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Space Exploration: The Role for Public-Private Research and Development Partnerships

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Abstract

The emergence of economic growth, sourced with space exploration, will depend critically upon research and development discoveries that are likely to take place in many fields of sciences such as astrobiology and life sciences, earth and planetary sciences and aeronautical engineering. Such discoveries will be enhanced by public private partnerships. In this paper, we examine how such partnerships can be structured and how incentives can be aligned between the private firms, the principal governmental agency, NASA, and universities with space exploration programs. The current governance structure of NASA is well established but the possible willingness to engage in such partnerships by private firms requires more detailed investigation. These private firms include aerospace and defense firms; new space-centered firms; new startup ecosystem financed by venture capital; and several other remote sensing companies.

Section 1: Introduction

What was once limited to the realm of science fiction and theoretical astrophysics models is now within an operational vision of exploring the "final frontier," otherwise known as outer space. With the advent of cost-effective launch technologies (i.e. reusable rockets) and the gradual deregulation of space launches and flights, the global economic activity in the space industry has begun to surge. While satellite services likely comprise most viable and profitable venture in space, the adoption of novel space-based goods and services, from space tourism to organ bioprinting, show tremendous potential to disrupt even incumbent industries on Earth.

The global space industry has increased in value from $162 billion in 2005 to $469 billion in 2021. While government spending increased 19% to add $107 billion to the space industry, much of the value growth can be attributed to the private sector: commercial enterprises provided an estimated $224 billion in goods and services and $138 billion from constructing infrastructure and support (1). The most recent space industry reports by Citi and Morgan Stanley project a $1 trillion valuation and $100 billion in annual revenues by 2040 (2-3).

Space-related research and development has expanded dramatically based on the 22% annual increase for the past five years attributable to the private sector, in contrast to the 10% increase for U.S. governmental expenditures in nominal dollars (4). While NASA and public sector expenditures have stagnated $12 billion[2] (in real dollars) in the past few decades, "NewSpace" companies,[3] or new companies emerging in the private space

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[2] Historical NASA budget and expenditures adjusted to FY2021 dollars

[3] NewSpace companies are defined as new companies that have emerged to strengthen the spaceflight, rocket launch and satellite capabilities, considerably decreasing launch costs, which ultimately ushered in new space industry sectors.

industry, have invested an estimated \$5-6 billion in 2020, up from less than \$1 billion in 2010 (4).

However, recent growth strategies in this industry suggest that the private sector have leaned towards M&A-focused approaches[4] rather than in-house research initiatives. The previous decade of the private sector was composed mainly of NewSpace companies developing end products and technologies for organic growth.[5] The rise of space-focused investment funds[6] and venture capital arms of traditional aerospace companies[7] not only suggest private sector consolidation but incentives for being in a position to scale the R&D efforts for value creation. For example, AE Industrial Partners, a private equity group, launched a joint venture fund with HorizonX, Boeing's venture arm. AE Industrial Partners also formed Redwire, a holding company that has acquired a number of high-profile startups including Made in Space and Techshot, who both provide additive manufacturing solutions in microgravity, as well as companies with spacecraft and launch system capabilities.[8]

To support research development, a natural evolution toward fostering collaboration between the private and public sector could, if properly designed, provide a superior research and development platform to increase the probability of successful breakthroughs. Traditionally, NASA has largely acted as the sole public partner for most space-related public-private partnerships (PPPs). The next natural step from NASA contracting with private companies is the establishment of a public-private research and development partnerships (PPRDPs) with an expanded scope for the public dimension including the possible codification of major discoveries. PPRDPs provide a diversity of cultures of research, which might be in some cases the key ingredient to breakthroughs. Government agencies (e.g., NASA) traditionally follow "invented and built here" approaches, which cannot keep with the pace of innovation of the private sector. The private sector carefully tries to optimize between productivity and adherence to government standards they might not need. Universities has unique ways to use commercial products for fundamental science discoveries different from government and industry methodologies. The inclusion of universities and fundamental research institutions as additional public partners may increase the likelihood of discovering tipping-point technologies and other research discoveries. With the rise in space-related research grants and human capital development offered in university degree programs, universities could expand the public dimension of NASA to offer valuable intellectual property and more opportunities for agglomeration externalities.

In this article, we first provide a historical evolution that demonstrates NASA's shift towards a collaborative research and development process to accomplish their research

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[4] e.g. investment funds, spin-offs, partnerships, special purpose acquisition groups

[5] e.g. SpaceX, Blue Origin, Rocket Labs, Virgin Galactic, Orbital Labs

[6] e.g. Space Capital, Manhattan West, Explorer 1 Fund, Ark Invest Space ETF, Lux Capital

[7] e.g. Lockheed Martin Ventures, HorizonX, RTX Ventures

[8] Such companies include Deployable Space Systems, Deep Space Systems, LoadPath, Adcole Space

agenda and mission operations in section 2. Relevant legislation (e.g. Space Acts) and NASA funding has introduced a host of new entrants within the private sector along with funding for more active R&D programs. In section 3, we outline public and private sector activities pertaining to major innovations that may occur within a 20-year horizon that will be instrumental in capturing the growth possibilities of the space economy. In section 4, we evaluate PPRDPs and the incentives of each partner using an emerging case study, as well as consider a novel form of governance to administer PPPs.

Section 2: NASA's Transition towards Private Sector Dependency

The 1957 Sputnik crisis prompted the passage of the 1958 National Aeronautics and Space Act, which restructured the wartime-focused National Advisory Committee for Aeronautics (NACA) to the National Aeronautics and Space Administration (NASA), absorbing four major research laboratories in the process. The 1958 Act also established "Space Act Agreements," which allow NASA to contract with any entity to fulfill programs and projects.

After finding considerable success in the Apollo program, the 1984 Commercial Space Launch Act recognized that the private sector was capable of developing and operating spacecraft and satellites. While regulatory guidelines and economic incentives were developed in later amendments, NASA was in a position to foster space entrepreneurship (5). Pressured by European post-war aspirations for technological independence from the US (nuclear, electronics, aviation and space in particular), leading to the emergence of Arianespace, a European launch company protected by the European Union from unlimited liability, the 1988 Commercial Space Launch Amendments Act was the first federal law to provide indemnification and financial support for commercial space companies. The act also directed the Administrator of NASA to design a program to support research into launch systems component technologies to develop higher performance and lower costs for commercial and government launches.

