From Sailing Ships to Space Ships:

An economic history of the manner in which commercial space transportation companies have utilized outside assistance historically available to emerging transportation firms

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New Shepard spacecraft take shape on the assembly room floor at the Blue Origin plant outside Seattle, Washington. Reproduced by permission of Blue Origin.

Introduction: The View from the Mezzanine in Kent, Washington

On first entering the headquarters of the Blue Origin Company in Kent, Washington, south of Seattle, the visitor encounters a modern reception desk in what appears from the outside to be an undistinguished industrial building. An upstairs lobby houses various models and memorabilia. Casually dressed employees work in an open office environment. A modern kitchen serves healthy snack food and beverages. Adjacent to the kitchen, a mezzanine allows workers to gaze out over a large assembly bay. The assembly room floor reveals the purpose of the firm. This is no ordinary manufacturing plant. The visitor sees spaceships and rocket engines in various stages of production. The company is reaching for the stars.[1]

Jeffrey P. Bezos, who founded Blue Origin in 2000, is attempting to overcome two huge challenges. First, there is gravity. Second, he wants to place humans in space without significant government help. Using the fortune he acquired as founder of Amazon.com, he is financing his own spaceship firm.

The Blue Origin experience raises two fundamental questions relative to the future of human space flight. First, can private entrepreneurs accomplish what heretofore only public officials, with their access to substantial tax revenues, have been able to do? That is, can entrepreneurs raise enough money to create privately owned space transportation companies? The ability of business firms to build rockets is not in dispute. Their ability to raise sufficient funds from private sources is.

Second, if they can, to what extent do they need government help? Heretofore, business firms building spacecraft depended upon government contracts to stay afloat. The new space movement that Bezos represents is different. It presumes that privately financed spacecraft companies can sustain themselves through revenues drawn from a combination of private consumers, international customers, and government agencies.

Experience to date, it appears, suggests straightforward answers to these questions. Privately financed space transportation is possible. Government help is convenient, but not essential.

Space travel, like aviation and various forms of terrestrial transportation before it, is enormously expensive. The technical term is capital intensive. To build a spaceship firm, a dreamer needs billions of dollars – money that must be spent long in advance of the profits that may (or many not) repay initial investors. It is hard to make a business case for such an ambitious transportation undertaking. Entrepreneurs must literally bet the company – or someone's fortune – on the hope that their product will succeed.[2]

Similar challenges faced previous transportation tycoons, notably nineteenth-century railroad owners and twentieth-century aviation pioneers. Without outside help, their ambitious transportation schemes proved very hard to organize. This observation encouraged government support for a variety of American entrepreneurs bent on constructing roads, canals and railway lines.

The study that follows presents the experience of five business firms devoted to the creation of commercial space travel. Before these cases appear, the study reexamines the history of the first transcontinental railway, specifically the creation of the Central Pacific Railroad Company. This experience helped to establish the mechanisms of government support for large, capital-intensive transportation schemes. The study also recalls the history of the Boeing 707, the aircraft that established the modern age of jetliner transportation. Government support for a military offshoot of that airplane significantly altered the business risks involved in the undertaking. Examination of the business case for the Boeing 707 reinforces the central theme of this study – that government support is useful but not essential. A synopsis of the business case for the Boeing 787 Dreamliner similarly appears.

These observations carry forward into the experience of five commercial spaceship firms. Boeing, SpaceX and Orbital Sciences benefited from government help in various forms. Blue Origin and Virgin Galactic found investment in other ways.

The five companies presented here and others like them have embarked upon a great experiment. Some may succeed; others will certainly fail. The outcome will determine the degree to which private entrepreneurs can accomplish the long-held dream of making space transportation as commercially viable as movement by ships, cars and trains. Significantly, the outcome also will determine the degree to which those entrepreneurs needed government help to do so.

Various individuals imagining the future of space flight have anticipated the development of privately designed and operated transportation vehicles. Source: Milan Martinec hppts://www.artstation.com/artist/plumm, with the permission of the artist.

