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Public–private partnerships in fostering outer space innovations

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As public and private institutions recognize the role of space exploration as a catalyst for economic growth, various areas of innovation are expected to emerge as drivers of the space economy. These include space transportation, in-space manufacturing, bioproduction, in-space agriculture, nuclear launch, and propulsion systems, as well as satellite services and their maintenance. However, the current nature of space as an open-access resource and global commons presents a systemic risk for exuberant competition for space goods and services, which may result in a "tragedy of the commons" dilemma. In the race among countries to capture the value of space exploration, NASA, American research universities, and private companies can avoid any coordination failures by collaborating in a public–private research and development partnership (PPRDP) structure. We present such a structure founded upon the principles of polycentric autonomous governance, which incorporate a decentralized autonomous organization framework and specialized research clusters. By advancing an alignment of incentives among the specified participatory members, PPRDPs can play a pivotal role in stimulating open-source research by creating positive knowledge spillover effects and agglomeration externalities as well as embracing the nonlinear decomposition paradigm that may blur the distinction between basic and applied research.

polycentric governance | intellectual property | agglomeration externalities | economics of space

What was once limited to the realm of science fiction 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 (see refs. 1–4). While satellite services likely comprised the most viable and profitable venture in space, the adoption of novel space-based goods and services, from space tourism to organ bioprinting, shows the potential to disrupt even incumbent industries on Earth.

Since outer space is an open-access resource without strict global regulation.* Any country or firm with sufficient capital can join the space race to capture the growth value of space. Therefore, countries and companies must accelerate their innovation processes to uncover new research findings and identify potential commercial opportunities. To support research development, a natural evolution toward fostering collaboration between the private and public sectors could, if properly designed, provide a superior research and development platform to increase the probability of successful breakthroughs. Traditionally, the NASA has largely acted as the sole public partner for most space-related public–private partnerships (PPPs). The available evidence makes it clear that NASA has created incentives† for the private sector to actively engage in R&D, helping to remove many of the obstacles (i.e., coordination failures) that arise in such efforts to expand the knowledge frontier for space exploration.

As NASA continues to contract with private companies, the next natural step is to establish public–private research and development partnerships (PPRDPs) with the inclusion of research universities. This expanded scope for the public dimension could include the codification of significant discoveries (5) as well as the potential for the open-sourcing of research findings. By strengthening multilateral research collaboration between NASA, research universities, and the private sector, such PPRDP can eliminate coordination failures by aligning incentives and resource integration, eliciting more capital investments that would increase basic research that generates public goods and commercialized technologies emanating from applied research.

The paper proceeds as follows. We first outline public and private sector activities pertaining to major innovations that will be instrumental in capturing the growth possibilities of the space economy. We then evaluate the partnership and incentive structures of PPRDPs. The next section addresses how PPRDPs can increase the probability of major research discoveries and innovations via agglomeration externality effects. Last, we introduce a novel form of polycentric governance to administer PPRDPs by using decentralized autonomous organizations.

*While each country has regulatory agencies and there are international treaties (e.g., Outer Space Treaty and Moon Agreement), these institutions actually promote free use of space via placing safety, indemnification, and peaceful measures.

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†Examples include NASA Innovative Advanced Concepts program, NASA Flight Opportunities program, and NASA Space Technology Mission Directorates.

Table 1. Space transportation

Current progress	Private entities	Public entities
Reusable space rockets, mass-scale 3D-printed rockets, logistics services, deep space exploration, and mining	SpaceX, Orbital Sciences, Sierra Nevada, Northrop Grumman, Blue Origin, Relativity Space, Rocket Lab, Qosmosys, SpaceTango, Redwire, Airbus, and Zin Technologies	Massachusetts Institute of Technology (MIT) Space Propulsion Laboratory, California Institute of Technology (CIT) and Jet Propulsion Laboratory, University of California, Los Angeles Rocket Project, University of California, Berkeley (UCB) Space Sciences Laboratory, and University of Central Florida

Research Cluster Synthesis

After synthesizing the existing literature, the following six innovative fields, or "research clusters," are likely to emerge as dominant space sectors over the next couple of decades; the current progress accomplished by private and public entities are listed in Tables 1–6.[‡,§] The first cluster is space transportation and logistics, in which research and development related to vehicle launch systems have been directed toward efficient production methods (i.e., reusable rockets and 3-D printed spacecraft) to lower transport costs of payloads and passengers (1, 6). The second field is in-space manufacturing (ISM), or the application of additive manufacturing in low-Earth orbit and in situ resource utilization, which have become a cost-efficient source for in-space consumption of necessary goods (7–11). By leveraging microgravity, ISM can also provide high-grade goods (e.g., ZBLAN fiber-optic cables) for consumption on Earth. The third research cluster is bioproduction, which is the production of organs (12–19), tissue chips, and drug therapies (20–27) under microgravity conditions as well as disease modeling (14, 28–34). The fourth innovative field is in nuclear launch and propulsion, which utilizes nuclear energy to potentially substitute current fuel sources that use chemical reactions as propellants (i.e., hydrolox and kerolox) (35–37). The fifth is space agriculture, as the production of food in space via controlled environment cultivation (38–40) and additive manufacturing (41–43) will lower food transport costs as well as make viable long-term space exploration and civilization. Last, the sixth is satellite services and maintenance. By expanding the scope of satellites to include quantum communication and remote sensing capabilities (44), the potential to strengthen the secure data and observation industry would unlock new economic opportunities. With the proliferation of satellites, servicing and debris regulations will also need to emerge (1, 45, 46).