Following the 1998 Commercial Space Act, a critical turning point for the engagement of U.S. private industry came with the passage of the 2004 Commercial Space Launch Amendments Act. The Federal Aviation Administration (FAA)'s Office of Commercial Space Transportation issued experimental permits that allows private companies to test new types of reusable suborbital rockets. This was an initiative to allocate opportunities to other private companies other than United Launch Alliance composed of the Boeing and Lockheed Martin, which dominated the NASA private sector contracting, whose value exceeded over $12 billion (6). Not only were indemnification extended to 2015 but the 2004 Act created a "learning period" for commercial spaceflights, prohibiting the US Department of Transportation (which the FAA is part of) from issuing safety regulations beyond the informed consent regime, in which safety requirements for commercial human spaceflights were limited to informed and written consent to undertake the risk of space travel. This meant private companies could generate revenue by taking on passengers without having to deal with liability issues, allowing for the rise of space tourism companies (e.g. Blue Origin and Virgin Galactic).

With the rise of newly engaged commercial space companies with technologies capable of launch and spaceflight operations, NASA fostered private entities with its Commercial Orbital Transportation Services (COTS) program (2006-2013), which provided contracts for space companies to demonstrate cargo delivery to the International Space Station (ISS), with a possible contract option for crew transport. Otherwise, NASA would not be forced to purchase orbital transportation services on foreign spacecraft since NASA's own Crew Exploration Vehicle would not have been ready until 2014. With the successes of SpaceX[9] and Orbital Sciences'[10] cargo delivery missions, in 2012, NASA was no longer purchasing any cargo resupply services from Russia and would rely mainly on the SpaceX Dragon and Orbital Sciences' Cygnus.[11]

The success of the COTS program allowed the 2008 Commercial Resupply Services (CRS) program to contract more commercial entities to make deliveries to the ISS. The first phase of the CRS program awarded SpaceX $1.6 billion for 12 cargo flights and Northrup Grumman $1.9 billion for 8 cargo flights. The second phase of the CRS program has contracted 15 missions with SpaceX, 14 missions with Northrup Grumman, and three missions with Sierra Nevada.

The most recent commercially operated space transportation program, the 2011 Commercial Crew program, has awarded numerous companies, including Blue Origin, Boeing, Paragon Space Development Corporation, Sierra Nevada, and United Launch Alliance in its first development phase. In its second phase, Blue Origin, Sierra Nevada, SpaceX, and Boeing were awarded contracts for various enhancements to its respective spacecraft. In its third phase, NASA requested proposals to have complete, end-to-end concepts of operation, including spacecraft, launch vehicles, launch services, ground and mission operations, and recovery. Sierra Nevada's Dream Chaser/Atlas V, SpaceX's Dragon 2/Falcon 9 and Boeing's CST-100 Starliner/Atlas V were awarded contracts.

The Commercial Space Launch Competitiveness Act of 2015 solidified NASA's reliance on the private sector by extended indemnification to 2025 and the learning period to 2023. The act also delegated property rights to private companies that mine resources from celestial objects (i.e. asteroids), providing another incentive for private space expansion.

NASA's most recent endeavor, the 2017 Artemis Program, aims to construct the Lunar Gateway, a space station in lunar orbit. Blue Origin, Dynetics (a Leidos company), Lockheed Martin, Northrup Grumman, and SpaceX were awarded contracts. Space

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[9] SpaceX was paid $396 million to develop cargo configurations for Dragon spacecraft and successfully launched Dragon C2 in 2012.

[10] Orbital Sciences was awarded $288 million and successfully launched a Cygnus spacecraft in 2013

[11] Notable exceptions include the European Automated Transfer Vehicle (ATV) and the Japanese H-II Transfer Vehicle.

venture capital activities have skyrocketed following NASA's commercial dependency; in 2021, $17 billion were globally invested into 328 startup companies, close to doubling the previous record of $9.1 billion in 2020. In total, space-related companies have attracted over $264 billion in 1,727 unique companies since 2013 (7). The available evidence makes it clear that NASA has created much in the way of incentives[12] for the private sector to actively engage in R&D, helping to solve many of the obstacles that arise in such efforts to expand the knowledge base for space exploration.

Section 3: Innovative Fields within a 20-year Horizon

In this section, we attempt to identify what we have learned from synthesizing the literature on the major innovations and discoveries that may take place over the coming 20-year horizon. We've classified these areas of innovation as space transportation, in-space manufacturing, space bioproduction, launch and propulsion systems, space agriculture, and satellite services.

3.1 Space Transportation (Launch Systems, Logistics Partners)

A significant barrier to the full development of a space economy is the capacity to support space mobility. In the last two decades on earth, the convergence of electrification, computation, communication, control and sensing on mobile devices and vehicles has enabled the self-driving industry to emerge and the shared economy to become a reality. In a similar manner, the space economy cannot function without propulsion, launch systems and space logistics, which are all part of a new space mobility ecosystem to be created. The development of such a mobility ecosystem relies both on advances of specific technologies (vehicles) and new network paradigms (in similar fashion to the FAA when it historically built its air traffic control system). High barriers to entry into the space industry stemming from high transportation costs and extreme risk management currently remain.

Technological advancements in the launch system industry, however, have shown great potential to scale such costs: a payload from SpaceX's reusable Falcon 9 rocket costs approximately $2,700/kilogram, compared to a conventional nonreusable rocket ($20,000/kg) and the 1981 Challenger space shuttle ($85,000/kg). SpaceX's Falcon Heavy rocket, in which a payload will cost ~$950/kg, is projected to save NASA an estimated $548 million for their 2024 Europa Clipper mission (8). Another entrant in the launch industry, Relativity Space, produces autonomous and additive manufactured reusable rockets that are projected to decrease costs even more; they have already pre-sold more launches than any other company since SpaceX. While launch costs are already 40x lower than in 1981, some preliminary estimates price launch costs to approximately $100/kg by 2040 (2). Such potential to reduce barriers to entry can

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[12] NASA Innovative Advanced Concepts program, NASA Flight Opportunities program, NASA Space Technology Mission Directorates

effectively unlock a stream for economic growth by creating more opportunities for technological innovations within the space industry's value-added chain.

Because this ecosystem is still nascent, some companies like Qosmosys are currently building ZeusX vehicles to be launched in 2026, with capabilities to mine Helium 3 on the moon for missions spanning 10 years each. There is currently no way to bring this precious cargo back, but the companies are working under the assumption that this ecosystem will exist by 2038 after the first mining mission is completed. In this nascent ecosystem, ZeusX moon spacecraft is compatible for a launch with Falcon Heavy, New Glenn, Vulcan or Ariane 64, as an illustration of the start of a logistics chain to be incrementally developed in the decades to come.

