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# Space, the Final Economic Frontier

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The Soviet Union launched its Sputnik satellite in 1957. A year later, the National Advisory Committee for Aeronautics, a little-known agency that had played a limited role in pursuing basic research in aeronautics since 1915, was transformed into the National Aeronautics and Space Administration. The surge of US government spending on human spaceflight through the Apollo program in the 1960s cemented a public-sector centralized model of the US space sector, putting NASA at its hub for the next 50 years. NASA set the strategy for exploration and use of space, and it also coordinated the market's structure, which largely involved government purchases from prominent aerospace firms. As NASA historian Joan Lisa Bromberg (1999) wrote of those early years: "[NASA Administrator James L.] Webb believed that national space policy should not be turned over to private firms. It was government acting in the public interest that had to determine what should be done, when it should be done, and for how much money."

After decades of centralized control of economic activity in space, NASA and US policymakers have begun to cede the direction of human activities in space to commercial companies. Figure 1 shows that NASA garnered more than 0.7 percent of GDP in the mid-1960s, but that level fell precipitously in the late 1960s and then gradually but persistently over the next 40 years to around 0.1 percent of GDP today. Meanwhile, space has become big business, with $300 billion in annual revenue. Recent valuations of innovative space firms like SpaceX ($21 billion), Orbital ATK ($7.8 billion), and dozens of small startups (receiving $2.8 billion in funding

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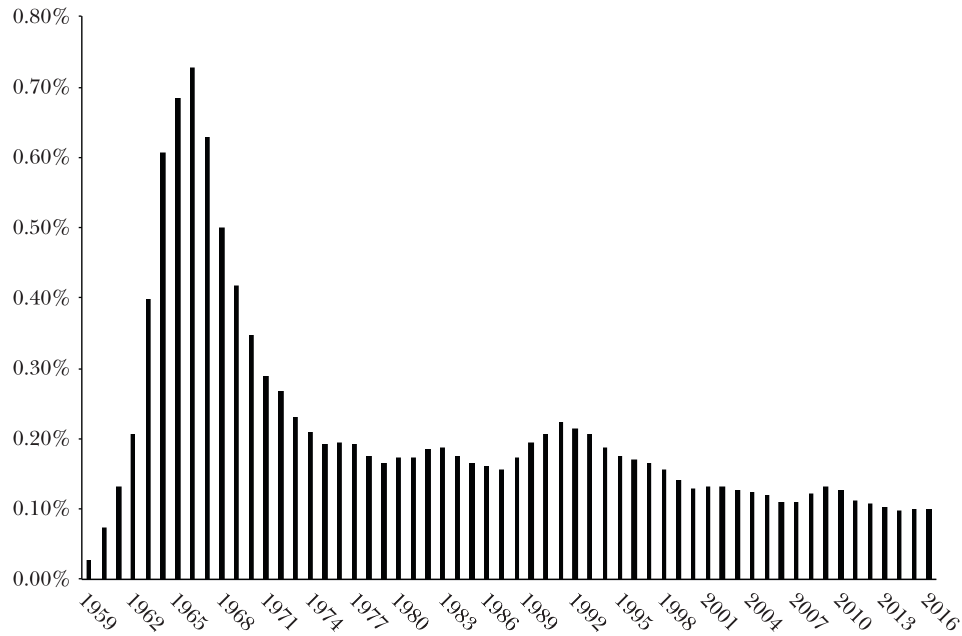
*Figure 1*
**NASA Budget as a Share of GDP**




in 2016) suggest the market is optimistic about what's next. Recent high-profile successes, most recently the launch and return of SpaceX's Falcon Heavy rocket, are generating a new surge of public interest and enthusiasm.

The shift from public to private priorities in space is especially significant because a widely shared goal among commercial space's leaders is the achievement of a large-scale, largely self-sufficient, developed space economy. Jeff Bezos, whose fortune from Amazon has funded the innovative space startup Blue Origin, has long stated that the mission of his firm is "millions of people living and working in space." Elon Musk (2017), who founded SpaceX, has laid out plans to build a city of a million people on Mars within the next century. Both Neil deGrasse Tyson and Peter Diamandis have been given credit for stating that Earth's first trillionaire will be an asteroid-miner (as reported in Kaufman 2015). Such visions are clearly not going to become reality in the near future. But detailed roadmaps to them are being produced (National Space Society 2012), and recent progress in the required technologies has been dramatic (Metzger, Muscatello, Meuller, and Mantovani 2013). If such space-economy visions are even partially realized, the implications for society—and economists—will be enormous. After all, it will be our best chance in human history to create and study economic societies from a (nearly) blank slate. Though economists should treat the prospect of a developed space economy with healthy skepticism, it would be irresponsible to treat it as science fiction.

In this article, I provide an analytical framework—based on classic economic analysis of the role of government in market economies—for understanding and managing the development of the space economy. That framework has three components: 1) establishing the market through decentralization of decision making and financing for human space activities; 2) refining the market through policies that address market failures and ensure a healthy market structure; and 3) tempering the market through regulation in pursuit of social objectives. The next three sections will focus on these issues. Some of the topics are familiar from Earth, while others are unique to space, but most of these questions—despite the pioneering work of space-focused economists such as Macauley and Toman (1991, 2004, 2005), Hertzfeld (1992, 2007), and MacDonald (2014, 2017)—remain largely unaddressed. I will focus on the US space sector, but the framework applies equally well to the efforts of any spacefaring nation.

## Establishing Markets in Space: Decentralization

### The Slow Decline of Centralization

Since the start of the Space Age, private-sector leaders have been issuing warnings that a centralized model would undermine progress on public and, especially, commercial priorities in space. For example, Ralph Cordiner (1961), the one-time chairman and CEO of General Electric, foresaw much of the development of the government-directed space sector over the subsequent several decades while forcefully arguing that, eventually, space's "development shall be under our traditional competitive enterprise system."