The Dream of Commercial Space Flight

Since the beginnings of modern rocketry, visionaries of space flight have anticipated the possibility of making space travel commercially viable.

When Robert A. Heinlein envisioned the first trip to the Moon for his 1947 novel *Rocket Ship Galileo*, he assigned the task to a private entrepreneur. Doctor Donald Cargraves, a nuclear physicist, quits his job with the fictional North American Atomics Company to build an atom-powered rocket that can travel to the Moon. Cargraves is interested in applying nuclear power to space flight, but North American Atomics wants to limit atomic technology to ships and trains. Commenting on the possible commercial returns from a lunar expedition, Cargraves explains to his young helpers, “When the Queen staked Columbus, nobody dreamed that he would come back with the Empire State Building in his pocket." The novel formed the basis for the classic 1950 film *Destination Moon* in which patriotic industrialists finance the lunar voyage.[3]

Heinlein followed *Rocket Ship Galileo* with *The Man Who Sold the Moon* (1951). Financier Delos David Harriman sells shares of the Moon as a means of financing a trip to the Earth's nearest celestial body. With the funds, he builds a single-passenger spacecraft that flies to the Moon and returns with diamonds gathered from the lunar dust.

Heinlein's expectation repeated a narrative offered by the famous German film-maker Fritz Lang in 1929. With help from members of the German Rocket Society, Lang produced *Frau im Mond* (English title *Woman in the Moon*), generally considered the first film to realistically portray an extraterrestrial voyage. Industrialists finance the lunar expedition and are rewarded when crew members discover a lunar cave full of gold.[4]

In the novel revealing the technical details for the influential movie *2001: A Space Odyssey*, screenwriter Arthur C. Clarke did not explain who operated the large rotating space station in Earth orbit and the winged space shuttle that transports humans thereto. Producer Stanley Kubrick corrected that omission. For the winged spaceship *Orion III*, Kubrick's model builders attached the logo for Pan American World Airways. To the large space station, they attached signage indicating that Hilton Hotels provided accommodations.[5] In that film, private entrepreneurs participate in humankind's most visible symbols of Earth-orbiting activity.

When saboteurs blow up the travel machine imagined by Carl Sagan in the novel *Contact* (1985), a wealthy entrepreneur rescues the mission by building another one. The entrepreneur, S. R. Hadden, made his fortune in the computer business through a firm called Hadden Cybernetics. The United States can barely afford to build another machine (estimated to cost $2 trillion), but Hadden has no difficulty constructing a spare. Ellie Arroway (the character played by Jody Foster in the cinematic version of the story) enters the machine, which transports her through a series of wormholes to a location near the center of the Milky Way and back home again.[6]

This is all fiction, of course. Modern space flight drew much of its early inspiration from members of privately organized rocket clubs, including the German Rocket Society (1927), American Interplanetary Society (1930) and British Interplanetary Society (1933).[7] Club leaders hoped that governmental agencies would support their activities. Yet they and their successors could not resist the temptation to imagine that cosmic activities also would attract private entrepreneurs.[8] In that regard, they anticipated that the history of past transportation activities would be repeated in space. Governments would help, but private entrepreneurs would do much of the heavy lifting.[1]

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[1] Science fiction writers did not always portray commercial undertakings in positive terms. While accepting the inevitability of corporate participation, many writers give nefarious objectives to the firms. In the classic 1972 movie *Silent Running*, American Airline executives maintain a fleet of space freighters containing biospheres that preserve plants and animals no longer found on Earth. The spacecraft botanist (played by Bruce Dern) resists the corporation when its executives issue an order to destroy the biospheres and return the privately owned spacecraft to their more profitable use as transport vehicles. In the 1979 film *Alien*, executives at the multi-planetary corporate giant Weylan-Yutani intentionally infect a member of the space freighter *Nostromo* with an extraterrestrial parasite as a means of collecting biological entities with warrior skills. Kim Stanley Robinson imagined a grand conflict between settlers loyal to the United Nations Organization Mars Authority and transnational corporations in his trilogy on the settlement and transformation of Mars (1993-1996). In *Moon* (2009), the Lunar Industries firm utilizes human clones as a means of reducing the cost of operations at a lunar mining station collecting Helium-3 for transport to energy-producing factories on the Earth. The human workers (who succeed each other one at a time) are not told that they are really clones. Executives from the non-governmental Resources Development Administration (RDA) maintain the spacecraft that transport personnel between Earth and Andora, a moon in the Alpha Centauri system where corporate employees mine a precious superconducting material in the visually stunning *Avatar* (2009). With assistance from a few environmentally- conscious humans, the local inhabitants rebel.