3.2 In-Space Manufacturing

3.2.1. Space-for-Space Manufacturing: While launch and other transaction costs are declining, the most efficient mode of production of goods for in-space consumption is in-space production. There also exists an exigency for building an in-space manufacturing (ISM) infrastructure to circumvent wait times and reducing risk for vital equipment during missions. Current manufacturing systems have already produced over 200 tools and parts in the ISS (9-10). This may have future significance in making long-distance explorations as well as long-term visits feasible (i.e. space colonization). ISM requires manufacturing techniques that with more control over the drastically different environmental factors of outer space (e.g. microgravity and related forces, heat transfer, non-equilibrium processing). Subsequently, novel processes have emerged to acclimate to such conditions. Companies such as Made in Space have used fused deposition modeling (FDM) and injection modeling to 3D print complex parts, such as finger splints and ventilator regulator valve. Faraday Technologies and MoonFibre produces covetic materials, or carbon nano-alloys that can be used for spacecraft and satellite components due to its efficient thermal conductivity (11). Within public and university research, through a grant awarded by the U.S. Department of Commerce, University of New Hampshire, in partnership with Purdue University, the University of Alabama and NASA, will focus on developing equitable industrialization of ISM by analyzing technical and commercial gaps (12).

The greatest challenge, however, is shipping the actual 3D printing machines, the resupply of feedstock and other input resources; because such equipment consumes considerable space and weight on cargo resupply missions, the high-cost factor inhibits scalability. Tethers Unlimited (acquired by Amergint Technologies) also focuses on ISM with their Trusselator, but also has invented the Refabricator to reduce resupply needs by recycling plastic waste into feedstock for 3D printers. Made in Space is also attempting to bypass the "tyranny of the fairing,"[13] in which payloads are limited in size by the nose cone of a rocket, with the invention of the Archinaut, a satellite capable of 3D-printing itself. After successful launch and orbit in space, the Archinaut will autonomously

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[13] The term "fairing," or payload fairing, is used to describe the nose cone that is used to protect the cargo onboard. Due to its cone-shaped structure, payloads are limited in size and shape.

manufacture and assemble its solar panels; if successful, future payloads will not be limited by size.

3.2.2. Microporous Materials & In-situ Resource Utilization

A variation of space-for-space manufacturing is *in-situ* resource utilization (ISRU), which use resources found in outer space rather than from Earth in for in-space use. The development of ISRU technologies is crucial for long-term space exploration and habitation to bypass the cost factor of launching supply missions. It is also essential for constructing a closed system capable of sustaining life for mass immigration to space colonies. The Environmental Control and Life Support System (ECLSS), or the water and oxygen supply system used in the ISS for over 20 years, is also in need of much improvement (13).[14]

Microporous materials, specifically metal-organic frameworks (MOFs) and covalent-organic frameworks (COFs),[15] may be a key component in actualizing *in-situ* resource utilization (ISRU) and closed systems. A key characteristic of MOFs and COFs are its high porosity capable of absorbing vast quantities of gas molecules (i.e. H_2, CO_2, O_2, CH_4) (14-15). MOFs and COFs have potential to replace certain life support systems in space:

1. **Oxygen Evolution Reaction (OER):** OER refers to the process of producing oxygen through chemical reactions such as water electrolysis. MOFs can act as ideal catalysts due to their high porosity and conductivity, increasing oxygen production efficiency (16-17). Current OER catalysts include iridium and platinum-based MOFs; due to their scarcity and exorbitant prices, these MOFs cannot scale. Preliminary studies suggest copper, cobalt and zinc-based MOFs can be substitute the need for noble metals (18-20).
2. **CO_2 Capture and Removal:** While many forms of MOFs are capable of carbon capture, magnesium-based MOFs is currently the most cost-effective carbon capture technology (21). Bismuth-based MOFs can also act as a catalyst for CO_2 electrocatalytic reduction reactions (22-23).
3. **Hydrogen Storage:** MOFs can safely store gaseous hydrogen, which can later be used for rocket fuel (24-26). This may be instrumental for long-distance missions as rockets are not limited to the fuel capacity at initial launch.
4. **Photocatalysis (Artificial Photosynthesis):** By mimicking photosynthesis, MOZs, or MOFs combined with certain amino acids, have successfully converted water and CO_2 to oxygen and fuel sources through photocatalysis (27). In other

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[14] The ECLSS has required continuous maintenance due to system failures over its 20-year period. Key technologies such as the Elektron oxygen generator and Carbon Dioxide Removal Assemblies (CDRA) have malfunctioned several times.

[15] MOFs are composed of metal ions with organic linkers, while COFs are organic solids composed of nonmetal light elements (i.e. hydrogen, boron, carbon, nitrogen, oxygen).

words, MOZs supplement the oxygen supply system as well as support long-distance missions with methane production.

5. **Pyrolysis:** The Sabatier reaction system (SRS) currently used in the ISS as a water supply system can recover only 42-50% of water from carbon dioxide and hydrogen (28-29). Methane (CH_4), the other byproduct of SRS, is wasted rather than stored or reused in pyrolysis,[16] lowering overall efficiency. Preliminary studies indicate manganese-based MOFs can act as templates for plasma pyrolysis, allowing for oxygen reduction reactions, which can convert oxygen to water (30). Iron-based MOFs can absorb waste products, specifically hydrocarbons, making the Sabatier process more efficient (29).
6. **Water Purification:** MOF membranes have shown capabilities in water treatment and remediation (31-32). Zinc-based MOFs can be used to remove lead and mercury ions from wastewater (33) and zirconium-based MOFs can remove phosphates in water and urine, having potential to enhance ISS' Urine Processor Assembly (34).

Conveniently, MOFs and COFs can be produced in a superior fashion in microgravity conditions with "unprecedented effects on the orientation, compactness, and crack-free generation" (35). While terrestrial applications, especially in the carbon capture and sequestration industry, are evident, comparatively, the same enthusiasm has not been displayed for in-space applications. The most relevant research discovery for in-space purposes has been made by Monash University and the Commonwealth Scientific and Industrial Research Organization in Australia has developed Airthena, a MOF direct air capture device capable of capturing eight kilograms of CO2 a day over 2680 cycles at approximately $35-350/tonnes of CO2 (36).

3.2.3. Space-for-Earth

The decisive comparative advantage of ISM is microgravity effects, which allow for more control over the manufacturing processes in many secondary industries, most notably in the semiconductor and nanotechnology industry. By being able to better control processes at an atomic level, microgravity effects include enhanced crystal growth in terms of purity and size, augmented diffusion/separation of mixtures, capabilities of producing ultrapure materials, and ready access to extreme temperatures (37). This provides ISM a comparative advantage over Earth manufacturing (EM) in many industries, most notably the semiconductor and nanotechnology industry, by being able to control processes at an atomic and molecular level. To mitigate microgravity effects during the production process, Iowa State University's NINJAS project (No-Gravity Ink Jet Printing for Aeronautics and Space) utilize electrohydrodynamic inkjet printing, which uses electric forces in lieu of gravitational forces to print myriad of goods,

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[16] Pyrolysis is a process of thermal decomposition without oxygen. Methane pyrolysis results in carbon and hydrogen atoms, which can be used as precursors for a multitude of uses (e.g. hydrogen combustion)

including semiconductors, flexible sensors, and other micro-devices (38-39). Auburn University was also awarded a NASA grant to develop a laser-based dry additive nanomanufacturing approach for electronic advancements in space (40).