The expansion of space-based economic activities will result in several implications for various industries on Earth. As the space transportation sector reduces launch costs by achieving scale and efficiency in rocket production and reusability, an increasing number of firms would be encouraged to invest and develop space-based goods and services. Although the majority of goods will remain more cost-effective to produce on Earth, in-space manufacturing (ISM) of essential components and tools to be used during missions and a varied food supply via in-space crop cultivation and additive manufacturing[¶] would significantly diminish or even eliminate the need for resupply missions from Earth.

Table 2. In-space manufacturing

Current progress	Private entities	Public entities
Production of vital and emergency equipment during missions (i.e., finger splints, ventilator regulator valves), circumventing space launch time and costs, in situ resource utilization via recycling plastics for 3D printing feedstock, potential for metal-organic frameworks to create closed-loop ecosystems in space, production of superior microdevices (i.e., ZBLAN), and semiconductor products leveraging microgravity	Made in Space (a subsidiary of Redwire), Faraday Technologies, MoonFibre, Tethers Unlimited (acquired by Amergint Technologies), Pratt & Whitney, Fiber Optics Manufacturing in Space (FOMS), Apsidal, DSTAR Communications, Physics Optics Corporation, and Axiom Space	Department of Commerce's National Institute of Standards and Technology Advanced Technology Roadmap program: University of New Hampshire, Purdue University, University of Alabama; NASA Institute for Model-Based Qualification & Certification of Additive Manufacturing (IMQCAM): CMU, Vanderbilt University, University of Texas at San Antonio, University of Virginia, Case Western Reserve University, Johns Hopkins University Applied Physics Laboratory, Southwest Research Institute; Texas State University; and Iowa State University

[‡]NASA is engaged in all of these innovative fields, but the purpose of this table is to show the amount of involvement from public and private entities.

[§]This table is not inclusive of all private and public entities currently pursuing research and development in the research clusters.

[¶]This provides opportunities for the agriculture and additive manufacturing sectors on Earth to expand their R&D scope to include in-space applications, which may result in novel technological and innovative advancements.

[#]In addition to the benefit of leveraging microgravity to create stronger protein crystallization that results in superior drugs, there is an ancillary benefit of improved disease modeling. 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 (29–31). In particular, modeling cardiovascular diseases (CVDs) in space has the potential to expand the current epidemiological research. While the risk of CVDs when exposed to moderate radiation doses is well established through clinical and experimental studies, the effects of higher doses have not been comprehensively studied despite the increased usage of radiotherapy applications to treat cancer (33, 34). 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 radiation effects.

Table 3. Bioproduction

Current progress	Private entities	Public entities
Organ and tissue chip biomanufacturing: Heart, liver, and muscle tissue chips with faster growth and superior quality (in terms of function and formation) and the potential for developing human-induced pluripotent stem cells to increase the supply of heart cells and transplants	LambdaVision, Redwire, Emulate, Roche, Takeda, and Bristol Myers Squibb	Harvard University Medical School, University of Washington, Emory University, National Institute of Health, Johns Hopkins University, Cedar Sinai Medical Center Regenerative Medicine Institute, University of Pittsburgh, Georgia Institute of Technology, and Sanford Burnham Prebys Medical Discovery Institute
Drug development and production: Enhancement of protein crystallization and drug development in microgravity conditions, including monoclonal antibodies, muscle wasting treatment, and eye retinas via bacteriorhodopsin protein crystallization	Merck, Eli Lily, and Maker Health	University of California, San Diego (UCSD) Astrobiotechnology Hub and Sanford Stem Cell Institute, and University of Toledo
Disease modeling: Identifying the health impacts of outer space (cosmic radiation and microgravity), which produce accelerated health conditions, specifically in musculoskeletal diseases	Nanoracks, Techshot, SpaceTango, and SpaceX	University of Colorado Boulder BioServe Space Technologies, Scripps Research Institute, Exomedicine Institute, New York Stem Cell Foundation Research Institute, MIT, University of Florida, University of Toledo, and UCLA

This allows the reallocation of resources to be directed toward the production of highly valued goods, such as organ and drug therapies, which have the potential to alleviate the supply bottleneck of high-quality drugs and organ transplants in the biotechnology and healthcare sectors.[#] Redistribution of investments and resources can also be allocated to develop new and existing infrastructure in space, especially satellites and communication networks, which can improve productivity on Earth. This provides the necessary foundation for advancing quantum computing, encryption, and communication services as well as refining remote sensing capabilities. Consequently, there is potential to expedite discoveries in the Big Data, finance, agriculture productivity, natural resource management, and climate sciences sectors as well as national security.