Perspective
The Boeing 787 Dreamliner: How corporate executives make major investment decisions

The Boeing 787 Dreamliner. Source: the Boeing Company

Before undertaking a private initiative like a new form of transportation, corporate executives prepare a business plan. The plan calculates the degree to which the initiative will produce corporate margins. Simply stated, does the proposed undertaking produce economic returns that justify the investment of funds?

The decision to build the Boeing 787 Dreamliner illustrates how these decisions are typically made. Boeing company executives closely guarded their calculations for the 787 initiative. Yet a sufficient amount of information emerged to reconstruct the company's original business case for building the plane.

Company executives thought that could develop the Dreamliner in four years at a cost of $5 billion. Toward the end of the development effort, the company would produce a few prototypes that it could not sell. Following certification, the company would begin manufacturing and selling airplanes. The first production units would cost more to manufacture than their price to sell. As production continued, manufacturing cost would fall. After a few years, the cost of production would drop below the sales price. The company would begin to make a profit on each plane sold – small at first but growing larger as production experience accumulated. Outside reports suggest that Boeing executives planned to start making significant profits halfway through the production process. That was the company's basic plan.

From these expectations, company executives performed detailed calculations. The calculations tested whether advocates of the program could make a viable business case for the plane under specific conditions. Under one scenario, company directors might expect to spend $5 billion during development plus another $4 billion to cover losses during the years when production costs exceeded sale revenues. Outlays typically accumulate at the beginning of a program; profits typically accumulate at the end. As those outlays persist, moreover, the interest cost on them accumulates as well. In effect, program managers are obligated to pay interest on the losses they accumulate but do not repay in early years. A $9 billion outlay can quickly turn into a $14 billion obligation.

Company executives could expect a 10 percent rate of return based on funds invested in the Dreamliner if the overall difference between average cost of production and average price paid by airplane buyers was 8.5 percent. The calculations are complex because sales price and production costs vary from year to year. Nonetheless, an average difference of 8.5 percent based on sales revenue would produce a 10 percent rate of return on funds invested, calculated annually. For Boeing, a ten percent annual rate of return on the funds it advances to complete the undertaking is a nice company margin.

Suppose company executives want a 10 percent rate of return on sales revenue instead of invested funds. For every $100 million in sales, they might anticipate $10 million in profit. Such a return on sales would produce an 11.8 percent return on investment. Program advocates typically make these calculations over a wide number of options to identify the range of acceptable returns.

For the Dreamliner, company executives anticipated that the company would invest its own funds rather than seeking outside monies. The overall business decision thus turned on the opportunity costs of investing company funds in the Dreamliner versus returns expected by investing those reserves in something else.

Based on a number of scenarios, the Dreamliner promised to produce margins of return around 10 percent. This met corporate expectations. Boeing corporate directors approved the 787 Dreamliner. In so doing, they incurred the risk that actual events would deviate from the original plan. This occurred. The development phase did not take four years; it took twice that long. Development did not cost $5 billion; estimates placed it at nearly three times that amount. Once into production, manufacturing costs remained stubbornly high relative to the airplane's actual sales price. Boeing continued to lose money on each airplane it produced. Some estimates placed the loss at $45 million per plane. Investment costs (essentially the interest owed on accumulated debt) continued to grow. Sources placed the overall investment obligation at $32 billion.