The "tyranny of the fairing" and weight-consuming attributes of ISM only justifies the production of goods and services with high economic value.[17] One profitable example is the ZBLAN, a fiber-optic cable that provides 10 to 100 times lower signal loss than standard glass fibers. Fiber-optic cables are crucial in global internet and communications infrastructure. ZBLANs, however, can only be produced in microgravity environments as impurities develop when its optical properties are distorted. ZBLANs are more capable of transmitting information quicker, making it attractive for a number of commercial purposes, including telecommunications for rural areas, surgical lasers, and even high frequency trading. Companies such as Fiber Optics Manufacturing in Space (FOMS), Apsidal, DSTAR Communications and Physics Optics Corporation have secured NASA grants and private funding to develop such viable and scalable manufacturing.

3.3 Space Bioproduction

A flourishing application of microgravity is bioproduction, especially in the biotechnology and pharmaceutical sectors. The pharmaceutical industry is positioned to capture economic benefits if they are able to utilize microgravity research and development, with some revenue growth forecasts estimating $2.4 – 4.2 billion annually once fully commercialized (41). Life science companies have worked with implementation companies such as Redwire, SpaceTango, Zin Technologies, and Nanoracks to take advantage of the decline in payload costs to: (1) establish experimental studies that analyze accelerated progression of diseases; (2) develop high-caliber drugs and therapies using microgravity protein crystallization and (3) utilize more morphogenesis control over organoid production to increase the supply of healthy organs and tissue.

3.3.1. Disease Modeling

Disease modeling in outer space can help scientists understand how certain diseases behave and spread to identify potential health risks for astronauts and cutting-edge sterilization technologies for spacecraft and space habitats. Novel conditions in outer space, especially microgravity and cosmic radiation, result in an accelerated loss of skeletal muscle, bone mass and cardiac conditioning, acute radiation syndrome, carcinogenesis, tissue degeneration, and fundamental modifications to the central nervous system (42-46). In particular, modeling cardiovascular diseases (CVDs) in space has potential to expand the current epidemiological research. While the risk of CVDs when

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[17] A notable example is Ohio State University's purchase of an in-space manufactured optical crystal at $2 million per kilogram (10).

exposed to moderate radiation doses is well-established through clinical and experimental studies, the effects of higher doses has not been comprehensively studied despite the increased usage of radiotherapy applications to treat cancer (47-48). Due to ethical concerns about exposing individuals to such doses of radiation on Earth, cosmic radiation in outer space provides a unique opportunity to potentially find novel insights and countermeasures to mitigate both in-space and Earth radiation effects.

Companies such as Nanoracks and Bioserve currently provide plug-and-play laboratories capable of centrifugation and microscopy on the ISS. Techshot has supplied the ISS with commercial bone-density scanners for osteoporosis research. After receiving a three year, $5 million NASA grant, SpaceTango and University of California, San Diego (UCSD) will construct on-orbit biomedical centers to further stem cell therapies in regenerative and translational medicines (49). Redwire has assisted UCSD in studying hematopoietic stem cells transforming into cancer cells as well as the National Stem Cell Foundation in modelling Parkinson's disease and multiple sclerosis using microglial cells in 3D organoids. The Tissue Chips in Space Initiative headed by the National Institutes of Health and the ISS National Lab (with prior research stemming from Stanford University aims to develop a multi-year study on observing human cell and tissue response to microgravity) (50). The Massachusetts Institute of Technology and the University of Florida are also investigating effects of post-traumatic osteoarthritis and muscle atrophy tissue chip experiments, respectively.

3.3.2. Drug Research and Development

Numerous degenerative diseases such as Alzheimer's disease, type 2 diabetes, Parkinson's disease, and certain prion diseases are caused by protein misfolding, in which a protein molecule folds into a nonfunctional shape due to genetic mutations and environmental factors (51-54). By maturing pharmaceutical processes under microgravity conditions, a novel method of developing and analyzing protein crystals may help in discovering new treatable pathways. Protein crystallization in space are developed with less defects; the lack of downward gravitational force allows for a slower and orderly process (55-57). Furthermore, the lack of gravity can lead to the production of higher-caliber protein therapies (i.e. antibodies) and drug deliveries.

The research of stem cells and stem cell-derived products shows great therapeutic promise. Pharmaceutical companies such as Merck, Bristol Myers Squibb and Eli Lily have already conducted microgravity experiments to analyze monoclonal antibodies, protein crystal growth, and a new treatment for muscle wasting. Biotechnology startup LambdaVision received a $5 million grant[18] from NASA to continue its research on bacteriorhodopsin protein crystallization retinas that are produced better in a microgravity environment as it reduces the material and manufacturing costs as well as accelerates the

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[18] NASA's *In Space Production Application* Initiative.

production time for high-quality retinas. The University of Toledo have successfully constructed a physical model of tryptophan synthase, an enzyme involved in salmonella and other bacterial infections in space (58-59).

3.3.3. Organ Manufacturing

There is a major shortage of organs available for transplants. In 2021, 41,354 organ transplants were performed in the United States; of these, 24,670 were kidney transplants (60). While this was a record number of transplants, over 106,000 patients were on the waiting list for kidney transplants, meaning over 80,000 were left on the waiting list, impending life-threatening conditions The imbalance in supply and demand for organ transfers presents a dire need for alternative solutions. Organ manufacturing via 3D printing in space is a potential solution to increasing supply of superior quality organs that have more immunosuppressive capacity than organs created on Earth (61-63). Under microgravity conditions, more delicate organs (e.g. diaphragm) can be biofabricated as well. Furthermore, the manufacturing of organ-on-a-chip, or accurate chips that emulate the function of organs, can further the research on the anatomical effects of space.

Research endeavors by the ISS National Lab along with private industry and university researchers have led to the discovery of several competitive advantages for tissue cell engineering in microgravity conditions, including superior cell proliferation rates, usage of lower viscosity biomaterials/bioinks, superior biofabrication processes[19] (37, 64-66). In 2021 and 2022, Russian company Invitro successfully printed bone tissues and skin bandages with their bioprinter, Organ.Aut, on the ISS. Techshot successfully printed heart tissue using its 3D BioFabrication Facility. Academic research by Harvard Medical School, University of Washington and Emory University to study and develop heart cells (e.g. cardiomyocytes) and cardiac muscle tissue from human induced pluripotent stem cells suggest much promise in increasing supply of heart cells and transplants.