The economic logic for the centralized model was clear, and for several decades it achieved its (remarkable) goals. Public goods such as national security, national pride, and basic science are typically underprovided if left to the market, and NASA was founded to provide them during the Cold War. Its command-and-control structure grew naturally from that objective, as the merits of decentralization took a back seat to the imperative of directed action. Under this model, the United States has been the leading space power and NASA has occupied the technological frontier. Most prominently, the success of the Apollo missions (including the 1969 moon landing) inspired grand visions for what would come next. In the early 1970s, studies of space colonization and diversified space-based economies proliferated, even at the highest levels of the space program (O'Neill 1976).

But after the last of the Apollo missions in 1972, NASA—and thus the US space sector—struggled to find a second act. Part of the reason was that the tight connection between the Apollo program and competition with the Soviet Union made NASA's budget vulnerable to the sense that the mission had already been accomplished (Logsdon 2015). Apollo astronaut Buzz Aldrin said: "After the Apollo lunar missions, America lost its love of space—there was no concentrated follow-up and we didn't have any clear objectives" (as quoted in Sunyer 2014).

When NASA decided that its next emphasis would be on the Space Transportation System, better known as the Shuttle, it applied largely the same centralized approach it had used in the 1960s, but with more mixed results. The first flight of the Columbia space shuttle was in 1981. Successive shuttle flights enabled two decades of achievements by NASA, including the construction of the International Space Station (ISS) and Hubble Space Telescope, and they demonstrated American technological prowess. But the Shuttle's costs were higher than hoped (roughly two-thirds of NASA's human spaceflight budget and around $220 billion in 2017 dollars) and its performance weaker (it missed more half of its planned annual flights). Moreover, public goods were prioritized over commercial priorities, handicapping the growth of the commercial space sector. Logsdon (2011), a prominent space expert, has written: "[I]t was probably a mistake to develop this particular space shuttle design, and then to build the future U.S. space program around it."

After two tragic accidents, with the Challenger shuttle in 1986 and the Columbia shuttle in 2003, momentum turned away from the Shuttle and the centralized model of space it represented. The President's Commission on Implementation of United States Space Exploration Policy (2004) came to a striking conclusion: "NASA's role must be limited to only those areas where there is irrefutable demonstration that only government can perform the proposed activity." The shuttle program was cancelled in 2011, leaving the United States in the embarrassing position of not being able to launch humans from domestic soil.

The vulnerabilities of centralized control will be familiar to any economist: weak incentives for the efficient allocation of resources, poor aggregation of dispersed information, and resistance to innovation due to reduced competition. In addition to these concerns, NASA's funding and priorities were subject to frequent, at times dramatic, revision by policymakers, making it hard for the space sector to achieve even the objectives set at the center (Handberg 1995; Logsdon 2011).

Anticipating these vulnerabilities, reform advocates had made previous pushes for at least partial decentralization and a greater role for the private sector in space. Near the dawn of the Shuttle era, President Ronald Reagan signed the Commercial Space Launch Act of 1984, saying: "One of the important objectives of my administration has been, and will continue to be, the encouragement of the private sector in commercial space endeavors." That same year saw the creation of the Office of Commercial Programs at NASA and the Office of Commercial Space Transportation in the Department of Transportation (NASA 2014). However, these early seeds would have to wait until the end of the Shuttle program to bear fruit.

An instructive contrast is provided by the approach the US government took to the development of the commercial satellite market. In 1962, Congress created COMSAT, a for-profit, private corporation owned by common shareholders and a group of telecommunications companies (though three of the company's 15 board seats were to be appointed by the US President). NASA was officially charged with providing technical advice to COMSAT, and the agency was given responsibility for COMSAT's launches. The idea behind this public–private partnership was to leverage the expertise of NASA to jump-start a private communications satellite industry. It was "industrial policy with a vengeance" in the words of NASA historian Bromberg (1999), and it led to the rapid deployment and use—for both public and private purposes—of the vast array of satellites that dominate the space economy today.

**The Rise of New Space**

When the shuttle program itself ended in 2011, commercialization-minded reformers in both the public and private space sectors seized their opportunity. In the words of Bretton Alexander, an executive at Blue Origin and former White House space official: "The failure of NASA to find a replacement for the shuttle for 30 years shattered the idea of NASA being in charge … When the shuttle was retired, it created this void that allowed NASA to look to the commercial sector" (quoted in Weinzierl and Acocella 2016).

The decentralized set of space companies that emerged is generally known as "New Space." Table 1 offers a (necessarily incomplete) overview of some of the main companies currently active in commercialization of space. The "space access" companies focus on launching people and payload into space. The "remote sensing" companies provide images of Earth and are closely related to the "satellite data and analytics" companies, which also serve a range of other customers. The "habitats and space stations" companies plan to provide secure facilities for manufacturing, research, and even tourism in so-called "low Earth orbit" (the space between 160 km and 2,000 km of altitude). The "beyond low Earth orbit" companies have goals ranging from space manufacturing to asteroid mining to colonization of the Moon and Mars. Not listed in the table are research and investment firms, whose increased involvement in space suggests a maturing of the sector as a wider range of investors seek information and access. Leading examples of these include Bryce Space and Technology and an array of investment firms ranging from those focused on space (for example, Space Angels) to those devoting a small share of their large resources to space (for example, Bessemer and Draper Fisher Jurvetson).