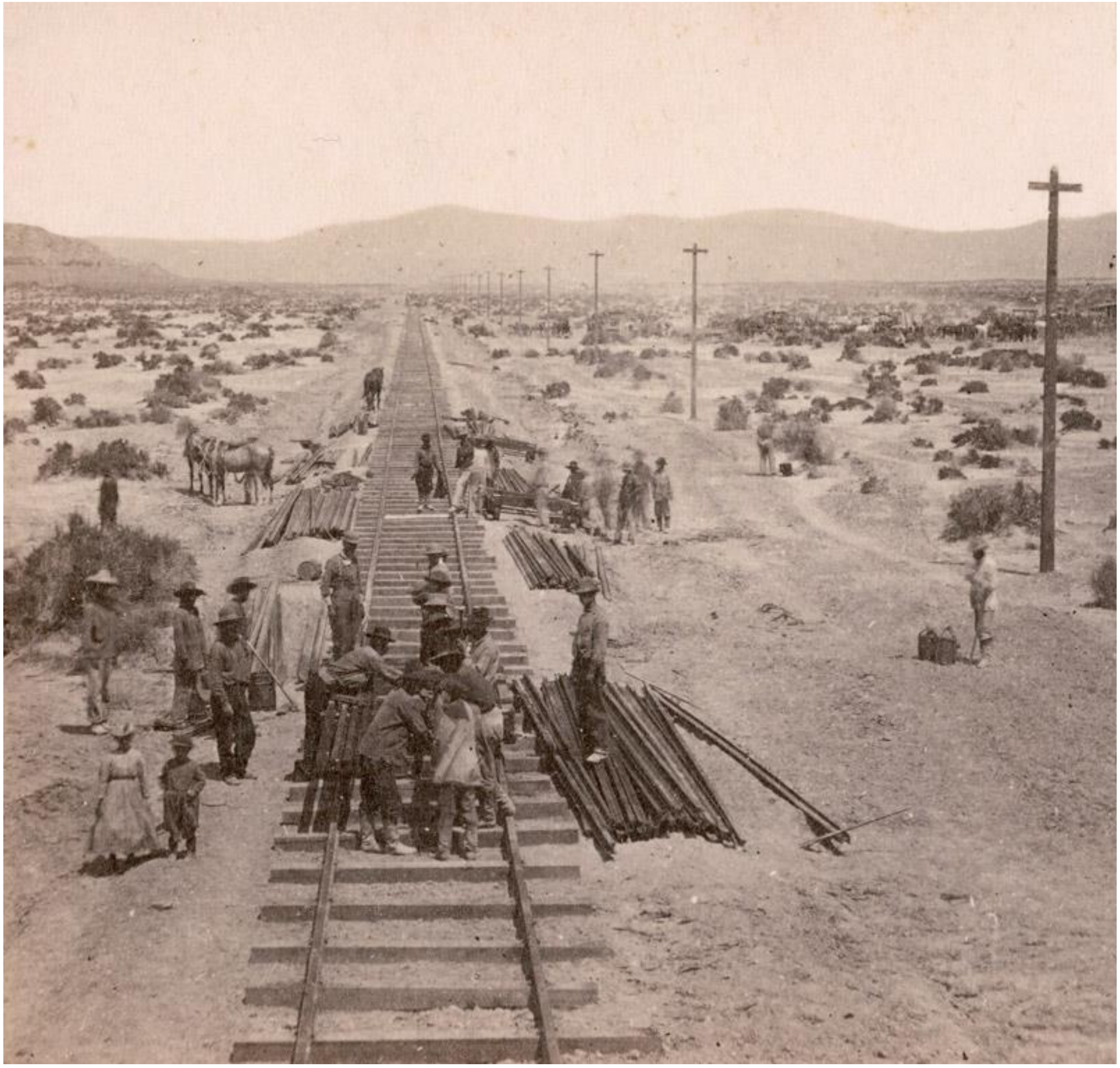
Smart business planners anticipate such risks and build them into their investment calculations. In principle, higher risks necessitate higher returns. Many risk mitigation strategies are available, including government support. Boeing executives took a different approach. First, they worked to stem the difference between sales price and manufacturing costs. In 2017, six years after the company delivered the first Dreamliner, corporate executives turned that corner. Extensive alterations to the manufacturing process allowed them to make a profit on each produced plane. Accumulated costs dropped below $30 billion. The value of company stock increased based on the expectation that an extended production run would ultimately justify the initial decision to proceed.

