amounts and rates of waste production and discharge have far surpassed the capability of the biosphere to absorb, neutralize, disassemble, and transform what we are throwing at it. This predicament is further complicated by the production of elaborate substances that nature would never have made on its own, such as plastics and mixtures of rare and heavy metal elements such as are used in electronic devices.

Earth's biosphere acts as a self-regulating organism that seeks to defend itself. This is the Gaia hypothesis postulated by British scientist James Lovelock in the late 1960s. At the dawn of the Space Age, he was a member of a team at NASA JPL investigating possible experiments to determine whether planets like Venus and Mars could harbor life. Lovelock reasoned that any prospective extraterrestrial planetary biosphere would require a fluid medium, water or air, or both, for the transport of nutrients and discharge of waste. As a consequence, the fluid medium would display a compositional mixture strikingly out of chemical equilibrium. As a matter of fact, this is the case for Earth's atmosphere. Take, for instance, the simultaneous presence of oxygen and methane. In the presence of sunlight, these two gases would react chemically and turn into carbon dioxide and water vapor. Methane should be almost entirely depleted within decades. Yet its concentration in the atmosphere is constant and, as analysis of ice core samples reveals, it has been present for millions of years. Even more captivating is the fact that to preserve this state, around 500 million tons of methane must be being released into the atmosphere annually. And because methane reacts with oxygen, there must also be a replenishment of the oxygen that is lost in the conversion of methane. The same goes for nitrogen, which forms some 78% of the atmosphere. As oceans cover 70% of the planet's surface, chemistry dictates that nitrogen should exist mostly in the stable form of the nitrate ion dissolved in sea water. Yet it is mostly present in the gaseous state in the atmosphere. In his book *Gaia: A New Look at Life on Earth*, Lovelock wrote: "Our results convinced us that the only feasible explanation of Earth's highly improbable atmosphere was that it was being manipulated on a day-to-day basis from the surface and that the manipulator was life itself. The significant decrease in entropy – or, as a chemist would put it, the persistent state of disequilibrium among the atmospheric gases – was on its own clear proof of life's activity."

Life therefore dynamically regulates Earth's atmospheric composition into a steady state. Furthermore, life acts to ensure the planet continues to offer an environment that favors its preservation and flourishment. For instance, the atmospheric mixture of 78% nitrogen and 21% oxygen prevents an outbreak of fire from rapidly spreading across the entire planet. With just a little bit less nitrogen or a little bit more oxygen, even a campfire would pose a severe risk! Any less oxygen, and most of the biosphere would rapidly suffocate, creating a mostly barren world. Thermoregulation is another feature of the biosphere. Our parent star has increased its output by at least 25% since the dawn of life around 3.5 billion years ago. Yet, ice core samples prove that the temperature of the planet has remained relatively constant throughout that time at a level favorable for life. This is potent evidence of how life regulates Earth's climate on a global scale, to establish and maintain conditions for its own survival. Since Lovelock's first peer-reviewed paper on the subject in 1968,[7] the Gaia hypothesis has attracted ever more attention and has been developed into an even more comprehensive framework that defines Gaia as "a superorganism composed of all life tightly coupled with the air, the ocean, and the surface rocks".[8]

In his book *The Vanishing Face of Gaia*, Lovelock says, "The disastrous mistake of 20th-century science was to assume that all we need to know about the climate can come from modelling the physics and chemistry of the air in ever more powerful computers, and then assuming that the biosphere merely responds passively to change instead of realizing it was in the driving seat ... Real observations and measurements falsify the 21st-century view of the Earth as a passive resource. ... The natural world outside our farms and cities is not there as

[7]The paper 'Planetary Atmosphere: Compositional and other changes associated with the presence of Life' was published in the Proceeding of the American Astronautical Society in 1968.

[8]As Mars and Venus lack any surface liquid body of water, the only medium any potential life can exploit for raw material transport and waste disposal is the atmosphere. Extensive surveys of both planet's atmosphere have shown that their composition are near chemical equilibrium. Consequently, based on the Gaia hypothesis, neither planet bears life.

decoration but serves to regulate the chemistry and climate of the Earth, and the ecosystems are the organs of Gaia that enable her to maintain our planet habitable." Despite our invasive way of living, "Gaia has long been resisting our interventions through negative feedback; opposing the way we change the air with greenhouse gases and take away its natural forest cover for farmland."

In the new age of the Anthropocene, this self-regulating mechanism, which also provides a comfortable environment for the human species, has come under serious threat. However, and perhaps unexpectedly, Gaia will always be the winner. As Lovelock continues, "It is often wrongly assumed that life has simply adapted to the material environment, whatever it was at that time; in reality life is much more enterprising. When confronted with an unfavorable environment it can adapt, but if that is not sufficient to achieve stability it can also change the environment. We are doing this now … and the Earth system seems to be giving up its struggle and is preparing to flee to a safer place, a hot state with a stable climate … A look at the Earth's climate history tell us that in such hot states Gaia can still self-regulate and survive with a diminished biosphere … This is how Gaia keeps an habitable planet: species that improve habitability flourish, and those that foul the environment are set back or go extinct." Humans are in the latter group.

And we are certainly aware of it, given that in recent years we have been witnessing a growing number of "green" activist movements that place emphasis on sustainability and caring for the environment in any infrastructure project, be that small or large. As noted earlier, access to and manipulation of resources are among the activities that are primarily responsible for the mistreatment of Gaia and the imperilment of our own survival. There are many suggestions for how we might reverse this trend, or mitigate the issue.

One reasonable approach would be to acquire resources and transform them into commodities in a place where the concept of environmental pollution simply does not apply. Could such a setting exist? If we want to attempt to mitigate our harm to Earth's biosphere, the only reasonable location where resource extraction and manufacturing of goods could take place would be in a territory that is lifeless.