Funding for New Space companies comes from a variety of sources. A set of high-profile entrepreneurs—Elon Musk, Jeff Bezos, Richard Branson, Paul Allen, and others—have used their wealth to overcome high fixed-cost barriers to entry, launching companies based on new approaches to the technology and management of space access. According to leading space industry analyst Bryce Space and Technology (2017), outside investment in start-up New Space firms has risen from less than $500 million per year from 2001 to 2008 to roughly $2.5 billion per year in 2015 and 2016.[1]

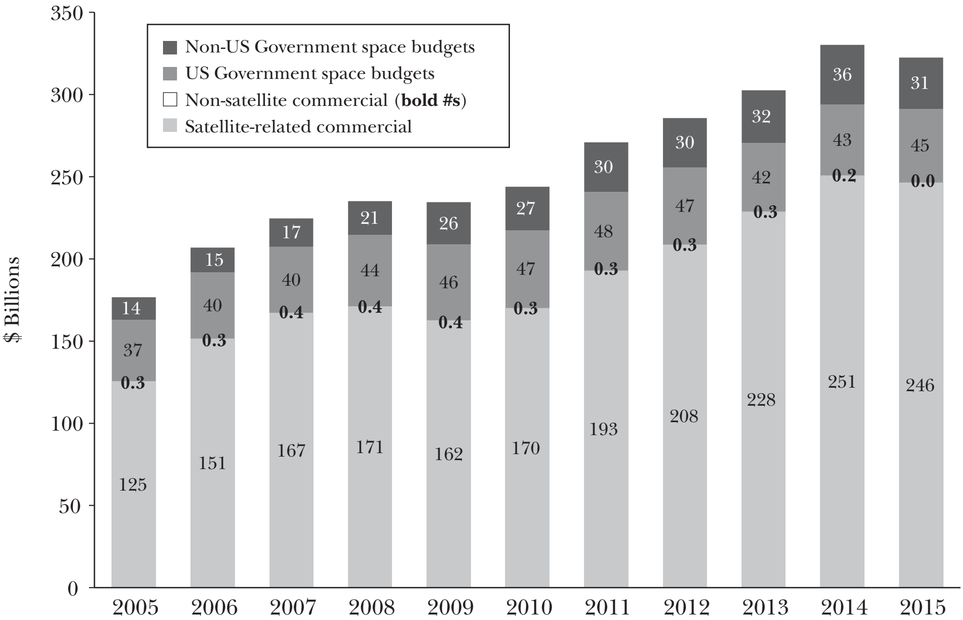
[1] In 2006, levels were higher, as there were large debt offerings (by the satellite provider Protostar and broadband provider WildBlue—now ViaSat). Investment flows grew to roughly $2 billion per year from 2009 to 2011, thanks mainly to interest from private equity firms and substantial debt offerings by Ligado Networks (broadband), Digital Globe (Earth imaging—recently merged into Maxar), and O3b (a satellite constellation provider). The years 2013 and 2014 saw some large acquisitions in this sector, including Monsanto acquiring the Climate Corporation ($930 million), Google acquiring TerraBella ($478 million, later sold to Planet), and SES acquiring O3b ($730 million). Levels in 2015 and 2016 included inflows of venture capital that were larger than $1.5 billion each year (Bryce Space and Technology 2017).

*Table 1*
**A Sample of Companies Involved in Commercial Space Activities**

| *Sector* | *Company (alphabetical by sector)* | *Year founded* | *Full-time equivalent workers (2016)[a]* | *Products/Services* |
|---|---|---|---|---|
| Space access | Astrobotic | 2008 | 11–50[b] | Transportation to the Moon |
| | Blue Origin | 2000 | 875 | Launch vehicles and engines, space tourism |
| | Boeing Aerospace | 1978 | 2,800 | Crewed LEO transportation |
| | Masten Space Systems | 2004 | 11–50[b] | Suborbital launches of small payloads |
| | Orbital ATK | 1982 | 12,700 | Orbital launches of satellites and ISS cargo |
| | Sierra Nevada Corp. | 1963 | 3,094 | Cargo and crewed LEO transportation |
| | Space Adventures | 1998 | 17 | Crewed LEO, lunar transport, and tourism |
| | SpaceX | 2002 | 5,420 | Reusable launch vehicles, colonization |
| | Stratolaunch Systems | 2011 | 501–1000[b] | Air-launched orbital launch services |
| | World View Enterprises | 2012 | 11–50[b] | High-altitude private spaceflight balloons |
| | United Launch Alliance | 2006 | 4,000 | Orbital launch services |
| | Virgin Galactic | 2004 | 200 | Space tourism; rapid commercial flight |
| | XCOR Aerospace | 1999 | 23 | Suborbital launches, human spaceflight |
| Remote sensing | Iceye | 2012 | 11–50[b] | Synthetic aperture radar remote sensing |
| | Planet (including Terra Bella) | 2010 | 251–500[b] | Earth imaging and video, data provision |
| | Spire Global Inc. | 2006 | 101–250[b] | Data gathering; Earth observation network |
| Satellite data access and analytics | Analytical Space | 2016 | 10 | Optical LEO comms network, full service |
| | Astroscale | 2013 | 11–50 | Space Debris Removal |
| | Bridgesat | 2015 | 3 | Optimal comms network, hardware |
| | Kepler Communications | 2015 | 5 | Internet communications to crafts in orbit |
| | Maxar | n/a | 5,000+ | Diversified: satellites, imaging, robotics |
| | OneWeb | 2012 | 101–250[b] | Large-scale satellite constellation |
| | Oxford Space Systems | 2013 | 11–50[b] | Deployable satellite structures |
| | Qwaltec | 2001 | 58 | Satellite and network operations |
| | Skywatch | 2014 | 11–50[b] | Satellite data integration Earth observation |
| | Vector Space Systems | 2016 | 11–50[b] | Micro satellite space vehicle |
| Habitats and space stations | Axiom | 2015 | 11–50[b] | Commercial space station building off ISS |
| | Bigelow Aerospace | 1999 | 135 | Inflatable space habitats |
| | Ixion Initiative Team | 2016 | n/a | Commercial use of rocket upper stages |
| | Made In Space | 2010 | 50 | Additive manufacturing in space |
| | Nanoracks | 2009 | 40 | Payload transport, deployment hardware |
| | Space Tango | 2014 | 5–10 | Microgravity research platforms |
| Beyond low Earth orbit | Deep Space Industries | 2012 | 11–50[b] | Asteroid mining |
| | Golden Spike | 2010 | 11–50[b] | Human lunar expeditions |
| | Mars One | 2011 | 11–50[b] | Mars colonization |
| | Moon Express | 2010 | 51–100[b] | Moon exploration and mining |
| | Planetary Resources, Inc. | 2010 | 11–50[b] | Asteroid mining |

*Source:* List and descriptions of companies compiled from the Commercial Spaceflight Federation website and author research.
*Note:* LEO is "low Earth orbit." ISS is the International Space Station.
[a] Employee data is from private communications with companies or Capital IQ, US Department of Labor, unless otherwise noted:
[b] Data from Crunchbase;
[c] Capital IQ, third-party data.