As demand increases for space-related goods and services, it is possible for the space transportation sector to experience a "virtuous cycle": Increased demand for launches and missions would result in higher revenues and retained earnings, which can be used to invest more into high-risk and capital-intensive R&D, such as nuclear thermal/pulse propulsion technologies. Such major breakthroughs and innovations would enable launch companies to offer lower prices for logistics services and thus expand their market penetration.

As the virtuous cycle continues, the overall space economy would allow the expansion of new markets and opportunities, generating public interest and support for space initiatives. One possible initiative is to develop specialized educational programs and training in space-related fields, such as space resource management and engineering, to nurture the next generation of space scientists and entrepreneurs. Not only would this offset the job displacement in Earth-based industries but also contribute to the growth and diversification of the space economy.

Public PRDPs

Historically, public–private partnerships (PPPs) between NASA and commercial enterprises have successfully encouraged private-sector research and development in the space industry. NASA's dependency on private contractors was evident since the 1961 Project Mercury and has only intensified, as observed by the 2006 COTS program, 2008 CRS program, and the 2017 Artemis program (45, 47, 48). With a multitude of policies that promote PPPs, such as the 2010 National Space Policy and the 2004 Commercial Space Launch Amendments Act, several major defense contractors and space companies have not only strengthened the United States' spaceflight and satellite capabilities but also ushered in new industry sectors (49, 50). Recent initiatives under NASA's Space Technology Mission Directorate display a strategic approach to utilize "spin-in" technologies from other industries (i.e., additive manufacturing, biotechnology, and quantum computing sectors), which have the potential to help form the foundation for breakthrough technologies in the space sector.

These initiatives, coupled with the maturity of launch companies and declining launch costs, spurred commercial enterprises and partnerships to invest, participate, and

Table 4. Nuclear power in launch and propulsion

Current progress	Private entities	Public entities
Leveraging nuclear thermal propulsion (NTP) to cut launch time by 25 to 50% relative to kerolox rockets, increased reliance of radioisotope thermoelectric generators as the power source for spacecraft	Westinghouse, Zeno Power, NDB, Nvidia, Agilent, AMD, GE, Lockheed Martin, Blue Origin, Ultra Safe Nuclear Technologies, X-Energy, Radiant Nuclear, General Atomics, Aerojet Rocketdyne, Hitachi, Ad Astra, Framatome, and Materion	MIT Advanced Nuclear and Production Experts Group, and US Department of Energy's Idaho National University

Table 5. Space agriculture

Current progress	Private entities	Public entities
Controlled environment agriculture: Inflatable pods capable of utilizing aeroponic, modular, and precision growing systems. Peppers, rice, lettuce, and chickpeas have been successfully grown in space	Interstellar Labs, Tupperware Brands, StarLab Oasis, Voyager Space, Orbital Farms, Cosmic Eats	University of Arizona Controlled Environment Agriculture Center, German Aerospace Center, Stanford University, and Lawrence Berkeley National Laboratory (Center for the Utilization of Biological Engineering in Space)
Food additive manufacturing: 3D-printing of customizable foods in terms of nutrition, shelf life, and shape	Aleph Farms, BeeHex, BigRedBites, Bistromathic, Deep Space, and Entomoculture	

innovate in the space industry. In order to advance the rapidly evolving space frontier, a public–PRDP (PPRDP) structure could be instrumental. Such partnerships have the potential to significantly enhance the development and application of technological innovations and novel research findings in space. In such a structure, there are three major participants: NASA, which creates opportunities for public good research and overcomes coordination failures; 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 financing, proprietary data, and collaborative researchers.

