Nature's Way of Making Audacious Space Projects Viable

Building a starship within the next 100 years is an audacious goal. To be successful, we need sustained funding that may be difficult to maintain in the face of economic challenges that are poised to arise during these next 100 years. Our species' civilization has only recently reached the classification as (approximately) Type-I on the Kardashev scale; that is, we have spread out from one small locality to become a global species mastering the energy and resources of an entire planet. In the process we discovered the profound truth that the two-dimensional surface of our world is not flat, but has positive curvature and is closed so that its area and resources are finite. It should come as no surprise to a Type-I civilization when its planet's resources dwindle; how could they not? Yet we have gone year by year, government by government, making little investment for the time when civilization becomes violent in the unwelcome contractions that must follow, when we are forced too late into the inevitable choice: to remain and diminish on an unhappy world; or to expand into the only dimension remaining—perpendicularly outward from the surface into space. Then some day we may become a Type-II civilization, mastering the resources of an entire solar system. Our species cannot continue as we have on this planet for another 100 years. Doubtless it falls on us today, the very time we intended to start building a starship, to make the late choice. We wished this century to be filled with enlightenment and adventure; it could be an age of desperation and war. What a time to begin an audacious project in space! How will we maintain consistent funding for the next 100 years? Fortunately, saving a civilization, mastering a solar system, and doing other great things like building starships amount to mostly the same set of tasks. Recognizing what we must be about during the next 100 years will make it possible to do them all.

1.0 Economic Challenges to Building a Starship

Now is a particularly challenging time to begin audacious space projects. Our economic plan must address the fact that all the non-renewable energy sources dominating our modern economy, and many minerals and metals, will become inadequate during this 100 year timeframe. Population growth will continue. Industrialization of China, India, and the Third World will put extraordinary pressure on the global economy by requiring an increasing share of the remaining resources. Water shortages, pollution and climate change will continue as serious geopolitical concerns. Science and engineering projects, including the 100 Year Starship, will compete for mankind's attention in what may be a very difficult century.

1.1 Non-Renewable Energy

The worldwide rate of discovery of new petroleum fields peaked as far back as the 1960's and despite modern technology and a tremendous profit motivation the rate of oil discovery is now only a tiny fraction of what it once was. Hubbert's model of oil production predicts that the world's oil fields reached their peak production rate in the 2006 to 2008 timeframe, and ever more rapid declines in oil availability will follow. With 800,000 oil wells worldwide in decline, it would take on the order 400,000 or so new wells to make up for it, and that is not possible. Production of coal is likewise predicted to peak in 2035 (*Coal…*, 2007). The peak production rate of natural gas is expected between 2020 and 2030 (Bently, 2002; USEIA, 2009). Uranium ore production already peaked in 1980 to 1981 (Vance, 2006; Meacher, 2006). The peaks for these non-renewable fuels are summarized in Table 1.

Table 1: Peak Production of Non-renewable Fuels

Energy Fuel	**Peak Date**
Uranium	1989
Oil	2006-2008
Natural Gas	2020-2030
Coal	~2035

A barrel of oil provides 6.1 GJ of energy. Giampietro and Pimentel (1993) estimate that human power output during agriculture is 0.1 horsepower, or 74 W. The US uses about 19,148,000 barrels of oil per day [USEIA, 2009]. For a US population of 307 million, this means that oil-powered machinery did the work of 250 machine "slaves" per citizen in producing goods and services. The total US energy usage from all sources is about 10^{20} Joules [USEIA, 2010]. (Renewable energy constitutes only 8.2% of that total.) The total number of US workers is about 154 million including unemployed. If each worked as hard as an agricultural worker, which they do not, they would expend 8.5×10^{16} J annually. The fraction of the energy expended by machines in producing goods and services is therefore >99.9%. Human muscles contribute <0.1%. Human labor is an insignificant contributor to the modern economy, apart from the fact that we are inventing, and (for now) guiding the machines.

Every dollar spent on a consumer product like cup of coffee represents the energy that produced, transported, marketed and sold it, including the prorated share of energy spent in building the factories and trucks and other capital in the vast network of contributing costs. Counting total energy this way is particularly enlightening when we assess the value of nuclear energy, which is coming back into political vogue as an alternative to carbon emissions and diminishing oil reserves. Infrastructure and operational costs for nuclear energy are quite high (Sovocol and Cooper, 2008). According to Jan Willem Storm van Leeuwen (2006), the processing costs of uranium ore is increasing as higher grade ores are depleted, and thus the net energy produced from uranium will begin to decline by 2056 until finally no *net* energy can be obtained from nuclear power by 2070. It is even worse if we consider building *more* nuclear power plants to replace coal or natural-gas fired power plants for environmental reasons or to replace diminishing fossil fuels. As David Fleming explains:

> It takes a lot of fossil energy to mine uranium, and then to extract and prepare the right isotope for use in a nuclear reactor. It takes even more fossil energy to build the reactor, and, when its life is over, to decommission it and look after its radioactive waste. As a result, with current technology, there is only a limited amount of uranium ore in the world that is rich enough to allow more energy to be produced by the whole nuclear process than the process itself consumes. This amount of ore might be enough to supply the world's total current electricity demand for about six years. (Fleming, 2006)

Other non-renewable energy sources such as tar sands and shale oil are probably necessary to minimize economic turmoil during the next 100 years, but they are more polluting and expensive to produce than petroleum and thus do not provide as much net energy to the economy without scaling up the operations significantly, and there are hidden energy costs in the infrastructure for these sources as well.