*Figure 2*
**Space Sector Revenue**




*Source: The Space Report* (Space Foundation 2018).
*Note:* Classification adjusted by the authors to separate satellite-related from other commercial revenue. Non-U.S. governments include (in descending order of amount of revenue) ESA, China, Russia, Japan, France, along with several others (which recorded less than $1 billion in 2015).

Figure 2 shows estimates from *The Space Report* (Space Foundation 2018) that revenues in the space sector have climbed from less than $200 billion in 2005 to more than $300 billion in recent years, with the vast majority of that activity related to satellite technology for telecommunications and other services. The rest is the space budgets of governments—US and others—and commercial revenues from nonsatellite space services). This dominance of the satellite business in space revenue is likely to hold for the foreseeable future, especially given projections of substantial growth in small satellite constellations for Earth observation, where published forecasts (Henry 2016) see revenue of $22 billion over the next decade.

Credible estimates of the ultimate economic potential of space in the long term are elusive, as many of its most ambitious plans have very uncertain prospects. As one example, a 2014 report by the Boston Consulting Group put global spending on luxury travel at $460 billion and the overall luxury "experiences" market at $1.8 trillion (Abtan et al. 2014). Some New Space companies such as Blue Origin are working to claim a slice of this vast market for space, but there is substantial skepticism toward space tourism among many in the industry. Revenues from space manufacturing or asteroid-mining will be negligible in the near term and perhaps also in the medium term, though active commercial research toward both is being funded in the marketplace. In the end, whether lower-cost access and infrastructure for working in space will generate an economic reason to be in space—as current investors hope and expect—remains unclear.

At this point, the terminology of "New Space" has come to represent not just a new generation of companies (after all, well-established firms like Boeing and Orbital Sciences are also important players) or a steady growth in space-sector revenues, but rather a new approach. In the centralized model, private firms working with NASA were largely insured against the enormous risks of investments in space through cost-plus contracts, but they had little ability to participate in the potential gains from a commercialized space market. In the "New Space" approach, private firms share in the enormous risks and (potential) returns of investments in space (Achenbach 2013; see also Weinzierl and Acocella 2016).

**A Channel for Decentralization: Commercial Orbital Transportation Services**

As the Shuttle program wound down, the primary channel by which NASA and the rising New Space sector came together to solve the space access problem—and thereby provide an example of how decentralization can work—was a set of public–private partnerships called Commercial Orbital Transportation Services (COTS). In 2005, Congress funded COTS with $500 million (less than 1 percent) of NASA's five-year budget, with the goal of "challenging private industry to establish capabilities and services that can open new space markets while meeting the logistics transportation needs of the International Space Station" (NASA 2014). As Lambright (2016) writes in a history of the program, "[NASA Administrator Michael Griffin's] vision was to build a new commercial space industry." In particular, it was hoped that COTS would lower cargo—and eventually crew—transportation costs and thus help to open up a set of untapped opportunities in low Earth orbit.

The key innovation in the Commercial Orbital Transportation Services program was to make NASA a customer and partner, not a supervisor, of its private contractors. In particular, COTS contracts replaced conventional cost-plus procurement for customized products with fixed-price payments for the generic capabilities of delivering and disposing or returning cargo and transporting crew to low Earth orbit (in other settings, COTS is an acronym for "commercial off the shelf").[2] This change shifted risk from NASA to private firms, reducing the need for NASA to use a combination of intensive monitoring and cost-plus contracts to control costs and encourage innovation.

New Space companies welcomed the new approach: their investors were comfortable taking on risk; innovation and efficiency were (they argued) their key advantages over established players; and they found intensive monitoring to be costly and invasive. Firms were given the freedom and responsibility to design and produce their products as they saw best, with NASA providing insight rather than

[2] More specifically, COTS agreements were structured using so-called Other Transaction Authority under the rubric of Space Act Agreements, replacing Federal Acquisition Regulation (FAR) rules that had governed the vast majority of NASA contracts prior to COTS.

oversight. Moreover, firms would retain the ownership of the intellectual property created for the COTS, whereas under previous contracts, the government was the default holder of intellectual property because the work was done at its behest, not for the broad marketplace (NASA 2014).