In the establishment of any PPRDP, preliminary work must be done to assess the relative research strengths, assets, and commitments of various potential partners (5). Such assessments will be particularly important with regard to research university partners as well as private sector partners. In this respect, preliminary evaluations for the inclusion of critical partners are as follows:

NASA. NASA staff headcount has diminished over time, and as a result, NASA 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 US 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, they also seek "intellectual capital,[‖] cutting-edge research technologies, proprietary research tools, new problem spaces, and technological sandboxes" (5), 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. Moreover, many universities may be keenly interested in

Table 6. Satellite services and servicing

Current progress	Private entities	Public entities
Quantum satellites and computing: Quantum channels established via entanglement, allowing for quantum encryption and communication	Cisco, Honeywell Quantum Solutions, Atom Computing, Quantum Xchange, Safe Quantum, and Arqit Quantum	DARPA, NASA Quantum Pathways Institute: University of Texas at Austin, University of California, Santa Barbara; CIT; National Institute of Standards and Technology; University of Colorado Boulder
Remote sensing: Real-time data of terrestrial weather conditions with forecasting abilities, synthetic aperture radar capable of rendering images through any weather conditions, geospatial analysis for carbon footprints, logistics, and military uses, and deep space coverage for incoming celestial objects; potential to be used to find asteroids/objects with dense amounts of precious metals	Capella Space, Maxar Technologies, Orbital Insights, Planet Labs, BlackSky Global, and Descartes Labs	University of Arizona Laboratory for Remote Sensing and Geoinformatics, University of Maryland Department of Geographical Sciences
Satellite servicing: Subscription for real-time data to detect any objects near satellite assets, satellite service vehicle capable of redirecting satellite away from collisions, in-orbit satellite repair and augmentation, in-orbit satellite refueling, end-of-life disposal services via deorbiting	LeoLabs, SpaceLogistics (a subsidiary of Northrup Grumman), Momentus, Orbit Fab, and Airbus	US Air Force Research Laboratory's Space University Research Initiative (Space Logistics): Carnegie Mellon University, Texas A&M, University of New Mexico, US Air Force Research Laboratory's Space University Research Initiative (Space Domain Awareness): University of Buffalo, Pennsylvania State University, Georgia Institute of Technology, MIT, and Purdue University

[‖]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.

developing their aerospace engineering and space sciences footprint. Research universities would also have an interest in promoting postgraduate opportunities for their students within NASA as well as various private companies, including those that are well established in addition to innovative startups.

Private Sector. Industry partners have a variety of incentives with respect to any participation in a PPRDP structure. Those private firms that appreciate and embrace "open innovation" are most likely those to be interested in a PPRDP.[**] Most participants from the private sector will not only be interested in commercialization opportunities emerging from the research but also in 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 potential 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, has incentivized research scientists to direct their research agenda toward 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 (51). 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 nonfederal entities (e.g., industry and universities).

While each of the three major stakeholder groups is pursuing major research discoveries, they could be much more effective through collaboration and cooperation via PPRDPs. One of the key reasons is resource pooling as each partner has a complementary supply and demand for human and intellectual capital. For example, a research university and NASA may need proprietary technology or datasets, while a private company and NASA may need a talent pool of faculty and graduate students with expertise in the subject matter.

Another key reason is the funding source; NASA and the private sector are expected to contribute monetary resources to support the PPRDP. Despite the major scientific breakthroughs from governmental funding of university research,[††] the government is pressured to decrease overall spending on research programs. In contrast, R&D expenditures in the private sector have grown dramatically, and universities are increasingly attempting to offset declining public funds with private resources (5). Universities recognize that private funds are not perfect substitutes for public funds, and research partnerships with the private sector present a unique set of challenges. Such challenges are exacerbated by the potential "crowding-out" of public good research, in which as a result of reduced government funding, public good research will be neglected, and the research agenda will be expanded toward commercial applications (5).

If the direction of the PPRDP is to produce more open-access research.[‡‡] The two public partners, namely NASA and research universities, have clear incentives to be active participants in PPRDPs. However, the private sector would be more hesitant to associate with such PPRDP as it does not necessarily lead to competitive advantages that might be embedded in exclusive patent and/or licensing rights. This perspective is valid if the linear decomposition paradigm of scientific research holds.

The traditional paradigm of scientific research, which was strengthened by Bush (1945), assumes a linear progression from basic research conducted by the public sector to applied research conducted in the private sector (52). In this paradigm, applied researchers are not responsible for driving basic research; knowledge only flows from universities to private firms. Additionally, this paradigm views the output of universities, basic research, as a public good that is both nonrival and nonexcludable. This means that basic scientific research discoveries cannot be diminished through use and should be accessible to all. Since private firms lack incentives to produce public goods, a result of this paradigm is that the government has the major responsibility to fund public goods university research.

The Bush paradigm has been challenged by the nonlinear, feedback loop research paradigm promoted by Kealey (53). Kealey's framework suggests that the interaction between basic and applied research is what drives scientific discovery. Unlike the linear progression paradigm, this framework considers the feedback loops between basic and applied research to be chaotic and unpredictable. As a result, the traditional distinctions between the public and private outputs of basic and applied research become blurred. Basic research discoveries can augment applied research, and private firms may pursue intellectual property rights to capture the value associated with their discoveries. This incentivizes private firms to invest in basic scientific research, shifting some of the burdens of funding from the public to the private sector.