3.4 Nuclear Launch and Propulsion Systems

Due to tradeoffs between power-cost-weight efficiency and the growing environmental concern of increased black carbon emissions, there is an exigent need to develop alternative energy sources to power launch and propulsion systems. Historically, NASA has utilized liquid hydrogen fuel to power rockets as it provides the most thrust power than any other power source, but its costly and precarious properties (e.g., hydrogen embrittlement, low storage temperature, complex tankage, heavier weight) limits its continuous use for the future. Commercial rocket engines such as SpaceX's Raptor and Blue Origin's BE-4 will use cryogenic liquid methane and liquid oxygen (methalox) fuel due to lighter weight and stable properties.[20] However, due to its lackluster propulsion compared to liquid hydrogen, a quest for an alternative fuel source for post-launch and

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[19] In other words, the ability to fabricate diaphanous biological structures that require atomic-level precision and control

long-distance travel remains. Nuclear energy, despite its reputation due to past nuclear accidents, is one of the safest and cleanest methods to create energy and thus may be the ultimate choice for future propulsion sources.

Nuclear energy has potential in the launch technologies, specifically through nuclear thermal propulsion (NTP)[21][22] as it can leverage the superior thrust of hydrogen cutting travel time by 25-50% in comparison to keralox rockets, enhancing NASA's current capital stock and rocket engines. Shorter travel time also means a reduction in astronaut's exposure to cosmic radiation and health effects of microgravity. When factoring in NASA's plans of constructing Kilopower nuclear reactors on the Moon and Mars, less hydrolox fuel would reduce launch costs. Furthermore, nuclear propulsion have performance advantages over conventional chemical propulsion, enabling long-term expeditions such as the Mars Mission.

In April 2021, the Defense Advanced Research Project Agency (DARPA) granted Blue Origin and Lockheed Martin $2.5 million and $2.9 million, respectively, to develop spacecrafts capable of nuclear propulsion. Under the same program, which is labeled Demonstration Rocket for Agile Cislunar Operations (DRACO), General Atomics was awarded a $22 million grant to build a nuclear reactor for space propulsion.[23] In July 2021, NASA and the Department of Energy granted $5 million grants to BWX Technologies (partnered with Lockheed Martin), General Atomics (partnered with X-energy and Aerojet Rocketdyne) and Ultra Safe Nuclear Technologies (partnered with Blue Origin, Hitachi, Generic Electric, Framatome, and Materion). While NTP has shown promise for efficient and lengthy space travel, there are many technical obstacles to overcome, including precise extreme heat control, a lack of ground-based testing facility, and the challenges of managing liquid hydrogen (69).

3.5 Space Agriculture

Approximately 10,000 kilograms of food is required for six astronauts on a 900-day mission to Mars (70). Currently, cargo resupply missions are the main source of food supply for astronauts. A myriad of concerns for developing a stable and sufficient food supply for long-term missions remains, including its nutritional value, palatability,

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[20] While keralox (liquid oxygen and kerosene, also known as rocket propellant (RP) is used in other commercial rockets, its carbon emissions and long-term unsustainability is leading to its subsequent phasing-out.

[21] While NASA had an active research program in NTPs, budget cuts and shifting priorities halted any more progress.

[22] Another alternative is nuclear electric propulsion, in which has the advantage while thrust is lower than NTPs, it is continuous, indicating its superior fuel efficiency, higher speeds, and potentially a 60% decrease in transit time to Mars than conventional chemical rockets (67). Ad Astra Rocket Company is currently developing its VASIMR plasma rocket that utilizes NEP in the form of electric fields while fusion rockets such as Princeton Field Reversed Configuration reactor concept furthers NEP technology by produce a direct fusion drive that directly converts the energy of charged particles produced in the fusion reactors.

[23] In May 2022, DARPA solicited proposals for Phase 2 of DRACO, which focuses on the "design, development, fabrication, and assembly of a nuclear thermal rocket engine" (68)

resource utilization and minimization, cooking preparations, and variety (71). A critically important concern, however, is the cost efficiency; the most recent SpaceX resupply mission CRS-24 contract was valued at $133.3 million, or around $44,608/kg. While SpaceX's Falcon Heavy and Starship payloads will be priced at $1,500/kg and $200/kg,[24] respectively, even at scale, strongly suggest economic infeasibility for a space colony with such an expensive food supply system. Such gaps in supply chain logistics warrants the need to develop in-situ manufacturing practices as a sustainable and cost-efficient alternative to current cargo resupply missions. An emerging interdisciplinary field in space bioprocess engineering (SBE) utilizes synthetic biology and bioprocess engineering to maximize the productivity of input resources while minimizing cost and risk (72). SBE may become the bedrock for sustainable and inexpensive agricultural and food supply.

3.5.1. Controlled Environment Agriculture

By leveraging vertical and indoor farming techniques, agricultural practices in space can be a cost-effective solution with limited input resources (e.g., water, soil, pesticides). While NASA has pioneered controlled environmental agriculture in 1988 at the Kennedy Space Center, outer-space applications have been minimal in comparison to vertical farming activities on Earth. This is due to the multitude of unique stresses plants face in outer space: the limited space and the lack of gravity affects root and nutrient development, the dependence on artificial sunlight, cosmic radiation effects, and water distribution challenges stemming from microgravity.

Recent advances in bioregenerative life support systems (BLSS) can provide large-scale artificial ecosystems that mimic the environmental conditions on Earth, allowing for the production of key biological mechanisms (e.g. carbon and nitrogen fixation) used as inputs for agricultural production (73). By enhancing regenerative capacity of the carbon reduction cycle and photosynthesis while minimizing oxygenation and photorespiration, yield output can significantly improve (74). Through a closed-loop system consisting of microorganisms recycling waste compounds and photosynthetic organisms intaking carbon dioxide to provide oxygen, BLSS would ultimately allow for longer missions after eliminating the dependency on resupply missions.

Companies such as Interstellar Labs, currently partnered with three governmental space agencies (NASA, CNES, ESA), are developing inflatable pods capable of utilizing aeroponic, modular and precision growing systems that maximizes the quantity and quality of production. Four major BLSS systems currently exist on Earth: Yuegong-1 in China, Biosphere 2 in the United States, BIOS-3 in Russia, and MELiSSA in Europe. Partnerships with other agencies and private companies have shown to enhance key technologies needed to create closed-loop systems: the German Aerospace Center, in conjunction with the German Institute of Aerospace Medicine have developed a biofilter technology capable of processing urine into nutrients for plant development.

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[24] There is a highly optimistic estimate made by Elon Musk in which the launch costs will be $10/kilogram.