1.2 Renewable Energy

Renewable energy sources like wind and solar require significant changes in global infrastructure: the installation of sufficient solar cells and wind farms, and the installation of energy storage systems for night and periods lacking adequate wind. Solar cells deployed at private residences take about 20 years to repay the financial investment. That means that all the energy used in manufacturing and installing them is 20 times more than they produce in a year. Extrapolating this to the global scale, manufacturing and installing enough solar cells to supply the world's entire energy needs will therefore expend the energy of 20 years worth of the entire global economy. If we spread the installation of solar cells over 40 years, that would require us to increase the world's annual energy expenditure by 50% during that period, which is not possible. Attempting it will exacerbate the economic problems in the short-term and produce no net energy for about 40 years[1], long after the non-renewable energy sources are unable to support a robust economy. This might be mitigated by economies of scale. However, Earth-bound solar collects energy only in the daytime, reduced by the cosine of the sun's angle off zenith and the variability of weather. For this reason, solar cannot serve as baseload capacity for a power grid unless we build energy *storage* on a sufficiently large scale, which is not economically viable using existing technology. The infrastructure cost for the massive power storage capability would not be paid back for many decades longer than the cost of the solar cells alone, and thus solar cannot provide any net energy into the overall economy for a very, very long time. Wind has similar challenges but also suffers from geographical limitations: only certain parts of the country have enough wind to pay back the infrastructure costs and thus actually produce a net flux of energy into the economy. The possibility of maintaining the vitality of our economy via renewable energy during the next 100 years looks bleak. There is no shortage of energy in the Earth, just a shortage of economically viable energy. We have already waited too late to begin addressing this.

1.3 Minerals and Metals

It is not just cheap energy that is running short during the 100 years of the starship project. A recent review has identified 11 minerals that are already "post peak" (Bardi and Pagani, 2007), meaning that the majority of easily mined ore bodies has already been exploited, leaving only the lower grade ore bodies that take longer and cost more money/energy to produce, so that the availability of these minerals to industry is declining. Furthermore, fitting copper production rates to the Hubbert resource model predicts that it may peak by 2040. Other metals may be facing similar economic depletion. This is summarized in Table 2.

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[1] By this (simplistic) estimation, installing globally adequate solar cells over 20 years would double the world's energy usage during that period and begin providing net energy after 30 years. Installing them over 100 years would increase global energy usage by 20% during that period and begin providing net energy after 60 years, if the cells last that long.

Table 2: Dates of Peak Production Rate for 12 minerals

Mineral	**Peak Date**
Mercury	1962
Tellurium	1984
Lead	1986
Cadmium	1989
Potash	1989
Phosphate Rock	1989
Thallium	1995
Selenium	1994
Zirconium	1994
Rhenium	1998
Gallium	2002
Copper	~2040

1.4 Demand Growth

Economic expansion can cause demand for a non-renewable resource that outpaces the geologically-limited supply rate even before the resource has gone post-peak. China and India are in the process of rapidly industrializing. This is rapidly accelerating the economic stresses that work against audacious space projects. The International Energy Agency's *2010 World Energy Outlook* states,

> It is hard to overstate the growing importance of China in global energy markets. Our preliminary data suggest that China overtook the United States in 2009 to become the world's largest energy user. Strikingly, Chinese energy was only half that of the United States in 2000. The increase in China's energy consumption between 2000 and 2008 was more than four times greater than in the previous decade. Prospects for further growth remain strong, given that China's per-capita consumption level remains low, at only one-third of the OECD [Organisation for Economic Co-operation and Development] average, and that it is the most populous nation on the planet, with more than 1.3 billion people. Consequently, the global energy projections in this *Outlook* remain highly sensitive to the underlying assumptions for the key variables that drive energy demand in China, including prospects for economic growth, changes in economic structure, developments in energy and environmental policies, and the rate of urbanisation. The country's growing need to import fossil fuels to meet its rising domestic demand will have an increasingly large impact on international markets.

1.5 Economic Assessment

Until recently, economists have underrepresented the role of machine labor and its energy sources in their economic models. According to the 1946 economic growth model by Harrod and Domar, economic output is the result of human labor, which is enabled by "capital" (which includes the machines); growth is the result of increasing the *human* labor supply along with capital investment. The neo-classical Solow-Swan model of 1956 adds another term to the Harrod-Domar model to account for the increasing efficiency of human labor via technological progress (which again includes the machines). The role of energy powering machines is hidden behind human labor in both of these models. Neither model allows that growth could continue after eliminating human labor, i.e., that the machines could continue laboring without humans. Furthermore, neither allows that the machines could burn through the limited supply of non-renewable resources and be forced to reduce their output. Neither has been that accurate in predicting economic growth, either. Ayres and Warr (2009) recently addressed this with an economic model in which energy usage rather than human labor is the primary predictor of an economy's output. Ayres has stated,

> According to the standard theory, energy is an intermediate good that can be 'produced' by some combination of capital investment and labour (plus technology). This means that economic growth is essentially independent of energy use, which suggests – in turn – that growth can continue indefinitely at historical rates. And when people talk about [economic] recovery, implicitly that's what they're saying – that right now the world economy has a hiccup or is perhaps suffering from a case of the swine flu, and that we can expect to get back sooner or later to a trajectory of growth that's based on the last 100 years. But if we're right – and I think there's much more than a small chance that we are – you can't make that assumption. It's a very dangerous assumption and it's leading to potentially very risky advice to political leaders. (Ayres, 2009)

Their energy-based model indicates that the economic downturn of 2008 resulted from the inability of petroleum exporting nations to further increase their oil production rates as oil had recently gone "post-peak" in the 2006 to 2008 timeframe. Therefore, Ayres says, a recovery might not be forthcoming. It is significant that the International Monetary Fund recently utilized this new Ayres-Warr economic model for one of three scenarios its April 2011 *World Economic Outlook*. The resulting prediction is that a significant drop in global GDP will occur during the next 20 years due to the reduction in the availability of oil.

The limitations of non-renewable energy and other resources, continuing population growth, and the spread of industrialization, are already affecting global economics and geopolitics. Extrapolating these trends over 100 years indicates very difficult times ahead. If we cannot find a way to radically change this scenario, economic stresses will result in diminishing GDP, fewer goods and services for consumers, unsatisfied consumer expectations, disruptive economic transitions, and unequal sharing of economic woes among all segments of the population, translating into severe pressure at the ballot box, and ultimately a loss of political will to "shoot resources off into space." Fortunately, there is a way to change the game, and the 100 Year Starship can play an integral role in meeting global needs as it synergistically develops its own technologies and meets its own requirements. This will provide the public with a motive to support audacious projects in space, rather than a motive to cancel them.