A notable case study of open-access-oriented PPRDP[§§] in space is the International Space Station National Laboratory (ISSNL), which is managed by the Center for the Advancement of Science in Space (CASIS). The ISSNL utilizes a number of agreements and contracts (i.e., MOUs, Space Act Agreements, IP Agreements, and Commercial Space Act Agreements) to govern its partnership with the private sector, the non-profit sector, and academic institutions. These partnerships conduct a variety of research, includ-

[**]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."

[††]This includes public health through the NIH, science, engineering, education, and technology through the NSF, and national defense through the Defense Advanced Research Projects Agency (DARPA).

[‡‡]Open access knowledge is any research discoveries that are made freely available without any restrictions and fees. By providing open-access information, any entity can advance further research and development, allowing for more efficient translation of fundamental research to practical applications that may improve a myriad of societal problems.

[§§]There have been joint research projects that allow exclusive licensing for private partners under special circumstances. If a private partner has already developed proprietary technology and is engaged in experimentation, any intellectual property derived from the partnership is exempt from becoming open access knowledge.

ing fundamental research, commercial service provider research, in-space production, and technology development via a sponsored research model; much of the research discoveries are open to the public (54).

From 2020 to 2022, CASIS showcased its success in generating scientific outputs, with over 75 peer-reviewed articles resulting from its sponsored research published in this period. Most of these publications pertained to fundamental research, driven jointly by the NSF and the NIH. Additionally, seven patents were granted for technologies developed through CASIS-sponsored research, including Emulate's intestinal tissue chip technology, Hewlett Packard's cooling system for space computers, and Redwire Space's sensor system for manufacturing optical fibers in space (55, 56).

Despite these accomplishments, CASIS has grappled with a myriad of issues that question its efficacy as a research platform. A notable challenge has been difficulties in securing non-NASA funding despite its public–private partnership model, threatening the commercial viability of joint fundamental research despite its public–private partnership model. Moreover, an audit from the NASA Office of Inspector General in 2018 revealed that CASIS had only utilized approximately 73% of its available research hours, suggesting potential inefficiency in resource use (57). Coupled with failing to meet certain performance metrics as well as leadership and operational instabilities, there is a need for the implementation of robust governance and oversight mechanisms.

Another case study is the University of California, Berkeley (UCB)'s Berkeley Artificial Intelligence Research (BAIR) laboratory, specifically its Open Research Commons program, an industrial affiliate program to develop open research in artificial intelligence (AI). UCB students and faculty members will lead the design of AI research projects, meaning they control the research agenda. Companies pay membership fees to have access to collaborative joint research projects, "with intellectual property shared jointly and equally by the parties" (58), and research spaces within the UCB campus. It is important to note that all research outcomes will fall under the categories of nonexclusive licensing and open-source research. Similar public–private partnership programs in the artificial intelligence space such as OpenFold (members include Columbia University and Bayer) rebuke the popular belief that intellectual property must be exclusive and protected in order for the private sector to have incentives to invest in fundamental research.

Private firms who believe in Kealey's nonlinear paradigm would be more likely to accept the open-access research agenda. However, in cases in which the private sector will only participate in PPRDPs that only focus on proprietary research, there is much uncertainty as to how such partnerships can operate without multilateral bargaining problems and unforeseen conflict. In other words, if valuable research discoveries do not result in open-sourced intellectual property, conflicts over IP allocation can unravel the partnership and any future collaboration.

To effectively navigate the initial stages of a PPRDP, it is crucial to address institutional misalignment of interests and negotiate a research agenda that satisfies all parties. While public sector organizations focus on developing public knowledge, private companies often seek short-term profitable projects for commercialization. Risks associated with private sector involvement in public research include the potential distortion of public good research, restriction of academic freedom, and crowding out of basic research. Moreover, pressure to delay academic publications may arise to offer private partners a first-mover competitive advantage, raising concerns about relying on private funding sources.

Challenges may also emerge in PPRDPs due to the need to allocate intellectual property rights (IPRs) following major breakthroughs. Research universities may prioritize public good or their own interests, while industry partners aim to protect and monetize research discoveries. Bureaucratic activities, particularly from technology transfer and licensing offices, can slow decision-making and lead to conflicts of interest. Furthermore, cultural misalignments, such as differences in risk tolerance, the pace of decision-making, and shareholder versus stakeholder accountability, can impede collaboration and hinder the effectiveness of a PPRDP.

By their very nature, PPRDP agreements can be characterized as incomplete contracts that cannot take into account all possible contingencies (5). Under such circumstances, however, "control rights" or decision rights must be structured. These rights, or "options," determine how decisions will be made when contingencies arise. In other words, control rights represent an option to control a decision or action that will arise at a later date, when more information is available or other contingencies have occurred.