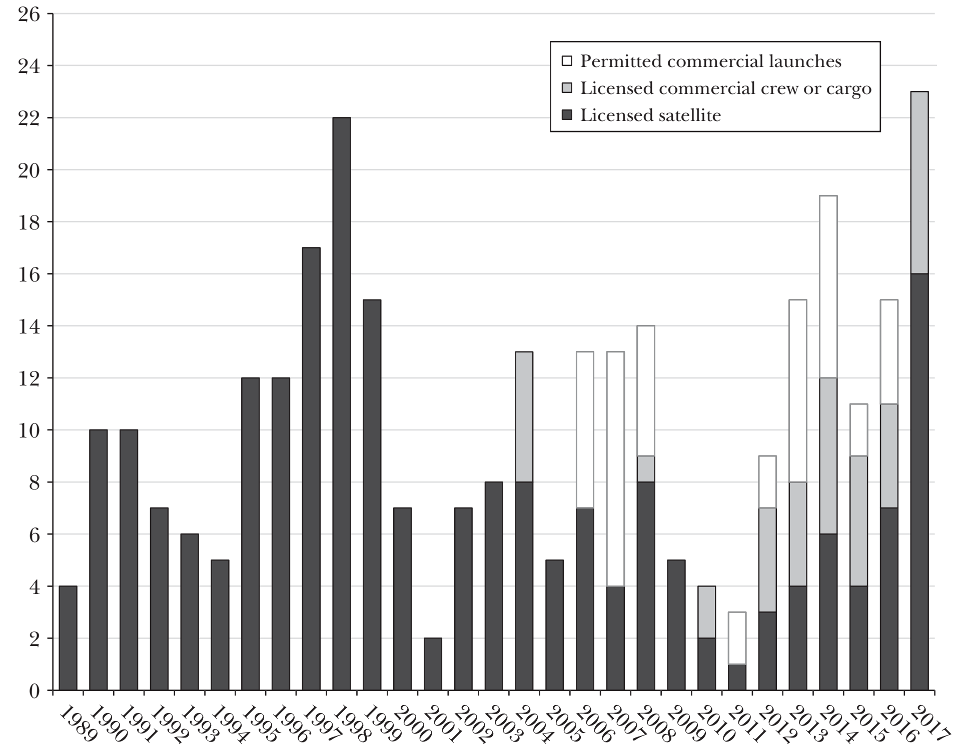
The Commercial Orbital Transportation Services program offered several advantages for NASA. First, the agency could leverage private capital to acquire its required services more cheaply: NASA (2014) reported that COTS provided "U.S.-based cargo transportation services at a significantly lower cost than previous Space Shuttle flights." In particular, NASA (Zapata 2017) provided a detailed breakdown of the cost savings from COTS, concluding that the all-in cost to deliver a kilogram of cargo to the International Space Station was approximately $89,000 through SpaceX and $135,000 through Orbital Sciences, one-third and one-half the $272,000 estimated cost per kilogram that would have been possible with the Space Shuttle. Second, and related, COTS would allow NASA to redirect its time and budget to projects like basic science and exploratory research. As NASA Administrator Charlie Bolden noted: "These agreements are significant milestones in NASA's plans to take advantage of American ingenuity to get to low Earth orbit, so we can concentrate our resources on deep space exploration" (as cited in Morring 2011; see also NASA 2014; Launius 2014).

Despite its appeal, the Commercial Orbital Transportation Services program was initially viewed by some within the established space sector as, at best, a backup plan for the more conventional approach. NASA already had in place a multifaceted exploration and space access program called Constellation, and part of that program (Ares 1/Orion) was focused on low Earth orbit. But the Constellation program ran over budget and behind schedule. When it was eventually cancelled by President Obama, COTS became far more than a backup.

In fact, the Commercial Orbital Transportation Services program has been making core contributions to achieving NASA's missions. By 2008, two companies had convinced the agency of their ability to provide full resupply services to the International Space Station, and NASA awarded fixed-price contracts for 20 flights valued at $3.5 billion to SpaceX and Orbital Sciences under a successor program, Commercial Resupply Services (CRS). These flights are now a main way in which the space station is resupplied. Even the program's missteps were seen as making progress: when NASA cancelled one of the initial contracts after the partner company, Rocketplane Kistler, failed to meet benchmarks, the agency proved that it took its role as a "customer" seriously (Lambright 2016). The successes of the cargo programs led to the Commercial Crew Development program, a multiphase project that has culminated in scheduled crew transportation to the space station by SpaceX and Boeing before 2020. In just over a decade, the relationship between the US space program and commercial providers had shifted, in NASA's (2014) words, "From Contingency to Dependency."

Moreover, these public–private partnership programs spurred activity and innovation within the space sector that presage a broadening of the space economy. To take one particularly important example, they fed a new surge of

*Figure 3*
**FAA-Licensed and Permitted Commercial Launches by Objective**




*Source:* Federal Aviation Administration (FAA) 2018.
*Note:* This figure displays the number of commercial launches that were officially licensed by the FAA (for satellite delivery or for missions related to resupplying the International Space Station with crew or cargo) or that were permitted by the FAA (permits for experimental launches can be granted in less time and with fewer requirements than a full license, pursuant to the 2004 Commercial Space Launch Amendments Act).

private nonsatellite-related commercial launch activity, as shown in Figure 3, that included a drive toward "reusability"—that is, the capacity to employ components of launch vehicles and spacecraft multiple times. Many in the space sector have expressed sentiments in agreement with SpaceX's Elon Musk, who has said: "If one can figure out how to effectively reuse rockets just like airplanes, the cost of access to space will be reduced by as much as a factor of a hundred. A fully reusable vehicle has never been done before. That really is the fundamental breakthrough needed to revolutionize access to space" (as quoted in SpaceX 2015). SpaceX's successful demonstrations of reusability for its launch vehicle (in 2016), its cargo capsule (in 2017), and most recently its heavy-launch vehicle (in 2018) were therefore seen as watershed moments in both aerospace technology and the commercialization of space. Musk has made clear the importance to his company's success of its participation in the public–private partnerships: "SpaceX could not do this without NASA. Can't express enough appreciation," he tweeted in February 2017.

**The Broader Commercialization of Low Earth Orbit**

In March 2017, the US space sector took a further step toward decentralization with the signing of the NASA Transition and Authorization Act, a comprehensive and bipartisan reauthorization bill. In essence, policymakers decided to go beyond asking commercial providers to carry out what would previously have been NASA missions, such as carrying people and payload to the International Space Station, and to cede the direction of activities in low Earth orbit to commercial space providers. If this transition succeeds, NASA will adopt a more targeted role focused on space exploration and basic science, the public goods that have long been its core competencies, leaving the economic development of space largely to the private sector. Historians such as Launius (2014) suggest there is a historical analogue to this relationship in the commercial aviation industry, where the US government played a critical role in basic research in the mid 20th century while leaving the operation of the aviation sector in private hands.

Despite the success of public–private partnerships in resupplying missions to the International Space Station, commercialization comes with risks, and the case for broader commercialization in low Earth orbit is hotly debated. Critics often argue that New Space companies are piggybacking in various ways: for example, off NASA technology that took decades to develop, and through marginal-cost pricing for the use of NASA facilities (NASA 2014) and indemnification from risk. A related critique is that public–private partnerships channeling resources away from established space contractors risk undermining the institutional knowledge and economies of scale that have been built up over decades. Finally, it is unclear whether NASA will stay hands-off as the scope of commercial space activities expands both in low Earth orbit and beyond (for discussion, see Martin 2011). In fact, current debates over the path to Mars provide a clear example of these tensions, and their resolution will tell us a great deal about the future of the space sector.