3.5.2. Food Additive Manufacturing

Advancements in 3D printing technologies and additive manufacturing technologies have allowed for novel materials, from extrusion-based ingredients (i.e., puree, jelly, cheese) to selective laser sintering ingredients (i.e. sugar, protein powder) to be used (75-76). Macronutrients such as carbohydrates and proteins will be in powder form and will mix with oil or water to become paste, which can then be used for printing. Due to its customizable in both nutrition, shelf life and shape, bioprinting may prove to be an efficient method of ensuring that astronauts receive their daily dietary requirements while reducing food waste as well as a morale boost due to the aesthetically pleasing appearance. This is important for long-term and long-distance missions where astronauts do not necessarily have easy access to foods from resupply missions and must rely on a limited selection of nonperishables. The major limitation, of course, is the amount of feedstock that is able to be stored in a spacecraft.

Bioprinting mitigates one of the biggest pain points for astronauts: a lack of meat, which requires hundreds of gallons of water for one pound of beef. Aleph Farms, in partnership with the Israel Institute of Technology, have successfully grown meat from cow cells on the ISS. BeeHex, who received a NASA grant, has developed a 3D printer capable of making and baking pizzas and cakes (77).

3.6 Satellite Services

An established sector of the space industry is satellite technology services, utilized in both communications and data services. Industry giants such as Amazon’s Project Kuiper (partnered with Blue Origin) and OneWeb have begun constructing satellite constellations to capture the global coverage market in hopes of bringing internet and cellular access to the remote areas of the world. SpaceX has already partnered with T-Mobile to provide cellular service to every part of the United States. The satellite sector is expected to expand its services, from quantum satellites and maturing remote sensing, as well as satellite servicing services to maintain satellite operations.

3.6.1. Quantum Satellites

Quantum satellites are satellites with quantum technology capabilities such as quantum communication, quantum state transfer, remote quantum computation, modular operation by linking quantum computers in separate locations, and multi-party quantum information protocols (such as secure bidding). Quantum communication provides the most secure form of information transfer due to the observer effect, Advanced Encryption

Standard (AES) algorithms,[25] and Quantum Key Distribution (QKD), which prevents and detects any intruders. Due to its reliance on single photons sources and exposure to transmission losses, there is a synergy between satellites and the viability of mass scale quantum technology usage. Quantum satellites are capable of transmitting information over long distances (i.e. from Earth to the Moon) that are faster than conventional satellites by many orders of magnitude; currently, radio waves to the Moon takes 2-3 seconds, and to Mars would take 5-20 minutes. Quantum satellites are expected to shorten the time to 30 picoseconds, not to mention it will be much more secure than current satellites (78). Furthermore, satellite-based quantum communication networks avoid the needs of underwater fiber or cable, which both come with known infrastructure vulnerabilities.

Because quantum communication via free space has potential to enhance national security, several governments have spearheaded collaborative initiatives with each other as well as private companies. China's Academy of Sciences has already successfully launched and is currently operating its Micius satellite to develop quantum encryption and teleportation technology; a constellation network that is projected to be complete by 2030. The European Space Agency recently announced a plan to establish a consortium of 20 companies to place a satellite capable of quantum key distribution (QKD) technology in orbit by 2024. Singapore's Office for Space Technology and Industry has partnered with SpeQtral as well as Thales to launch its QKD satellite in 2024. Virgin Orbit and Arqit Quantum have planned for QKD satellite launches for members of the Five Eyes Alliance (United States, Australia, New Zealand, Canada, and the United Kingdom). Japan's Tokyo QKD Network consists of five domestic companies (NEC, Mitsubishi Electric, NTT, and NICT) along with three European partners (United Kingdom's Toshiba Research Europe, Switzerland's Id Quantique, and Austria's All Vienna PPRDP).

3.6.2. Remote Sensing

Remote sensing technologies (RSTs) via satellites provide one of the most cost-effective methods to observe coverage of vast areas and even the whole Earth continuously, allowing for accurate analysis of geophysical and biophysical parameters (79). Use cases range from military and intelligence-gathering to land cover mapping, strengthening national defense and providing delineating and mapping information for resource planning and unlocking dead capital (80). Capella Space provides proprietary synthetic aperture radar imaging capable of accurate rendered images through any weather conditions (i.e., fog, clouds); they have secured contracts with the U.S. Air Force and the National Reconnaissance Office. Orbital Insight provides geospatial analysis for businesses to track human activity; such data has been used to track carbon footprints, logistics, poverty, and other economic conditions (i.e., consumption patterns).

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[25] The AES algorithm is a standalone encryption method used along with QKD. QKD only creates and distributes a secret key to access the encrypted information

Arguably, its greatest economic impact lies in natural resource and commodities management throughout the supply chain: (1) precision farming becomes more profitable with field-level insights, accurate weather forecasts, vegetation detection and index estimation, soil health level; (2) logistics data for commodity procurement and distribution, allowing for accurate shipping as well as carbon emissions tracking and (3) forecasting short-term commodities prices based on geospatial data, from farm level to consumer level markets. Planet Labs manages a constellation network of over 200 CubeSats capable of capturing 3-5 meters high resolution images using multispectral, panchromatic, and video sensors, allowing for military, underground, and oceanic measurements and data. Such data have assisted Norway's Climate and Forest Initiatives as well as the Food and Agricultural Organization to combat deforestation through tracking base maps of countries with high forest densities. A partnership with the California Forest Observatory (CFO) allows Planet Labs to dynamically map forest composition down to the tree level to provide a more accurate tools for assessing wildfire risk. Argentinian company Satellogic also provide key agricultural metrics for crop management, and predictions of biophysical variables while Descartes Labs, founded by Los Alamos National Laboratory scientists, have established a pipeline of data flows to provide instant access to images of the Earth; DARPA will be using Descartes' platform to build global-scale applications and offer them in the marketplace as a commercial service for data scientists (79).

Remote sensing is not limited to terrestrial applications; discovering locations of ice/water deposits and other natural resources on the Moon and Mars as well as precious metals on celestial objects for optimal spacecraft landings and travel can streamline logistic operations. Furthermore, remote sensing can aid in structuring property rights as well as determining property valuations of extraterrestrial land.