In the context of research agreements, control rights specify the degree to which a partner retains control over the research process as it unfolds. Simply, the balance of these rights should be tied to the overall goals of the PPRDP. If generating innovations that can be commercialized along with supporting the local business community is the primary goal, relatively more control rights should be turned over to the private partner because the private partner is likely to make the most efficient decision when facing unexpected research events (59). If, on the other hand, the primary goal is generating basic research, the public partner should wield more control in the face of contingencies.

Agglomeration Externalities to Increase Returns on Space R&D

A well-structured PPRDP will expand the network of private companies interested in participating in joint research with research universities and government agencies in efforts to capture increasing returns to scale from R&D. Ideally, a PPRDP would also include a proximity provision for all partners to have a physical presence near each other to promote positive agglomeration externalities, namely, externalities stemming from a concentration of firms and sectors in close proximity with one another that makes it easier to achieve scale economies. Agglomerated regions would experience an increase in intellectual activity and firm productivity, which can be reflected by higher wages, the number of patents filed, or greater revenue generation in comparison to a similar city or region (60–62).

There are two major categories of agglomeration externalities: i) Marshallian-type 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 (63–65). ii) Jacobs-type externalities stem from the clustering of firms from diverse sectors, which can lead to creative insights and knowledge spillovers that have interdisciplinary and cross-industry benefits to productivity; in other words, cross-fertilization of ideas and knowledge is possible even in random and unplanned interactions due to close proximity (66, 67).

One major agglomeration externality is the knowledge spillover effect, which is the low-cost exchange of ideas between an originating firm and a recipient firm (68, 69). Agglomerated regions promote incidental contact, making knowledge spillovers more likely. By enabling firms to access knowledge from others, industries can adopt best practices and accelerate learning, resulting in unique discoveries and innovations. This can lead to increased returns to scale of R&D.[¶¶] An agglomerated region can generate additional benefits from close proximity to research institutions (e.g., universities) for knowledge creation and spillovers (71–73).

Agglomerated regions also experience labor pooling and resource sharing between firms. Because some workers can become associated with a new firm, and if similar companies with similar needs, qualifications, and other labor hiring criteria are in close proximity, workers are able to borrow knowledge and skills from each other in industrial clusters over a short period of time. Enterprises have the opportunity to recruit trained employees with ready-to-use knowledge and skills, which reduces the cost of training staff. There also occurs a positive feedback loop in which labor pooling may attract skilled labor and relatively higher human capital in agglomeration regions due to the professional development opportunities. Similarly, firms share common infrastructure (i.e., transportation and communication networks) as well as service and supply providers, which result in cost savings and increased productivity from economies of scale.

Because firms in agglomerated regions can share resources and human capital, they are also implicitly sharing economic risks, such as fluctuations in the labor market, consumer preferences, or even shifts in regulation. This allows firms to be less risk-averse since industry risk is implicitly hedged by the collective network of similar firms. In regions with a cluster of diverse sectors, industry-specific economic shocks would be mitigated by the diversification across sectors, providing resiliency to agglomerated regions.

The space sector is in a unique position to benefit greatly from both Marshallian and Jacobs externalities due to the heterogeneity of firms in different lifecycle stages. Startups and early-stage firms can learn from and collaborate with established firms, while the latter can benefit from the agility and innovation brought by newer entrants. For example, the rise of partnerships between space logistics startups and a variety of established firms from the biotechnology sector to pursue novel applications of biotechnology in microgravity settings is a clear indication of the increasing scope of innovation in space. This dynamic environment can lead to faster innovation cycles and a greater capacity for adaptation to changing market conditions and technological advancements.

Heterogeneity among agglomerated economies highlights the importance of a network vs. firm-based organization system in promoting externalities and cross-disciplinary research. While Silicon Valley's high technology sector is the quintessential example of localized and urbanized agglomeration, the regional cluster of technology firms in Route 128 beltway in Boston had a chilling effect on potential agglomeration externalities. Saxenian points out the key difference in their network vs. firm-based organizational system: While Route 128 did not deviate from conventional corporate structures (i.e., centralized authority via tight hierarchies, vertically integrated firms that promoted self-reliance, and closed-door policies), Silicon Valley promoted open labor markets, loose company hierarchical structures as well as social networks between competitors, and other research institutions with vast "absorptive capacity" (74, 75).[##] In other words, Silicon Valley can be characterized as one vast network with localized technology firms that were competitors but also frequent collaborators in both intellectual output and labor pooling, ultimately resulting in Marshallian externalities. This also allowed for the advent of diverse, cross-disciplinary sectors such as FinTech, MedTech, BioTech, FoodTech, AgriTech, and HealthTech, complementing Marshallian externalities with Jacobs externalities for consistent growth in innovation (77). This signifies the importance of leveraging spatial proximity to develop a decentralized network of firms with institutional and governance flexibility in order to capture agglomeration externalities.