2.0 Thinking outside the Globe

Despite everything written above, humanity is not really facing a shortage of energy, metals, minerals, fresh water, hydrocarbons, or anything else. We live in a solar system that contains literally billions of times more of every resource than contained on the Earth

2.1 Distribution of the Resources

There is a simple story that explains the distribution of resources throughout the solar system. Because this explanation is based on repeatable physical law, we should expect that any habitable solar system in the universe would tell a similar story, including those solar systems our starship may visit. It therefore provides a "universal strategy" for any sentient race to adopt. We should adopt it here, and when a starship reaches another star, our space travelers can adopt it there.

When the sun formed from its nebula, solar pressure drove lighter elements outward while heavier elements like metals and silicon accreted closer to the sun, forming dust, then planetesimals, and finally planetoids and planets. Thus, the terrestrial or rocky planets are found in the inner solar system while the gas giants and icy bodies are further out beyond the "frost line." The gas giant closest to the sun naturally obtained the largest share of these volatiles, and thus Jupiter is both the largest and the nearest gas giant to the sun. As the terrestrial planets formed, radioactive elements heated their bulk volume while thermal radiation carried the heat away from their surfaces. Because the heat-generating volume increases by diameter-cubed, but the heat-shedding surface area increases only by its diameter-squared, the temperature on that surface has to become hotter as the diameter gets larger. Thus, there exists a diameter at which the planetoid or planet melts. The heavier elements then sink while the lighter elements float forming a core, mantle and crust in a process known as *differentiation*. Only if some heavier elements were chemically attracted to lighter ones did they manage to stay in the crust during differentiation. Thus, in the terrestrial planets, essentially all of the heavy metals like iron were lost thousands of miles below the surface to the core and are now inaccessible as a resource for the economies of technological civilizations. Therefore, the inner planets are great locations to find lighter minerals containing aluminum, silica, and potassium, but not a good place to find heavier ore bodies containing gold, iron, or lead.

Lighter molecules like water are also scarce in the inner solar system since they had been swept to the outer solar system during accretion. Now that accretion is finished, the planets' localizations of gravity and shadowing can retain volatiles. Icy bodies from the outer solar system subsequently brought water back into the inner solar system resulting in isolated quantities in Earth's oceans, beneath the frozen regolith and in the polar caps of Mars, and in the shadowed polar craters of Mercury and the Moon. The volatile reservoirs on the Moon have been found to contain as much CO and CO_2 as water (so the making of hydrocarbons including plastics and rubbers is now possible on the Moon).

The terrestrial planets' crusts have likewise been enriched after differentiation by the impact of metal-bearing asteroids. During the chaotic period that larger bodies were still accreting, some planetoids had already undergone differentiation and then collided with one another, breaking apart. These fragments accreted into larger bodies again and underwent differentiation a second time, or a third time, and so on, until most of the material in each orbital band was included in one large planet and further large collisions became rare. However, just inside the frost line when those planetesimals broke apart, the gravitational influence of nearby Jupiter stirred them up and prevented their re-coalescing, spreading them into the Main Asteroid Belt, which necessarily exists just inside the frost line because the largest gas giant exists just outside it. Because many of the planetesimals that formed the Main Belt had already undergone differentiation prior to breaking apart, the asteroids now include many that are made entirely of pure metal, and many that are composed of very high-grade metal ore. Thus, the metallic content of an entire planetary core lies exposed and accessible in the asteroid belt. An asteroid belt is the primary location for metals in a solar system.

The gas giants and their moons, and the trans-Neptunian objects in the Kuiper Belt and Oort Cloud, are the main location of our solar system's volatiles, including hydrogen, ammonia, methane, and water. Recently, however, it has been discovered that the frost line is not such a sharp boundary as previously believed, and vast quantities of water are probably contained in many asteroids, too. The largest asteroid, the dwarf planet Ceres, is believed to have a water mantle that contains a million times more water than all of the Earth. There may be water accessible at or near the surface of its crust. Water is easily accessible on the moons of the outer solar system. The Galilean moons (Jupiter's four largest) together contain one billion times more water than Earth. Other volatiles are in equally large abundance; Charon (the larger moon of Pluto) for example is probably composed of methane and ammonia.

In the movies, the aliens and machines always want to conquer the Earth for its resources. In reality, we do not need to fear the Matrix or the Terminator, because the intelligent machines will immediately bid us a fond farewell and escape to space where the resources are. If malevolent space aliens ever visit, they will take over the asteroid belt, not the Earth. Because we have such poor imaginations, most people think that expanding our civilization into the solar system right now is a crazy idea. That is because we have not noticed that we already have an economy dominated 99.9% by machines doing the work in place of the humans. With only slightly greater autonomy to overcome the communications time delay, the machines could also do the harvesting of these vast space resources to save civilization on Earth, and they could simultaneously prepare habitats in space where we could do research and eventually live, as well as build the audacious spacecraft so we can travel to other stars.

2.2 Making Solar System Resources Accessible

The primary barriers to using space resources are the launch and landing costs of Earth's deep gravity well and the vast distances and travel times involved in getting to the resources and bringing them back. During that time in space, human travelers would be subjected to cosmic radiation that causes cancer, weightlessness that leads to bone and muscle loss, and tremendous boredom. Once at the site of the resource, we would in most cases still be in low gravity, where it is very difficult for a human to walk. Also, the cost of sending humans across such distances while sustaining their biology is tremendously high. All these problems are solved by using machines instead of humans to do the resource extraction and space manufacturing.

As for the launch and operational costs of this space machinery, it can be brought to zero, eventually, and we can expect it to be quite low in the near-term. The key is that, if machines can make things in space, then they can start out by making more of themselves. They will get their materials and energy from their own environment. This network of self-supporting and self-reproducing machines will therefore become the equivalent of a life form, or an entire ecosphere of interconnected life forms, specifically adapted to the environment of the solar system. This infrastructure in space will then continue expanding and providing increasing benefits back to Earth. With resources in space billions of times greater than on Earth, this *robotosphere* can expand its production capacity to millions of times greater than the industry of Earth in just a short amount of time. Currently, the US uses 10^{20} J of energy annually from all sources. If the robotosphere begins on the Moon with one set of machines operating at 1000 horsepower (740 kW), expending 2.3×10^{13} J energy annually (which it will collect by making solar cells from lunar regolith), then by doubling its own capacity yearly for 43 years it will have the capacity to produce one million times more goods and services annually than the entire US economy. After 53 years it would exceed the US economy by a factor of one billion, and having achieved a Kardashev Type-II civilization we would need to start thinking about conservation of solar system resources. However, there would be no need to expand so rapidly.