Clearly, a number of questions remain to be addressed on the way to a decentralized space economy. Will the public–private partnership approach be an effective model for encouraging further commercialization, or would a clearer separation of public and private sectors be more effective? How should the industrial structure of commercial space be influenced by the public sector, including NASA? Will decentralization of economic activity in space focused on private goods undermine or bolster support for NASA and the public goods it produces?

## Refining the Market: Addressing Market Failures

The original justifications for NASA included its ability to provide public goods like basic science, national pride (Logsdon 2004; Launius 2006a), and support of national security (although NASA is a civilian agency). In other words, NASA was a response to classic market failures. As the evolving economics of space push toward a greater role for market forces, risks of other market failure arise. Two examples are already complicating the sector's development: the problem of complementarities and coordination (which in turn is related to a risk of insufficient competition), and the problem of externalities like those caused by space debris.

**Complementarities and Coordination**

Many New Space companies have business models that make sense only when other, complementary models are already in place. Consider some technologies widely believed to be essential for the commercialization of space: low-cost, frequent launch capabilities; in-space manufacturing; scalable habitats; in-space resource extraction and energy collection; and reliable radiation shielding and debris mitigation. Individually, each of these technologies has only a limited payoff. Low-cost launches are still expensive if there is nothing to do and nowhere to go in space. Building habitats for manufacturing or tourism is of no use if they cannot be secured from the dangers of space. And so on. If these technologies were realized together, however, they would form a self-sustaining system with potentially enormous profit potential. In the economics of human space activities, the whole may be much greater than the sum of the parts.

One can imagine a self-reinforcing virtuous cycle of development that would support the space economy. For example, cheaper and more frequent rocket launches might facilitate short-term tourism, along with industrial and scientific experimentation on suborbital and orbiting spacecraft. If these activities become routine, demand might rise for commercial habitats to support longer flights. In turn, these habitats could generate demand for resources in space, increasing the opportunities for workers and residents.

But one can also reasonably doubt that such an ideal path will be realized easily or without some nudges along the way. Limits on or asymmetries of information, the high level of risk inherent in space, and the challenges of capturing surplus from such complementarities will make it difficult to move forward on the most efficient path—or even to move forward at all.[3]

Even if the market "succeeds" in capturing these complementarities, the economics of the sector suggest that the outcome would feature a high degree of concentration. After all, complementarities mean large profits for actors that integrate the pieces of the whole, and entrepreneurs at the forefront of New Space (Jeff Bezos, Elon Musk, Richard Branson, and others) are masters of such a strategy on Earth. Economies of scale and scope have, in fact, always characterized commercial

[3] Consider, for instance, a classic stag hunt game in which an inferior but less-risky equilibrium is selected rather than the more efficient coordinated equilibrium. In this game, two individuals go hunting. Each must choose whether to hunt for a high-value stag or low-value hare. However, choosing a hare is guaranteed to succeed, while choosing a stag only succeeds if the other person also chooses "stag." See Brynjolfsson and Milgrom (2013) for a relevant review of complementarities in economics.

space: NASA historian Bromberg (1999) points out that one of the agency's earliest goals was to retain competition among its contractors and avoid monopolization.

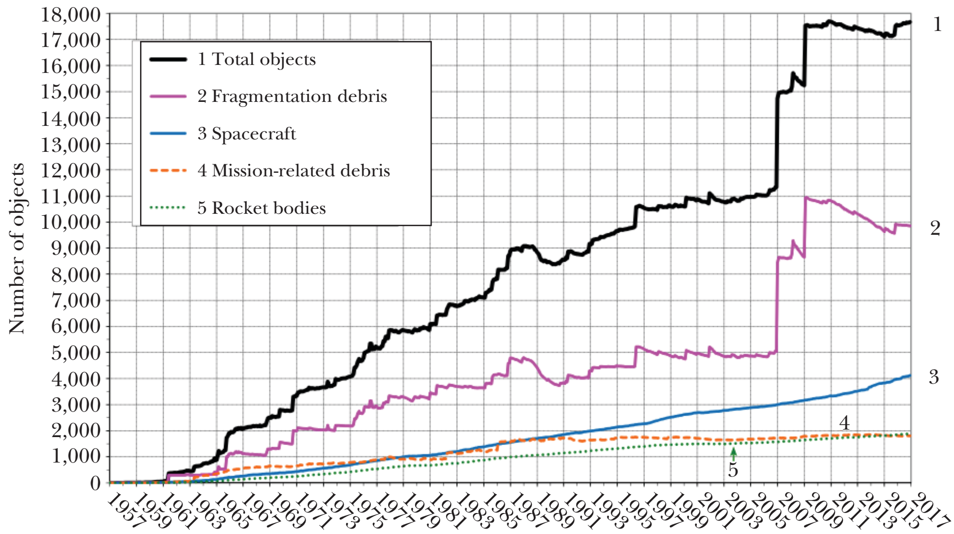
Carefully designed public-sector coordination can help: indeed, Hertzfeld (1992) made similar arguments at an earlier stage of the US space sector's development, when commercialization was far less advanced. NASA's recent efforts at coordinating the commercialization of space have scored some successes.

For example, Commercial Orbital Transportation Services and related programs not only subsidized commercial launch vehicles, they also maintained a competitive market structure through a diversified set of award contracts. The Commercial Crew Development program awarded contracts to six companies in its first round, four companies (plus three more without funding) in its second round, three in its third round, and two in its final round (NASA 2014). NASA has tried to play a similar role in encouraging habitat technologies. Most prominently, Bigelow Aerospace has been allowed to dock its inflatable expandable activity module on the International Space Station to prepare for its use in modular commercial stations. But NASA has also actively partnered with five other companies to develop deep-space habitat technology through its NextSTEP and NextSTEP-2 public–private partnerships (for details, see https://www.nasa.gov/nextstep).