Decentralized Governance

As noted in our introductory section, space is an open-access resource. The nature of the resource is recognized in the 1967 Outer Space Treaty (OST), to which 113 United Nations member countries are party, permit access to space by any nation or entity, and prohibits ownership claims of celestial bodies such as the Moon (78). Additional provisions in this treaty and subsequent agreements discourage the generation of harmful environmental contaminants, detail liability clauses for damages to foreign assets, and promote multilateral cooperation and mutual assistance during space exploration.

With the lowering of barriers to entry resulting from the ongoing commercialization and innovations in the space launch system sector, global competition can be expected to increase dramatically for in-space goods and services over the next few decades. As a result, the degree of support for cooperative ownership has diminished; this is reflected in the most recent United Nations treaty: The 1979 Moon Treaty has only 18 parties (in contrast to 113 parties in the OST), with Saudi Arabia withdrawing from the treaty in January 2023 (79). Domestically, the 2015 US Commercial Space Launch Competitiveness Act has established property rights for any resources in space returned to Earth. More recently, the 2020 Artemis Accords have further under-

[¶¶]In contrast, closed-door policies may lead to the duplicity of inefficient industry practices and a knowledge bottleneck, dramatically stunting R&D growth (70).

[##]This reflects an extension of Marshallian externalities called "Porter externalities," which argues that local competition instead of local monopoly in regions that experience knowledge spillovers fosters the rapid adoption of innovation (76).

mined the OST with the specification that "the extraction of space resources does not inherently constitute national appropriation under Article II of the Outer Space Treaty" (48). Sixteen countries have signed the Accords, and three signatories, namely Japan, Luxembourg, and the United Arab Emirates, have already enacted domestic legislation to protect space property rights.

As the in-space economy evolves and becomes mature, disparities between established firms and newcomers may arise. Companies that acquire market power, perhaps resulting from the enforcement of exclusive intellectual property rights, will hinder competition and innovation while creating negative environmental externalities like space debris and low-Earth orbit congestion. Furthermore, since space is a global commons, addressing market failures and promoting public goods through government intervention is challenging as hegemonic actions infringe on the sovereignty of other nations. This situation could eventually turn outer space into a depleted common pool resource with minimal ex-post correction opportunities.

Hardin's argument (80), extending Lloyd (81), asserts that open-access resources require centralized authority to avert catastrophes. Coase, however, offers a counterargument in which under specific prerequisites of low transaction costs, well-defined property rights, and perfect information, parties could negotiate and manage resources efficiently (82). Ostrom (83) presents an alternative framework to Coase (82), proposing sustainable management of common pool resources through collective action and self-governance. Local ecosystems such as pastures and irrigation systems have been successfully managed using Ostrom's "polycentric governance" model that is reliant on similar factors (i.e., low transaction costs, uniform values, and incentives) (83, 84) (Polycentric governance refers to multiple, overlapping decision-making centers that cooperate together to manage resources).

In the case of international regimes such as those needed for space exploration, the application of Coase bargaining and Ostrom's polycentric governance faces significant challenges. In the case of Coase, property rights for outer space resources are not well articulated, and there exist high transaction costs to enter space, which clearly have a chilling effect on any bargaining that takes place. In the case of Ostrom, diverse actors with varying preferences and power disparities make consensus for stable self-governance difficult to achieve. The enforcement of agreed-upon rules without a centralized authority, and the absence of adaptive governance mechanisms to mitigate conflicts, could potentially undermine the efficiency of Ostrom's governance strategies.

The principles of polycentric governance, however, can be used to structure PPRDPs to increase open-access research output. Private participants who recognize the continuous and interactive relationships between applied and basic research that have been described in Section 2 are provided the opportunity to develop the open-access research agenda. Furthermore, open-source research from PPRDPs will lead to "crowding-in" of public good research than what would otherwise have not taken place (5). PPRDPs can achieve economies of scale to drive increasing returns for all participants but in addition can capture a larger amount of agglomeration externalities if the partners are sufficiently in close proximity to one another.

To maintain public sector interests in terms of setting the research agenda while allowing for contractual research and development commitments between universities, NASA, and the private sector, a decentralized autonomous organization (DAO) framework (DAOs are a novel governance structure that exists on a blockchain protocol in which an organization can operate with no centralized authority) has the potential to align incentives and produce acceptable control rights for successful joint research projects. DAOs are able to maintain decentralization using "smart contracts," [Smart contracts are software programs that execute automatically when preestablished "if–then" conditions are met. Use cases of smart contracts include escrow services (funds are held in escrow between two stranger parties until conditions of the transaction are met), prediction market (automatic distribution of funds after a certain outcome, such as an election or a stock price), and voting (automatic decisions after a vote is tallied)] or contracts that are programmed to be self-executing when predetermined conditions are met. A smart contract is analogous to a nation's constitution, except it is extremely difficult for procedural drift to occur because of its immutable and self-executing nature (5) (Once the terms of the smart contract are programmed and deployed on the blockchain, it cannot be modified without the consensus of the DAO). Once smart contracts are established, there is no need to trust other members or a centralized third party for the DAO to operate, reducing counterparty risk and the dependency on trust among members (85) (Note that a network of firms in agglomerated regions that embrace resource and labor pooling as well as R&D collaboration can be unofficially considered a form of polycentric governance. However, the level of decentralization and collaboration can affect the magnitude in which positive agglomeration externalities are captured. Due to the trustless-based mechanisms of a DAO, specifically smart contracts, decentralization cannot be relinquished, mandating collaborative activity, potentially resulting in greater positive agglomeration externalities).