The process of robotically colonizing or *robolonizing* the solar system is analogous to what life did on the continental land masses of Earth: bacteria colonized the land first and over deep time converted minerals from the regolith plus carbon from the air into topsoil; plants then colonized the same land and converted the topsoil plus sunlight into vegetation; animals then colonized it and converted the vegetation into flesh and bone; humans then colonized it and converted what we found into civilization. Contrary to the popular slogan, human explorers *didn't* live off the land – we lived off the food chain, and only the lowest parts of that food chain lived off the land. There is no food chain in space. The correct sequence is that the robots colonize space first by living off the land, and then humans will come next and live off the robotosphere.

At first, Earth will provide the space robotics with the parts that cannot be made easily in space, like computer chips. As space industry expands, Earth will provide a decreasing share of the further investment and operational costs. As we proceed, we will seek a pathway that provides a strong return on our economic investment as quickly as possible, eventually becoming profitable and then hugely profitable. In the near-term, it can profitably provide resources for government-funded exploration of the Moon and Mars and any other commercial activity like space tourism. We will tout the other benefits of space robotics such as planetary protection from asteroids and other unknowns of the space environment. We will find what resources can be brought back to Earth for a profit in the early stages, including metals from asteroids and possibly beamed power from Earth orbit. The use of space robotics to harvest solar system resources is the only, and inevitable, way for a civilization to go forward; it is the pathway that our environment naturally provides.

2.3 What about the Singularity?

The Technological Singularity is the idea that sometime in the next several decades mankind will invent computer super-intelligence, and the results upon civilization will be profound and unpredictable. Some "Singularitans" believe we should not worry about energy or resource problems in the face of this coming revolution. However, we biological creatures will still need energy and food to avert disaster, and it doesn't take super-intelligence to solve the problem. If we do experience the Singularity, the super-intelligent computers will tell us to get off our duffs and start building the robotosphere.

3.0 Technical Feasibility

3.1 Self-Reproducing Systems

Several studies in the early 1980s, (Freitas and Gilbreath, 1980; Freitas and Zachary, 1981; von Tiesenhausen and Darbro, 1980), and two more in the early 2000's (Lipson, 2002; Chirikjian, 2004), investigated the concept of self-replicating systems in space. The first of these showed that self-reproducing machines are not a violation of some fundamental mathematical or thermodynamic law. They further argued that robots in space building other robots, relying entirely on energy and resources harvested in space, would revolutionize humanity's condition. Freitas and Zachary defined in broad terms a replicator unit that would operate on the Moon to do all these processes, having a mass of only 100 metric tons per replica. Today this single-replicator concept seems too simplistic after our recent experience flushing out the realities and challenges in utilizing lunar resource (Mueller and King, 2007; Everingham et al, 2008; Metzger and Mueller, 2009; Metzger et al, 2009; Metzger et al, 2010; Mueller et al, 2010b; Mueller et al, 2010c). The earliest studies did not address many practical problems, such as how to make the vast assortment of materials typically used in complex machinery or how to do without them. A completely closed network of industry in space would probably need to be as complex as the analogous network on Earth[2] unless we simplify it considerably, as discussed below. Nevertheless, these studies were a good start. Lipson discussed advances in Solid Freeform Fabrication technology ("3D printing") to reduce the complexity. Chirikjian addressed some of the resource extraction issues and concluded that despite the complexity the overall concept of lunar manufacturing is feasible. During the past seven years, the Exploration Technology Development Program (ETDP) has addressed these resource extraction issues more comprehensively and our technological progress indicates the same conclusion.

Furthermore, we appear to be on the cusp of revolutions in robotics, artificial intelligence, and additive manufacturing (3D printing). Most of the technologies needed for space industry will be developed for terrestrial applications and can be re-purposed at minimal cost. Technology is advancing so rapidly in the private sector that the paradigm in which technologies developed for space exploration are "spun off" to the private sector is now being overtaken by a new paradigm in which technologies developed for the public sector are "spun in" for use in space. Additive manufacturing technology will be critical to simplify space manufacturing. For example, instead of extruding metal to make wire, dipping the wire in plastic coating to insulate it, rolling it onto a spool, later rolling off the spool a length needed for some assembly, and then peeling back the insulation from both ends and soldering it to the assembly, the entire assembly can be printed in final form in just one step with the wire and its insulation already in-place.

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[2] In the short term, the complexity could be avoided by an on-going dependence on Earth's industry to provide computer chips and such. There is no reason to disconnect completely from Earth.

3.2 Robotics Technology

Currently, global demand for robotics is estimated to be $21.8 billion in 2011 and more than $30 billion by 2016 (Trade Newswire, 2011). A business analysis group remarks,

> ...venture capital is again flowing to robotics-based start-ups. All of these indications point in the direction of a healthy market for robotics in the near future...international and external circumstances had created a technological and business climate in which the robotics industry would see enormous change. (Trade Newswire, 2011)

Bill Gates recently wrote that robotics "is developing in much the same way that the computer business did 20 years ago," and that it will soon be "a nearly ubiquitous part of our day-to-day lives" (Gates, 2007).

Hans Marovec in his book Robot: Mere Machine to Transcendent Mind predicts four phases of robotics in the coming decades (Marovec, 2000). The first he calls Lizard-scale robotics, which possesses general-purpose perception and the capacity for manipulation and mobility. The second is Mouse-scale robotics, which can learn and improve on its own through positive and negative feedback. The third is Monkey-scale, which like human minds has sufficient computational power to possess and continually assess an internal model of the world in which it is acting, including both the physical and relational elements. This allows a robot to predict possible outcomes of its actions, providing foresight as well as insight into the real intent of other agents in its world while planning a course of action. The fourth phase is the Human-scale robotics, which possesses general reasoning so that it can abstract and generalize. At that stage, robots may become as broadly capable as humans and even surpass us. In 2000, Marovec predicted these four scales would be achieved approximately every ten years beginning in 2010 for the Lizard-scale and reaching Human-scale by 2040. In 2003, he revised his estimate with a ten year delay (Marovec, 2003). He also reported in 2003 that personal computing power and automation software had already reached the level of insect nervous systems.