3.6.3. Satellite Servicing/Debris

With the expected growth in space exploration, there is likely to be unintended consequences such as the rapid proliferation of satellite and satellite debris. The increasing demand for space goods and services indicates a proliferation of satellite constellations and other LEO objects; an estimated 100,000 satellites majorly proposed by broadband satellite companies,[26] observational satellite companies,[27] CubeSats/small satellite companies,[28] and others, are projected to be in orbit by 2030 (81). While there are an estimated 4,500 active satellites, NASA estimates 9,000 metric tons of space debris composed of inactive satellites, partial rocket and satellite components, and micrometeroids are unaccounted for, with 70% of debris in LEO (82). This jeopardizes key space assets such as the ISS and the Hubble Space Telescope to collisions, exposing

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[26] e.g. SpaceX's Starlink, Telesat Lightspeed, OneWeb, and Amazon's Project Kuiper

[27] e.g. Maxar Technologies, Planet Labs

[28] e.g. RocketLab's Electron rocket, FireFly Space System's Alpha Rocket, Aerojet Rocketdyne's SPARK rocket, and Virgin Galactic's LauncherOne rocket

multilateral space agencies to billions of dollars of potential damages. Without satellite servicing, regulatory guidance to ensure stable increases in satellites, technological advancements to control systems, and methods to exterminate space debris, a possible Kessler syndrome[29] can occur. On the other hand, innovations to mitigate space debris are highly sought after due to the sheer number of projected and current satellites in need of liquidation, repair, or maintenance.[30]

This necessitates preventive and non-preemptive mechanisms to reduce the amount of space debris. Preventive measures include satellite mapping to track objects in LEO; LeoLabs currently provides a subscription service to satellite operators (e.g., SpaceX, Planet, OneWeb, Black Sky) and regulators (US Department of Defense, Air Force Research Lab) with real-time data for any celestial object in close proximity to their assets. Such measures also include satellite servicing, in which satellites are maintained and repaired in-orbit by autonomous and robotic satellites. While DARPA's Orbital Express project and DARPA Phoenix partnership were focused in disposing of geosynchronous orbit debris, industry firms such as SpaceLogistics, a subsidiary of Northrup Grumman, has seen success in providing the first life-extension services to Intelsat 901, a communication satellite, using Mission Extension Vehicle (MEV-1), a satellite service vehicle capable of controlling orbit of a satellite. The second generation of the MEV has also successfully docked to Intelsat 10-02, another communication satellite. DARPA has partnered with SpaceLogistics for its Robotic Servicing of Geosynchronous Satellites program in 2020, in which in-orbit satellite repair and augmentation is projected to occur. Companies such as Momentus are aiming to capture the CubeSat servicing market, while companies like Orbit Fab are attempting on-orbit satellite refueling.

In terms of non-preemptive measures, anti-satellite weapons[31] (ASAT) have been successfully demonstrated by China, India, Russia, United Kingdom and the United States. However, ASATs generate more space debris in smaller parts capable to damaging other satellites. Companies capable to end-of-life disposal services include Airbus, in which its multitool RemoveDebris satellite includes a space harpoon used to capture micrometeroids debris, a net to capture debris up to 2-meter diameter and 2 tons of mass and a drag sail that accelerates deorbiting of a defunct satellite. Japanese start-up Astroscale has developed two satellites capable to searching, inspecting, and docking onto defunct satellites after a proximity rendezvous to ultimately move it farther away from other LEO satellites.

Section 4: Public-Private Research and Development Partnerships

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[29] The Kessler syndrome is a phenomenon in which a cascade effect of collisions will render the whole satellite system inoperable; first proposed by NASA scientist Donald Kessler

[30] As space debris is a negative externality with no individual costs to the satellite operator, as launch costs decrease and satellite manufacturing reach scale, it may be economically feasible to instead replace the old satellite with a new one.

[31] Missiles capable of reaching LEO and eliminating defunct satellites

Given all the innovative opportunities presented in section 3, this section turns to organizational structures among aligned participants that will enhance the probabilities of successful discoveries. Given all the likely participants, an appropriate structure comes in the form of public-private research and development partnership (PPRDPs). Such partnerships can take many forms including formal contractual commitment, resource allocations among the participants and well-established rights for each of the various parties to the partnership (83).

For space exploration innovations and discoveries, there are three major participants: NASA, who provides legacy knowledge and expertise of the space industry; research universities that provide a present and future workforce capable of pushing out the frontiers of both basic and applied fundamental research; and private companies, who provide proprietary research technologies, collaborative researchers, and financing. Any PPRDPs must be designed around the alignment of incentives among the various participants. The incentives for each partner to welcome the inclusion in a PPRDP are as follows:

> **NASA:** NASA staff headcount have diminished over time and as a result has a greater reliance on private contractors. NASA has a significant need for human capital in emerging scientific fields and workforce retraining, especially during the development of joint projects in which they do not necessarily have historical expertise (e.g., machine learning, robotics, data science). NASA is driven in part by the 2021 U.S. Space Priorities Framework that has increased funding to spur R&D initiatives. NASA could more easily accomplish its research agendas and mission of advancing scientific discovery through a PPRDP.
>
> **Research Universities:** While universities are interested in financial capital,[32] they also seek "intellectual capital, cutting-edge research technologies, proprietary research tools, new problem spaces, and technological sandboxes" which ultimately enhances a university's ability to provide a first-rate education to its graduate students and even to serve the regional community's economic development goals (83). Moreover, many universities may be keenly interested in developing its aerospace engineering and space sciences footprint. Research universities would also have an interest in promoting post-graduate opportunities for their students within NASA as well as various private companies, including those that are well-established in addition to innovative startups.
>
> **The Private Sector:** Industry partners have a variety of incentives and goals with respect to any participation in a PPRDP structure. Those private firms that

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[32] In addition to research funds that may stem from technology licensing fees and royalties, universities are interested in the accompanying overhead payment. While these indirect costs vary from one university to another, in some cases these costs to the industry partner are significant.

appreciate and embrace the nonlinear feedback loop relationships between basic and applied research are most likely those to be interested in a PPRDP (84).[33] Most participants from the private sector will not only be interested in commercialization opportunities emerging from the research but also direct access to a talent pool of both undergraduate and graduate students. Both incidental and formal collaborative research with university faculty would also be welcome by private firm participants. Finally, industry partners may well have an interest in subcontracting with NASA.

The alignment of incentives among the three major potential participants in the PPRDP is well established by a long history of governmental legislation. The passage of the 1980 Bayh-Dole Act, which granted intellectual property rights (IPR) from federally funded research to universities, have incentivized research scientists to direct their research agenda towards potential commercial applications. Since this act, over 11,000 startups have been spun off from universities, technology firms and parks near universities have increased, and technology transfer offices have been formed to handle IPRs (85). In parallel, the 1986 Federal Technology Transfer Act established Cooperative Research and Development Agreements (CRADAs), allowing government agencies/national laboratories to facilitate R&D partnerships with non-federal entities (e.g. industry and universities). Under CRADAs, research results are protected under the Freedom of Information Act and while non-federal entities provide 100% of funding, they also retain joint patent rights.

Ultimately, whether any PPRDPs increases the rate of discoveries and commercial innovations depend on whether agglomeration economies can foster externalities such as knowledge spillovers. Two schools of thoughts have emerged to explain the externalities from agglomeration: Marshallian externalities occur in which industrial localization of a specific sector can lead to external economies of scales via knowledge spillovers, labor pooling, and input sharing (86-88). On the other hand, Jacobs externalities stem from a clustering of diverse firms which can lead to creative insights and knowledge spillovers that have interdisciplinary and cross-industry benefits to ultimate productivity (89).