Historical analogies suggest lessons for how the public sector can play this facilitative role. Launius (2014) provides an in-depth analysis of six relevant historical episodes. The construction of the US transcontinental railroad in the late 19th century is commonly cited in the space community as an example of how government support—massive in that case—can facilitate development of a new frontier. (Donaldson and Hornbeck 2016 find that growth in the American West was moderately higher as a result.) The story of the railroads suggests the range of forms such support might take: direct transfers, lower taxes, guaranteed contracts, and even grants of property. The story of the railroads also reveals risks of such efforts, however, as early government support led to a concentration of economic (and political) power. The differences between space and such an analogy are instructive, as well. Unlike with the railroads and the West, rockets are the only means of accessing space and no national government has authority over property rights in space. Also, while the railroads linked communities of eager customers, demand for easy access to space is still nascent and will depend on the development of complementary technologies. Launius's other five case studies are a diverse group—fostering the aerospace industry; creating the telephone industry; supporting research in Antarctica; advancing public works; and making accessible conservation zones (scenic and cultural)—each of which provides additional lessons.

The complementarities at the heart of developing a commercial space sector raise a number of policy questions. What role should the government play in coordinating and subsidizing these interdependent technologies? Which forms of subsidy—cost-sharing, revenue guarantees, prizes—would be most effective? If the provision of these linchpin technologies turns out to have the features of natural monopoly, how should policymakers respond? How will the surplus from such an interdependent set of inputs be shared among its participants?

*Figure 4*
**Space Debris**
*(monthly number of objects in Earth orbit)*




*Source:* From NASA (2017) with only minor stylistic changes.

**Crowding and the Space Debris**

The development of space is already generating concerns about overuse and crowding in the most useful regions of low Earth orbit. In time, such concerns seem likely to spread to the richest asteroids and orbital space in general. In fact, Earth's orbital space is already being described as "congested, contested, and competitive" (Duff-Brown 2015). To illustrate this problem in more detail, consider the case of space debris.

Space debris—including defunct satellites, spacecraft parts, and the pieces created by collisions between them—is accumulating, as shown in Figure 4. Even small debris can inflict major damage: a piece of metal the size of a cherry carries the explosive power of a grenade when in orbit. Current estimates are that 23,000 objects larger than 10 centimeters in diameter, 500,000 particles between 1 and 10 centimeters, and over 100 million particles smaller than 1 centimeter are flying through low Earth orbit. Most of these objects have been created in just the past ten years, as shown in Figure 4, in part due to two major events. As explained in Weinzierl and Acocella (2016b), "On Feb 10, 2009, an active US communications satellite (Iridium 33) exploded on impact with a defunct Russian satellite (Kosmos 2251), spewing 2,200 trackable objects and hundreds of thousands of smaller, undetectable fragments into Earth's orbit. ... In 2007, a Chinese weather satellite (Fengyun-1C) was destroyed by a kinetic kill vehicle traveling at nearly 18,000 mph as part of China's anti-satellite ballistic missile test, creating over 2,000 pieces of trackable objects—those larger than 10 centimeters in diameter—and an estimated 150,000 smaller fragments." While the current threats from debris are generally considered manageable through shielding and avoidance technology, the long-term problem is daunting, especially when considering the enormous increase in the size and number of orbiting objects required for a developed space economy. Warnings of an uncontrollable chain reaction of debris-generating collisions—in which debris creates collisions that lead to more debris—came as early as the 1970s from NASA scientist Donald Kessler, and the issue is only becoming more pressing with time.

The space debris problem is a classic example of negative externalities but in a setting in which the conventional remedies suggested by economic analysis and applied on Earth have limited traction. For example, Hanson (2016) suggests a standard Pigouvian price on debris, but also notes that a main obstacle is the lack of any space taxing authority. A Coasian (1960) solution in which affected parties negotiate to internalize externalities will be difficult in the case of space debris because this approach requires clearly delineated property rights, and no such rights exist in space. A polycentric governance solution as in Ostrom (2009), in which public and private actors would collectively manage orbital debris in a way similar to how a range of actors manage large-scale irrigation projects and water rights in some emerging economies, may be possible but faces an uphill battle. After all, the conditions under which Ostrom found this kind of cooperation most promising—including the ability to monitor and discipline actions—are missing in space (Weinzierl, Acocella, and Yamazaki 2016). In short, without some centralized action, space debris could generate an outcome similar to the tragedy of the commons.[4]

International agreements have made some progress on the issue of space debris by requiring that objects put into space in the future have automatic de-orbiting capabilities, but the main provision of international treaties relevant to debris—the assignment of responsibility for debris to the party or country from which it was first launched—has fallen far short. In fairness, identifying the origin of pieces of debris is difficult, assigning responsibility for an object having become debris (say, due to a collision with another object) is often impossible, and enforcing countries' obligations threatens their national security and economic interests in other assets. The analogy to global climate change, where a decades-long effort to generate international coordination has gradually confronted these obstacles, is both useful and daunting. A more encouraging analogy is to international efforts to reverse the depletion of the ozone layer, where over the several decades multiple rounds of agreements have turned the tide. Advocates of action on space debris often point to the need for public awareness of the problem, a factor often credited with encouraging swift action on the ozone layer.

[4] Some industry consortia have recently proposed self-regulation to address space debris (as reported in Foust 2017). Hertzfeld, Weeden, and Johnson (2016) suggest that these efforts will be more effective if they focus on how the debris problem differs from the textbook "tragedy of the commons" scenario.

With this challenging landscape, economists have the tools to pose and address some key questions. Are private interests, like those of satellite providers or space tourists, likely to create sufficient demand for debris removal and a more systematic stewardship of space? If not, what policies can governments adopt, or what markets can governments create, to price or regulate these externalities? How can these negative externalities be internalized without working against the subsidization merited by the positive externalities discussed above? Can unilateral actions succeed, or is cooperation across countries imperative? How can historical (or current) examples inform our answers to these questions?