3.3 Computer Technology

According to Marovec, the computing power needed for each scale will be 3,000 MIPS, 100,000 MIPS, 3,000,000 MIPS, and 100,000,000 MIPS respectively (MIPS = Million Instructions Per Second). Computer hardware is progressing fast enough to support Marovec's dates. A survey of microprocessor speeds is shown in Fig. 1. These are inexpensive microprocessors that can be used in robotics, not top-end supercomputers which are already much faster. In 2003, microprocessors were nearly at 10,000 MIPS, already fast enough to support Lizard-scale. By 2011, this had improved by more than a factor of ten to 159,000 MIPS, powerful enough to support Mouse-scale. At this rate, the 100,000,000 MIPS needed for Human-scale will be available by 2030, twenty years ahead of Marovec's schedule. This may be called into question because industry experts are expecting

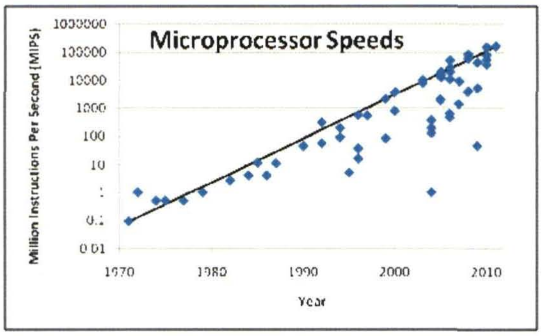

Fig. 1: Progress in Microprocessor Instruction Processing Speeds by Year (wikipedia.org)

Moore's Law with silicon transistors to continue only until about 2023, which will achieve 12,000,000 MIPS (exceeding the needs of Monkey-scale) per the trend of Fig. 1, unless a replacement for silicon can be found (Kanellos, 2005). Replacements that might extend Moore's law could involve epitaxial graphene (Sprinkle, et al, 2009), carbon nanotube multi-gate transistors, quantum well transistors or phase-change materials, heterogeneous integration, non-planar arrangements, and new architectures. Gargini believes these may extend Moore's Law indefinitely (Gargini, 2005). In any case, the real goal is affordable computing power, and this can be increased even beyond the end of Moore's Law by making larger chips, by parallelizing the microprocessors, and by parallelizing the overall computer. It seems likely the hardware speed for Human-scale robotics will be achieved by Marovec's schedule if not much earlier. Even if it does not, a robotic resource network in space needs only Lizard-scale to be functional, or preferably Mouse- or Monkey-scale to be less expensive and more efficient, and these will easily be met.

3.4 Artificial Intelligence Technology

The real challenge is not in the hardware, but the AI software. Some areas of AI have already shown dramatic progress. In 2006, Tom Mitchell of Carnegie Mellon University predicted that computers will automatically "read" and contextually process the information contained in human language obtained directly from the Web by 2015 (Olson, 2006). Already by 2011 this has been proven possible (along with auditory language processing), as IBM's computer "Watson" famously defeated the champions of the TV game show Jeopardy, processing complex verbal questions and formulating appropriate verbal answers in a wide variety of knowledge areas. Computer vision has also made dramatic progress as computers are now able to identify a vast assortment of objects based on 2D photographs. In medicine, a panel of experts concluded in 2009 that AI is now "coming of age" (Patel, et al, 2009). Automotive applications of AI are making great progress. Wolfgang Wahlster describes the AI present in smart-cars by 2005:

> Speech recognition, speech synthesis and dialog understanding are used to enable the driver to control the air conditioning, to select music or to program the navigation system. The age and gender of the driver is detected by biometric voice analysis and the cockpit displays are automatically adapted to the selected user model. Semantic web services can be activated that find the lowest price gas station close to the current position of the car. Up-to-date information about historical landmarks and points of interest on the car's route is retrieved in a location-sensitive way from the Internet. Automated deduction is the basis for correctness proofs of safety-critical car components like ABS both on the hardware and software level. Pattern recognition is used to classify sensor signals and warn the driver e.g. about the risk of aquaplaning. Messages are sent via wireless ad-hoc networks to succeeding vehicles to warn their drivers of potential road hazards. The analysis of biosensors and the driving behavior is used to infer the cognitive and emotional state of the driver, so that the smart car can assist the driver in a personalized and situation-adaptive way. (Wahlster, 2005)

The level of sophistication in these areas (language, machine vision, medicine, and automotives) is adequate for Lizard-scale perception in space mining and industry. However, what these maturing areas of AI have in common is a wealth of human experience to draw from plus great commercial potential to drive the technologies forward. Creating new algorithms for space industry, where we have very little experience and little commercial potential in the short-term, will not be as easy. It will be vastly easier when robotics achieves Marovec's Mouse- or Monkey-scale so that much of the learning can be done by the robots themselves while they are in space (or running simulations), rather than pre-encoded by humans based on our limited knowledge and expectations of space operations.

Progress is expected to achieve this robotic learning. For example, the on-going projects at DARPA (Defense Advanced Research Projects Agency, www.darpa.gov) are expecting progress in all the key areas. If successful, DARPA's Microsystem's Technology Office will essentially develop Marovec's Lizard-scale intelligence (or higher) into single computer chips that will "sense, process, and act on data" in the environment where it operates. DARPA's "Personalized Assistant that Learns" program is working on the equivalent of Mouse-scale learning,

> *...creating robust software assistants that can help users perform a wide variety of tasks* while adapting to the environment and the user's goals without programming assistance or technical intervention."

DARPA's "Deep Learning" program intends to exceed basic Mouse-scale learning, to

> ...revolutionize machine learning by creating a new class of learning machines that overcome the computational limitations of current "shallow" learning machines. This will be accomplished by building machines that can use many layers of processing in a manner similar to that used by biological brains. The Deep Learning program will develop a Core Deep Learner that creates rich encodings of input data by using the same set of algorithms across multiple layers.

The "Mind's Eye" program is working on some basic elements of Monkey-scale world-modeling,

> ...the capability to learn generally applicable and generative representations of action between objects in a scene directly from visual inputs, and then reason over those learned representations.