Decentralized Autonomous Organizations Conceptual Framework

A key challenge in structuring PPRDPs is how to share any benefits that might be generated. With PPRDPs, university partners are looking to augment their portfolio of intellectual capital, mainly through publishing research discoveries to the public but also through patent monetization (e.g. licensing rights and commercial spinoffs). The private sector, on the other hand, relies on comparative advantages and profitable investments to remain competitive in their respective industries and will protect any proprietary

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[33] As Louis Pasteur states: “There is no such thing as a special category of science called applied science; there is science and its applications, which are related to one another as the fruit is related to the tree that has borne it.”

discoveries. The initial allocation of control rights is crucial to avoid a "tragedy of the commons" problem, in which individuals deplete a common resource despite it being not efficient for the collective whole.

It is important to recognize that space is a common pool resource. Hardin (1968), which extends Lloyd (1883), argues the only way to avoid this phenomenon is to establish a centralized authority that oversees public, open-access resources (90-91). Ostrom (1990) debunks this theory presenting numerous cases in which economic agents in common pool resource (CPR) institutions effectively self-govern and sustainably manage such resources without privatization and centralization (92). CPR institutions diminish the need for taxes, a major transaction cost; any potential impacts of constitutional organization can be quantified in terms of expected transaction costs that arise in pursuing the collective interest (93).

To maintain public sector interests and university integrity in terms of setting the research agenda while allowing for implementing contractual commitments between universities, NASA, and private companies, a decentralized autonomous organization (DAO) framework has the potential to align incentives and produce cooperative behaviors rather than rent-seeking ones, subsequently producing greater net economic output. DAOs leverage "smart contracts," or contracts that are programmed to be self-executing when predetermined conditions are met. Once smart contracts are established, there is no need for any third-party regulatory agent for the DAO to operate (94), allowing DAOs to be democratically run by members with common rules and purpose. In other words, DAOs have the potential to debunk Hardin's tragedy of the commons.

The institutional framework advanced in Rausser and Johnson (1993) are satisfied by a constitutional smart contract (95). When structuring the constitutional design, any prescription must essentially define: (1) the degree of centralization; (2) the balance of power; (3) identifying interest groups; (4) the space of issues over which those interests can negotiate; (5) the degree of consensus that is sufficient to conclude negotiations; and (6) the appropriate course if negotiations break down (96).[34]

Second, smart contracts can provide legal and regulatory infrastructure that allow for the strict reinforcement of the constitution. In particular, the security or private property, enforcement of contracts, and assignment of liability for wrongful damage must be established (96). This is consistent with the Institutional Analysis and Development (IAD) framework's scope and payoff rules (92). This allows DAO partnerships to have greater transparency and "prescriptive force," or the knowledge and acceptance of a rule leads individuals to recognize that if they break the rule, other individuals may hold them accountable (92).

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[34] Such constitutional smart contract would be consistent with Ostrom's IAD in establishing position, choice, aggregation, and boundary rules.

Third, DAOs, by design, admit that the collective interest of the PPRDP is able, for crucial matters, to rise above immediate self-interest of any particular participants (95). This is accomplished by allocating the majority of tokens to public sector agents, who have internal incentives and mechanisms to preserve the advancements of fundamental knowledge.

Fourth, provisions that discourage collusive activities coupled with policies that provide opportunities to partners who have a comparative advantage are key in achieving sustainable economic growth (95). The transparency and accurate logging of data using blockchain technology allows for these provisions to be fulfilled. While DAOs have a systemic risk of shadow centralization, in which a cabal of rent-seeking interest groups will collude to gain majority decision-making power, a governance provision of the constitutional smart contract will provide the public sector partner, or universities, with 51% of all voting rights to order to assure the partnership will ultimately be to conduct fundamental research with positive spillovers in the space industry.

One possible approach to structure the partnership is summarized here. After the PPRDP fee is paid, partners will receive “soulbound” governance tokens (SBTs), or irrevocable tokens that cannot be sold or transferred to another wallet, to join the DAO. Because of its unique attributes, SBTs can accurately represent and store an entity’s credentials, history with the PPRDP (reputation), as well as implement reputation-based voting, which reduces the occurrence of Sybil attacks[35] and can incentivize active and meaningful participation. Because SBTs can create “novel markets with decomposable, shared rights, and permissions” (98), control rights for IP are less susceptible to IP theft and administrative transaction costs. With these tokens, PPRDP partners have an active say into the governance structure and process. The amount of tokens unlocked will decrease over time; a company who joins the PPRDP in the first year will be allocated more tokens in comparison to a company who joins in the fourth year. The university partner would allocate its governance tokens (51% of all tokens available) to researchers, professors, and staff members in order to satisfy the decentralization requirement.

Other than governance power, a key utility in holding SBTs is the eligibility to buy security tokens for research projects that are in progress within the PPRDP. Security tokens reflect the potential market value of research discoveries that may well lead to patents and/or commercial applications; such tokens are akin to equity shares of startup companies. During the inception phase, an initial coin offering will be conducted with a valuation that estimates what an investor would be willing to spend on an IP of a similar type. Based on the market share percentage and choice, a PPRDP partner would own either: (1) a proportionate percentage of the patent’s income streams (e.g., royalties); (2) right of first refusals; (3) exclusive licensing rights or (4) proportionate payout from another PPRDP partner. Ultimately, a PPRDP in which the sharing and structure for sharing any value of discoveries are determined by the PPRDP.

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[35] Sybil attacks are 51% coordinated attacks utilizing multiple pseudonymous identities to change transaction activity and thereby controlling the blockchain network (97).

PPRDP participants can sell security tokens with one another at market prices or sell it back to the university at a 25% discounted price should they lose faith or have high opportunity costs for other research projects. In other words, liquidity is provided for all PPRDP partners with mechanisms to prevent premature investment retractions, mitigating liquidity concerns industry partners are burdened with while hedging financial risk for public partners. In fact, PPRDP partners are incentivized to provide research personnel or in-kind services in exchange for additional security tokens and increased probability of research discoveries. No more than 51% of total security tokens offering should be sold before the maturity of IPs; the public sector would collectively maintain a majority stake in all holdings to protect the public sector interest and research agenda by prohibiting collusive action from participating private firms.

Section 5: Conclusion

A recent collaboration between NASA Ames Research Center and UC Berkeley might provide a case study for the framework described in section 4. Its goals include the revitalization of the Moffett Federal Airfield and its transformation it into an ecosystem for research and education in space-related fields. The project will bring together researchers and students to focus on innovative fields of section 3, to pursue cutting-edge projects and advance fundamental research in space-related fields. This ecosystem may well migrate into a PPRDP, inviting private companies to partner on research projects, with the goal of fostering both research discoveries, agglomeration externalities and entrepreneurial opportunities in the space industry. The evolution of a PPRDP at this location may well establish the Moffett site as a leading center for space research and education.

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