## Tempering the Market: Pursuing Social Objectives

Even an established, efficient space marketplace offers no guarantee that the pursuit of private priorities in space will serve the public or respect the public's ethical judgments. Some questions lie outside the natural scope of economists (for example, with regard to our moral responsibility to preserve outer space as we find it). But if we fail to exert oversight over the space economy, its legitimacy—and thus its success—will be undermined.

As a tangible example of the challenges in protecting the public interest without handicapping the private space economy, consider the case of asteroid mining. A number of private companies are interested in mining asteroids for precious metals, in-space manufacturing inputs, habitat materials, and (perhaps most likely) water. The technological challenges to asteroid mining are formidable, but the regulatory landscape is also a risk. The heart of the economic issue is who has the right to mine and profit from the resources to be found in asteroids. As Krolikowski and Elvis (2017) caution, if commercial interest in asteroids conflicts with the public's interest in them for scientific exploration or space settlement—for example, because mining destroys material of interest to scientists while extracting material that is useful to settlers—how are such conflicts to be sorted out?

Similar legal and ethical challenges apply to the management of two terrestrial frontiers: Antarctica and the oceans. In Antarctica, international treaties have kept development to a minimum, at least for the next several decades. As discussed by Ehrenfreund, Race, and Labdon (2013), the Antarctic Treaty System commits signatories to a range of limitations intended to leave undisturbed the Antarctic ecosystem, the most important of which are the prohibitions on military and mineral resource extraction activities. Scientific research and exploration, including tourism, are allowed but carefully managed by international bodies. Similar goals animate the treaties governing the management of the oceans—the UN Convention on the Law of the Seas—but centuries of military and commercial activities (and claims) complicate the picture. For example, the United States has not formally ratified the Convention and has, at times, expressed concern over its proposals on mining rights and fees applied to the international seabed beyond the defined economic zones of coastal countries. In the oceans, the tension between economic and environmental priorities is therefore more apparent than in Antarctica, perhaps because there is more economically at stake.

Existing international space treaties neither endorse nor prohibit the private use of resources in space. The 1967 Outer Space Treaty, which continues to be the main framework for international cooperation, strikes an ambiguous middle ground on the development and use of resources in space. It encourages—but does not require—cooperation on responsible use. An attempt by some nations to put in place a more restrictive agreement, the 1979 Moon Treaty, has not been signed by any spacefaring nation. The resulting ambivalence over property rights in space has had no real effects for decades. But with the rise of commercial space, choosing a regulatory approach to property rights has taken on new urgency.

The United States upset the regulatory status quo—and facilitated the growth of asteroid mining companies—by passing the Commercial Space Launch Competitiveness Act in 2015, a law that grants property rights to the resources on a planetary body (though not to the body itself) to whoever "gets there first." The law's treatment of property rights reflects the principle that the first actor to utilize a resource earns the right, as the law says, "to possess, own, transport, use, and sell." The fundamental tradeoff rooted within this approach is that a property right granted in this way may be utilized in a way that conflicts with society's interests, but without that right the resource may be left undeveloped altogether. A resolution to this tradeoff offered by Locke (1689) and made famous by Robert Nozick (1974) is the so-called "Lockean proviso," in which appropriation of a resource is justifiable if each individual is left at least as well off as in a world where all resources had remained unowned. This justification was at the heart of supporters' case for the 2015 act.

While some other countries were critical of the bold creation of property rights in space by the Commercial Space Launch Competitiveness Act, arguing that space resources should be common property, others rushed to follow suit. For example, small but high-income Luxembourg has played a key role in commercial space as the headquarters of SES, a major satellite owner and operator. In the context of space resources, Luxembourg's key advantage is its regulatory responsiveness to firms. In fact, both of the leading asteroid mining companies—Planetary Resources and Deep Space Industries—have opened offices in Luxembourg and praised the country's business-friendly setting. In other words, Luxembourg is positioning itself to be for asteroid-mining companies what Delaware has been in recent decades for major American firms.

It appears that the right of private companies to mine and profit from asteroids is quickly being formalized. An open question is whether, if asteroid miners ever turn their visions into reality, these legal commitments will hold. The distributional questions arising from the development of space will be contentious. Complicating matters further, some of the greatest disparities in the returns from space may be across countries or generations—or even across on-Earth and off-Earth societies—rather than within traditional boundaries.

The uncoordinated structure of space regulation raises a number of questions that economists might help to pose and answer. As the space economy is developed, how will the value it creates be shared among the countries, and people, on Earth and off, now and in future generations? Does competition across nations pose a risk of a race to the regulatory "bottom" in the context of asteroid mining? What is the first-best structure of property rights in space, and what is the (politically) constrained second-best option?

## Concluding Thoughts

The successful economic development of space tests the limits of imagination. However, it might plausibly share some of the features of postwar American suburbanization. In each case, the locations from which emigration occurred (urban cores; Earth) were becoming polluted, crowded, and fractious. Innovations in transportation were making migration feasible for workers (mass transit and automobiles; low-cost launch). Innovations in residential technology were making housing workers in the new locations possible (mass-produced housing units; space habitats). Complementarities were leading a proliferation of supportive activities to develop (shopping malls and office parks; resource extraction and in-space manufacturing).

One can even imagine that "supraurban" societies in space would compete to attract settlers and workers, extending Tiebout (1956) competition—with its benefits and costs—in a new direction. For economists, the possibility of extraterrestrial experimentation with alternative institutional and policy arrangements will bring to mind issues that have arisen with the so-called "seasteading" movement to found autonomous floating city-states (challenges to which are discussed in Friedman and Taylor 2012) and Romer's (2010) proposed "charter cities," which are jurisdictions within existing countries whose institutions are designed on a "clean sheet" basis (although political resistance has handicapped their development).

The achievement of such visions will take time, perhaps a very long time. Many of the key questions for the economic development of space will be technological. But there will also be considerable room for scholars of economic development, industrial organization, public finance, economic history, and other specialties, to begin the work of understanding, improving, and even shaping the development of the space economy.

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