3.5 Space Resource Technology

Technology to utilize space resources has made great progress in the past seven years but needs more emphasis. The following have been developed, typically to a Technology Readiness Level of 4 to 6: methods to prepare work sites and landing pads by grading and stabilizing the soil (Mueller, et al, 2010a; Hintze, 2008); tools for prospecting for resources (Taylor and Martel, 2003; Muscatello, et al, 2009; Paulsen, et al, 2009); lunar/martian excavators (Mueller and King, 2008) including methods to reduce the excavation forces to work in low gravity with low-mass vehicles (Zacny, et al, 2009; Zacny, et al, 2010); ice mining devices (Gertsch, et al, 2006); methods to transport soil in and out of chemical processing modules (Mueller, et al, 2010c); beneficiation devices to concentrate desirable minerals found in the lunar soil (Captain, et al, 2007; Metzger, et al, 2010); and chemical plants to extract oxygen from lunar or martian soil (Gustafson, et al, 2009; Sanders and Larson, 2011). We need further work in all these areas as well as: construction processes; mining lunar ice and performing chemistry to make a variety of materials from the volatiles (including rubber, plastic, and hydrocarbons like methane); mining and refining metals from regolith and from M-type asteroids; methods to work in the ultra-low gravity of asteroids; additive manufacturing that prints with space-derived materials; advanced additive manufacturing that utilizes multiple material streams to print complex machinery; and applications specifically designed for Mars.

In developing technologies for a self-reproducing robotics system, we must keep in mind the inappropriateness of "high tech." The robotic network in space will be analogous to a primitive colony and will need to avoid complex mechanisms and processes that cannot be readily replicated in that environment. In colonial America, for example, colonists made log homes and lived a simplified life compared to their European counterparts. Just as the "Appropriate Technology" movement is now pushing to use only technologies that can be locally maintained in under-developed villages (e.g., pedal-powered water pumps constructed from local materials), so we must build appropriate technology for space robotics: mechanisms that trade weight and inefficiency for simplicity; crude machines that can be built with an equally crude 3D printer; and a small set of locally-derived materials from which to build everything. The vastness of solar system resources renders these inefficiencies unimportant. So far, all space technology has been designed to be "high tech" and launched directly from the Earth. That is not sustainable over the scale of the entire solar system. Our focus has got to change if we want to enable a space economy. Low-tech should be the new objective. Developing high tech (other than computers and AI software, which we will continue to export from Earth for the foreseeable future) is a waste of precious time, money, and people.

4.0 Benefits for Humanity

In America, it is legendary how the colonization of our continent depended on Christopher Columbus convincing the Spanish Queen Isabella to commit resources for his expedition. Columbus gained her support, but in retrospect his arguments were deeply flawed. In the long run, did that matter? He argued that he would discover a new trade route to the East Indies and gain Spanish access to its vast wealth. What he found instead were the West Indies, notably under-developed as civilizations go, and not exactly what the Queen had in mind. However, Spain benefitted greatly in the long run, over a timeframe that was a bit longer than the Queen expected. So how do we convince the political powers in our world today that we need to robolonize the solar system? People on Earth need food and energy, and it is not likely any robotic space system will be landing sufficient quantities of these in spaceships any time soon. Nevertheless, there are several arguments we may make, which resolve into six models that can be pursued individually or in parallel. They may be called the Global Relief Effort, the Great Migration, Restoring Eden, the Foundation, the Space Endowment, and Anti Virus.

4.1 "The Global Relief Effort"

The first model is to "air drop" energy, food and resources from space onto the Earth, similar to air dropping humanitarian aid packages into a region that is suffering from a famine. Mass could be landed using disposable re-entry craft built from space metals, ceramics, or even water ice. Energy could be beamed. However, relief may not be feasible on a global scale in time to avert disaster; we need to investigate further to find out. This effort might only be a bandage covering up a deeper wound: if humanity always populates beyond the limitations of its resources, we could return to the same problem again. We could enable mankind to convert the entire Earth into an unrelenting, global slum. Nevertheless, if the alternative is billions of people dying for lack of something we could provide, then we have a moral imperative to provide it. Also, it might buy time to work on the deeper problems. In the author's opinion, it is important regardless the outcome that we explain to humanity that our resources on Earth are limited, but for the foreseeable future the resources of our home solar system are not, and that we need to get started accessing them today.

4.2 "The Great Migration"

If the Global Relief Effort is to bring resources to the people, then the Great Migration is to bring the people to the resources. With industrial power millions of times greater than the entire US, the robotosphere could build O'Neill-type space colonies easily and for no cost to the world's economy. Terraforming planets would be feasible and equally free. Terraforming is usually described as a process we pursue one planet at a time. It will be vastly easier to robolonize a solar system first, gain access to the full power of the star and its resources, and then have the massive industry of the robotosphere affect the planet.

4.3 "Restoring Eden"

Another model is to move all industry into space where the energy and resources are located while keeping the people on Earth. It delivers manufactured goods to the surface and cleans up the Earth's environment and atmosphere so the people can enjoy its restored beauty. Humans might still do agricultural work on the Earth, or in principle even agriculture could be moved into space and the food delivered to the surface along with every other material good.

4.4 "The Foundation"

The first three models, above, may be too late to avert disaster. This next model is a fallback position. Isaac Asimov's famous "Foundation" novel series describes a galactic civilization that enters a dark age predicted to last 30,000 years. To reduce that to a mere 1000 years, a genius mathematician and his colleagues set up "the Foundation" to preserve the knowledge of civilization and actively guide it back onto the right course. Following this model, if a solar system robotosphere is determined incapable of salvaging Earth's economic vitality throughout the turbulent 21st century, then at least it can help Earth's civilization recover more quickly. In this model, it is important to get the robotosphere off the Earth before economic chaos begins so that it will have its own resources, energy, and freedom to complete its task apart from untrustworthy politics. Otherwise, the robotics trapped on Earth without access to the vast resources of the solar system might never become capable of re-starting civilization. The thinking behind this model is that we have a small window of time to set up the robotosphere before Earth's economic woes kill off space exploration, and if we miss that window, then without the robotosphere to harness solar system resources we may never again have a sufficiently vibrant economy to get a second chance.