The institutional framework advanced by Rausser and Johnson is satisfied by a constitutional smart contract (86). When structuring the constitutional design, any prescription must essentially define: 1) the degree of decentralization; 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 (87) (Such constitutional smart contracts would be consistent with Ostrom's Institutional Analysis and Development Framework in establishing position, choice, aggregation, and boundary rules). Smart contracts can provide the legal and regulatory infrastructure that allows for the strict reinforcement of the polycentric governance structure. In particular, the security of private property rights, enforcement of contracts, and assignment of liability for wrongful damage must be established (86). This allows DAO partnerships to have greater transparency and "prescriptive force." The knowledge and acceptance of a rule lead individuals to recognize that if they break the rule, other individuals may hold them accountable (83).

DAOs, by design, admit that the collective interest of the PPRDP is able, for crucial matters, to rise above the immediate self-interest of any particular participants (86). This can be accomplished by allocating the majority control to public sector agents, who have internal incentives and mechanisms to emphasize fundamental knowledge advancements. The transparency and accurate logging of data using blockchain technology allow for these provisions to be fulfilled.

The PPRDP can be structured by a public research institution, partnered with NASA and other government agencies relevant to space research, to create a DAO on a public blockchain. The DAO's main objective is to provide necessary resources and capital for several research clusters, which are organized research groups that vary by areas of study with the potential for public good research as well as commercial innovations in the space sector. Each research cluster would consist of human and intellectual capital from the public sector as well as potential for private sector personnel to engage in collaborative research. Companies who wish to participate will contribute what would be research funds to the DAO. In return, companies receive three types of tokens (An analogy for the three types of tokens is as follows: A soulbound token is akin to an identification card (i.e., passport, driver's license) that cannot be forged or given to another person. A governance token is akin to a voting share that entitles a holder to vote on policymaking within a firm or organization. A nonfungible token is akin to a virtual deed or title that proves ownership of intellectual property). The first is a soulbound token (SBT), which is an irrevocable token that cannot be altered, sold, or transferred (88). Because of its unique attributes, SBTs can accurately represent and store an entity's credentials, and history with the PPRDP, which reduces the occurrence of Sybil attacks [Sybil attacks are 51% coordinated attacks utilizing multiple pseudonymous identities to change transaction activity and thereby controlling the blockchain network and can incentivize active and meaningful participation (89)].

Second, as with NASA and research universities, private sector participants will receive governance tokens, with the amount equivalent to their investment (i.e., a $1 million investment would result in 1 million tokens). With governance tokens, members acquire voting privileges for two major decisions. First, members can vote on how the research funds will be allocated among the research clusters via a voting mechanism. Second, members can vote on the entry of other participants to a particular research cluster.

Each research cluster would then have the control right to determine whether the cluster will be open-source vs. codified intellectual property with exclusive licensing.

After a consensus has been achieved, research clusters will receive funds and will commence research operations. Members of the DAO will receive a nonfungible token (NFT), which states their share of the investment in that research cluster. Depending on demand, members of the research cluster can provide in-kind contributions (i.e., researchers, proprietary data, and lab facilities), which will be valued for additional influence or NFT share into the potential intellectual property that may result from major research discoveries. The NFTs will be used to distribute various forms of IP, whether it is a proportionate percentage of the patent's income streams (e.g., royalties), right of first refusals, and exclusive or nonexclusive licensing rights.

Conclusion

The space economy is poised to transcend traditional boundaries as it ventures into uncharted frontiers rich with unprecedented technological and economic opportunities. To capitalize on the potential of space and its resources, it is crucial to foster open access to intellectual property, which serves as the lifeblood of innovation for further space exploration. By implementing such a strategy, the innovation cycle can be accelerated, unlocking the potential growth value of emerging sectors in space. PPRDPs play a crucial role in fostering this open innovation ecosystem by eliminating coordination failures between public and private stakeholders, facilitating agglomeration externalities of greater magnitude, and encouraging synergistic advancements in research by blurring the distinction between basic and applied research. By embedding the nonlinear decomposition paradigm of research within PPRDPs, such partnerships can further incentivize private firms to support open-access research, ultimately increasing returns to scale for both public good and commercial innovations.

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