Space is such a domain. As far as we are aware, nothing lives in space. In fact, just about any physical property of space is inimical to life in the absence of extraordinary precautions by means of sophisticated technology. The idea of exploiting the resources of space and of producing goods in orbit is not new. Even before Apollo 11 landed on the Moon, NASA and many visionary engineers were proposing a space program that would just do that. In the 1970s and 1980s several notable studies were undertaken to investigate such possibilities; reports were published, conferences were held, and timid experiments of on-orbit manufacturing undertaken. But no serious consideration was ever given to the possibility that space might not only be a venue for discovery but also a useful resource for the betterment of Earth and Gaia.

The time has now come to revisit this idea, particularly now that we have come to realize the damage we have already inflicted on our planet. I firmly believe that space-related activities can, and should, be part of the list of solutions we are implementing to preserve and repair the environment. Space-related activities cannot, and should not, be merely the way that a country parades its technological prowess or achieves military supremacy, or even how it satisfies its thirst for pure knowledge.

Recalling what O'Neill wrote, space-related activities must satisfy humanitarian needs such as "finding high-quality living space for a world population" and providing "unlimited new material sources, available without stealing or killing or polluting". A clean environment, or to put it another way a biosphere that is not burdened beyond its regenerative capabilities, would undoubtedly assist in providing a high-quality living space. Jeff Bezos, Amazon's CEO, is a strong advocate for exploiting the resources of space and transferring heavy manufacturing industries into space. He too is a follower of O'Neill's vision. As often happens, visionaries are regarded as oddities who should not be taken too seriously. We live in a fast-paced word that seeks instant gratification. This has made us almost incapable of following a long-term plan that might not come into fruition until after we are long gone. But if we want to preserve the magnificence of our planet's biosphere and live in harmony with its countless ecosystems, we should implement as many options as possible, one of which is space resource mining and the establishment of in-space manufacturing industries to augment (and later replace) their terrestrial counterparts.

This is the theme that we will develop throughout the next chapters. Rest assured that it is not my intention to offer such space-related activities as a panacea to solve all our environmental crises. The problem is sufficiently multifaceted to require a diverse mix of solutions. But I am convinced that space-related activities have the potential to be a significant part of a blend of solutions, each targeted towards one or more specific issues. Chapter by chapter, we will see how this capability can first be expressed, then transformed into reality.

Chapter 2 will focus on the resources that space has to offer, and summarize what decades of observations and sample analyses have told us about the compositions of the Moon and asteroids.

In Chapters 3 and 4 we will explore methods suggested for mining and processing such resources, to transform them to feedstock materials suitable for the manufacturing of highly valuable products in space. Although resource mining is a practice almost as old as humankind, we will appreciate how the environment of space and extraterrestrial surfaces can either hinder or promote the extraction and processing of raw materials.

Chapters 5 and 6 will show us how manufacturing can be undertaken both in orbital space and on celestial bodies. As stated earlier, industrial production is another crucial player in the alteration of the planetary biosphere. Space-based manufacturing can ease some of the stress that we have been placing on the terrestrial environment.

Chapter 7 will look at several technologies that are already available to us or are in development that can help us to jump-start a space-based manufacturing infrastructure capable of partially replacing what we have on Earth.

In Chapter 8 we will wrap up by highlighting how it is not beyond our capabilities to implement a space program that can deliver genuine benefits to humankind, and will consider some additional rewards that might accrue from space-based manufacturing.

Let us build a space program worth undertaking!

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IMAGE LINKS

Figure 1.1: The International Space Station. Operating an Outpost in the New Frontier. (2018). NASA, p.19.

Figure 1.2: https://mars.nasa.gov/resources/3650/curiositys-sky-crane-maneuver-artists-concept/

Figure 1.3: https://settlement.arc.nasa.gov/teacher/70sArt/art.html

Figure 1.4: NASA Spinoff 2017. (2018). [pdf] NASA. Available at: https://spinoff.nasa.gov/Spinoff2017/index.html [Accessed 24 Jul. 2019].

Figure 1.5: https://www.overshootday.org/newsroom/past-earth-overshoot-days/

2

Extraterrestrial Resources and Where to Find Them

RESOURCES: EARTH VERSUS SPACE

"Resource" is a term widely applied to a variety of fields ranging from business to economics to geology. Before we explore the materials available in the Solar System, we had best clarify what we mean by "resource" in this context.

First, we have to recall what a mineral is. A simple definition is that a mineral is a compound of one or more chemical elements, usually in a crystalline structure, and is the result of natural unanimated processes rather than ones that are related to life. Some 3,000 minerals have been identified dispersed throughout Earth's crust. But there are regions in which the concentration of one or more minerals is increased by several orders of magnitude relative to the average, and for which geological surveys have ascertained a potential economic benefit that might derive from the extraction and exploitation of such mineral(s). These areas are defined as *mineral reserves or mineral resources*. However, often not all of a mineral resource is up for mining, as the conditions of the region might be too challenging or costly to permit profitable extraction. Aspects to consider are the available extraction technology, the logistics infrastructure required to deliver resource to a processing plant, market demand for that particular resource, environmental concerns arising from disturbing the area that is to be mined, and government control. Those sectors of a mineral reserve for which a mining company can initiate a profitable extraction operation are defined as *ores* or *ore reserves*.[1] Hence an ore is a subset of a mineral resource. As the demonstrated economic profit is a cardinal parameter that regulates the establishment of an ore reserve, it

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[1] For certain reserve types other terms have been adopted such as "seams" for coal and "wells" for crude oil.

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