4.5 "Space Endowment"

Very similar to the "Foundation" model is the Space Endowment model. However, the objective is not to save civilization, but just to promote some good elements of civilization whether there is a global disaster or not. It establishes an institute in space for humans to do science, engineering, the arts, and other activities that may not otherwise be funded adequately, especially during the economic strain of the 21st century. The robotosphere exists as the endowment for this off-planet institute, building and operating its massive observatories and state-of-the-art labs, conservatories, libraries, meeting halls, and dormitories in space. There the academics, artists, researchers, and technologists will work and live in community, freed from economic concerns. The robotosphere builds transportation systems to shuttle the humans throughout the solar system to various observatories and labs: on Mercury, in the Oort cloud, and everywhere in between. Of course, this endowment can grow geometrically and admit an almost endless number of human participants, so with sufficient growth the Space Endowment model merges into the Great Migration model. One possible outcome of this model is the support of the 100 Year Starship program, which will then have no economic limitations.

4.6 "Anti Virus"

The Anti Virus model is concerned with negative aspects of a robotosphere. Obviously, if one rogue nation seeds the solar system with a robotosphere first and keeps it under its national control, then that nation rules the world. An endless quantity of vehicles, weapons, chemicals, and fuels can be made in space at no cost and landed on the Earth for that nation's exclusive use. In surprisingly little time—just a few decades—the coming advancements in robotics, AI, and additive manufacturing may make it simple for even third-world nations to do this. Besides such national concerns, many smaller groups or individuals can set up their own parallel robotospheres with their own focused agendas, or they can add Trojan elements to an existing robotosphere, co-opting its machines or harvested resources. Robotosphere hackers may design viral elements, both as software and self-reproducing physical machines to leverage the robotic ecology. Terrorists may hijack it for violence. A robotosphere might also mutate on its own. With so much power for good, a robotosphere also possesses great power to do harm. The Anti Virus model presumes that with relevant technologies progressing so rapidly, it is inevitable that all these scenarios will eventually come into existence. Therefore, it behooves the benevolent nations of Earth to build a vibrant robotosphere first, one with an "immune system" that patrols the solar system, identifies harmful intruders, stops them from reproducing, and prevents horrific tragedy.

5.0 Benefitting the 100 Year Starship Program

From the perspective of the 100 Year Starship Program, there are at least eight benefits from pursuing solar system resources robotically.

5.1 Public Support

Because space resources hold promise to save Earth's economy and civilization, aligning the 100 Year Starship program with one or more of the above models will show the public that it is not just "shooting resources off into space." This holds the promise of not only garnering voter support, but of attracting investors.

5.2 Financial Independence

As solar system resources come into the economic sphere of the 100 Year Starship program, the program will become increasingly self-sustaining. Scientists, engineers and technicians building the starship can live in space near the construction site, perhaps at a Lagrange point or on the Moon where the robotosphere makes everything free.

5.3 Avoiding Launch Costs

Launching out of Earth's gravity well is one of the largest costs in space exploration. The starship, if it has significant size, will need to be built or at least assembled in space. Deriving solar system materials for the construction and propellants for flight operations will avoid launching them from Earth's gravity well.

5.4 Develop Cost-Saving Capabilities

The technologies needed for a self-reproducing robotosphere are the same technologies needed for in-space construction of the starship. Robotic "wasps" can crawl around on the spacecraft's superstructure building spars and longerons by 3D additive manufacturing using titanium derived from lunar regolith. Simple levels of artificial intelligence will enable the robots to perform the construction with minimal human oversight. Multiple starships can be constructed for only slightly more than the cost of one.

5.5 Possible Auxiliary Technologies

Since a robotosphere will enable mankind to do truly audacious things in space, we may consider additional technologies besides the starship, which will support the starship program and build additional public support. These include: space elevators, constructed robotically down from space using lunar carbon from the polar craters; beamed power from space; orbiting colonies; etc. None of these are impossible once the solar system's resources have been harnessed. They would support 100 Year Starship by reducing costs to orbit, providing a commodity (power) that can be sold commercially to support the program's objectives, providing living quarters for space workers, etc.

5.6 Synergy in the Solar System Economy

Various missions within the solar system will build a commercial space economy and produce synergy for 100 Year Starship objectives. These include: scientific missions to Mars and elsewhere in the solar system, comprehensively surveying and then altering the trajectories of asteroids for planetary protection, novelty items made from space materials, and space tourism. Each of these brings its own public, political, and/or commercial support independent of the support garnered by the starship. Therefore, to a large degree they will not compete with each other for funding. However, their economics and ability to succeed are not independent. They will each support commercial providers and develop technologies and capabilities that are common.

5.7 Develop In-Flight Repair Capability

During a long journey on a starship there may be hardware failures necessitating repairs, that must be performed without the support of Earth. This requires in-space manufacturing from basic feedstock materials, a basic capability that will be developed to harvest solar system resources.

5.8 Preparing the Destination

When the starship reaches its destination star, the crew can use the local resources to resupply their ship with energy and consumables, setup outposts, construct massive communication antennas back to Earth, terraform planets for long-term habitation, build a return ship, or build ships to go on to the next star. They can do all these things using technologies they bring with them, developed in common with our solar system's robotosphere. Even better, our robotosphere can send out a ship to the destination star years before the humans set forth. That ship can set up a replica robotosphere to leverage the resources of that distant star and set up a port of call in advance of human arrival, preparing habitation, food, consumables, and antennas, or set up O'Neill-type colonies for long-term habitation while beginning to terraform a planet.

Robotically leveraging the resources of the destination star years before the humans arrives is the most logical way to approach colonization outside our solar system because it will provide a robust economy to support human activity once we arrive. We are not a species adapted to living off the land. Wherever we go, we need a vast "food chain" of simpler entities that are adapted to living off the land and one another in a pyramid of complexity. Without this we will be forever bound to the network of that sort that already exists on Earth: a pyramid that includes Earth's networked biosphere and civilization's networked industry. To release ourselves from the complex networks of Earth, we need to create a separate, richly networked economy wherever we go, consisting of the simpler entities that can digest the local resources and support us. Developing the network here is a prerequisite for building one wherever we travel away from the Earth. Without it, our activities away from Earth will be necessarily limited by time, energy, and complexity.

Strategy

There is a "hump" that needs to be crossed to get a robotosphere started. If the hump were not so high, then Earth's biosphere would have crossed it and colonized the solar system long ago. Even with the industry of human civilization, the hump is high and so we find it economically difficult to cross. Here is a notional strategy to cross it.

5.9 First Stage

Technologies for robotics, AI, and utilizing space resources are developed on Earth and tested in analog sites, such as the lunar test site on Mauna Kea in Hawaii, and the Haughton Mars Project on Devon Island in Canada.

5.10 Second Stage

The technologies are deployed at the International Lunar Research Park (ILRP) for further development in space. There, they are teleoperated with increasing levels of autonomy using their Lizard-scale perception and mechanics. One goal at the ILRP is to derive materials and parts from lunar soil: metals, ceramics, glass, oxygen, water, methane, plastics and rubbers from the carbon in polar volatiles, solar cells, and power distribution cables, for example. The next objective is to achieve closed-cycle 3D printing of Appropriate Technology. That is, simple excavators, resource processors, and 3D printers are designed and operated to build another copy of themselves (minus some components like computers, which are exported from Earth).

5.11 Third Stage

Once adequate self-replication is achieved, we use that to expand industrial capacity on the Moon, building many more excavators, processors, and replicators. We develop and perfect Mouse-scale learning. This capability then further builds and fuels spacecraft to spread to the Main Belt.

5.12 Synergistic Interlude #1

At this point with a giant throughput of lunar-derived materials and manufacturing, we may choose to build space colonies near the Earth to support activity of the 100 Year Starship or in support of the Space Endowment Model. We may also choose to test space elevator or beamed energy technologies or build other infrastructure in cis-lunar space in support of the Global Relief Model or eventually the Great Migration Model.

5.13 Fourth Stage

We follow to pattern of the ILRP by building a Ceres Technology Development Park (CTDP) on the dwarf planet Ceres in the asteroid main belt. Here, we develop greater robotic autonomy, including Monkey-scale self-learning. Greater autonomy is needed at the long time delay to Ceres. We adapt lunar technologies to the new environment, including solar power collection and distribution, communication and navigation, excavation, and manufacturing. We also design, robotically build in-situ, and test vehicles to serve as asteroid mappers, prospectors, and miners. We test metal refinery modules located in the CTDP on Ceres. One objective is to create commercial profit for businesses in space mining and thus leverage Earth's economic participation outside of governmental funding.

5.14 Synergistic Interlude #2

At this point, we may perform a series of human Mars expeditions, enabled by utilizing resources on its surface and outside its gravity, on Phobos, using technologies developed at the CTDP. Mars' gravity will keep it from becoming a significant exporter into the solar system economy. However, the Mars missions bring their own support from the scientific community and the general public. It would thus bring government funding to develop synergistic technologies.

5.15 Fifth Stage

Just as the ILRP led to expansion of industry across the Moon, so now the CTDP will lead to the expansion of industry across the asteroid belt, where metals and probably even water are more abundant than on the Moon. At this point, the planetary protection program to comprehensively control all small bodies in the inner solar system becomes viable, protecting the Earth from an asteroid impact that could wipe out the human race. This stage also focuses on using asteroidal materials to build a great fleet of transport ships that traverse the inner and outer solar system to transport resources, finished goods, and researchers to a variety of destinations.

5.16 Sixth Stage

Now, we are ready to construct research outposts and observatories to be permanently manned by researchers throughout the solar system. They may be on the poles of Mercury, in orbit of Venus, on the surface of Mars, on the moons of gas giants, or beyond. They can study the solar system itself, or the astronomy and cosmology of the sky more visible away from the electromagnetic spectral disturbances of Earth, or the processes of local physics where gravity, nearby cities, or lack of space and resources could impede progress. Human-scale robotics enables construction crews to function efficiently many light-hours away from Earth building complex facilities for research. The entire solar system is now a laboratory for robust, well-funded scientific investigation.

5.17 Seventh Stage

With abundant transportation and manufacturing throughout the solar system, the resources of the innermost and outermost parts of the solar system are now brought into the economic sphere of humanity. It is no longer too expensive to transport volatiles from Trans Neptunian Objects, or to beam energy across planetary distances. Artificial intelligence helps manage the massive space economy. At this point, we have become a Type-II civilization on the Kardashev Scale, having mastered the resources our solar system.

6.0 Conclusion

We are at an important juncture in human history. We have already expanded industry across the globe and have achieved an essentially Type-I civilization on the Kardashev Scale, one that has mastered the resources of an entire planet. It is now large enough to rapidly deplete the most economically valuable resources of Earth. This drives us to the momentous choice between two options. We can stay confined to the Earth and let dwindling resources drive civilization backwards, resulting in tragedy for the billions of people that depend on machine-enhanced agriculture and transportation. Or, we can expand civilization to encompass resources of the solar system. However, we are a species adapted to living at the top of a food chain, and we are unable to survive and perform the most human of our activities without a rich network of simpler entities to process resources for us. There is no such network in space. Fortunately, we have started developing the robotics, artificial intelligence, and manufacturing technologies that will make it possible to construct an artificial food chain, the robotosphere. Because of the exponential growth of these technologies, we may be able to initiate it within a single generation. A robotosphere holds the promise to relieve Earth's resource pressures, in part for the near term, and completely in a few decades beyond. It also holds the promise to maintain scientific progress, technological development, and vibrant participation in the humanities regardless of conditions on Earth. It also supports objectives of the 100 Year Starship Program by freeing us from the economic and political milieu of Earth, by developing necessary and synergistic technologies for use in designing and constructing the starship, and by providing a method to prepare the destination solar system for human arrival, resupply, colonization, or return. With the robotic leveraging of solar system resources, the starship project seems eminently achievable within the next 100 years. Nature has ensured that there are literally billions of times more resources available in a habitable solar system than there are in the biosphere of one of its isolated planets. The physics and the technology needed to take advantage of it are now well understood and within our reach. This is nature's way of making audacious space projects feasible.

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