Company officials could retire a $30 billion investment by selling 700 aircraft at an average profit of $43 million per plane. Yet that solution fails to account for the accumulating interest costs on the obligation not yet retired at the end of each fiscal year.

A number of strategies are available to resolve this difficulty. The company might not worry about meeting corporate margins on all of the accumulating interest costs if the cost of borrowing is significantly less than the expected margins. In Boeing's case, the company used its own cash reserves to finance the undertaking. For those funds, the real cost of borrowing was essentially zero. The company might apply profits from activities related to the project but not included in the original plan. Aftermarket services (repairs and spare parts) is a multibillion-dollar activity and the company makes a significant amount of money by helping buyers finance or lease the planes.

Boeing executives softened the effect of accumulating interest costs by utilizing an accounting practice accepted within the aerospace industry. They counted the income value of orders received at the point at which customers placed their orders. Financially, this is more advantageous than counting income when a buyer takes possession of a product since it reduces the effect of compound interest and shortens the path to overall profitability. It is justifiable on the grounds that customers typically pay a deposit when they order an airplane and may use company lending instruments to finance the plane.

As noted above, the specific calculations can be quite complex. In concept, however, the plan provides an overall approach that a company can use to decide whether a business case exists for creating a new product.[9]



Construction of the transcontinental railroad helped establish the precedent that the government would provide as much assistance as necessary to allow private investors to finance the line. In this photograph, workers for the Central Pacific Railroad lay track near Humboldt Lake in northwestern Nevada. (Courtesy of the California History Room, California State Library, Sacramento, California.)

Financing Transportation: Lessons from the Transcontinental Railroad

To early 19th century travelers, the west coast of the United States was as far away as Mars. Settlers traversing the Oregon Trail commonly took six months to reach their destination. A railroad line that crossed the continent would permit travelers to journey from the American Midwest to the Pacific coast in as little as three days. Drawing on prior precedents, the U.S. Congress developed a set of policies famously designed to "do enough and just enough" to encourage private entrepreneurs to build a series of transcontinental railway lines.

In principle, public officials in 18th and 19th century America favored private financing of roads and canals. Private entrepreneurs built turnpikes and river crossing and canals linking seaport cities with rivers further inland. In practice, the undertakings often required government support. When private entrepreneurs failed to obtain sufficient financing to construct a 363-mile long canal from Lake Erie to the Hudson River, the New York State legislature established a mechanism with the authority to raise and spend funds. Further south, the U.S. Congress provided financing for a National Road that ran from Cumberland, Maryland, to Illinois. The funding mechanisms legislators established were often as innovative as the construction methods involved.[10]

America's first transcontinental railroad firmly established the prior precedents favoring public support to supplement private undertakings. The first transcontinental railroad stretched from Council Bluffs, Iowa, to San Francisco Bay along what became known as the overland route. The story of its creation has a popular and historical telling, the popular tale being as prophetic as the story of Queen Isabella and the financing of the Columbus voyage. In its popular form, the story exalts the importance of using government assets to encourage private initiative. We begin with the popular version.

For nearly twenty years, advocates of a transcontinental railroad sought financial support for the building of a line uniting the continent. The most devoted advocates could not generate sufficient funding for the line. In the popular retelling, no sensible banker in San Francisco would invest money in a venture that proposed to link railway lines in Iowa with San Francisco Bay. The risks were too great, the returns too small. So the advocates of a transcontinental railway line went to Sacramento. There they advanced an intriguing tale. If local entrepreneurs who had made money in the gold rush business would advance funds necessary to start construction, the federal government would provide a subsidy, primarily in the form of land. For every mile of railroad track the investors financed, the federal government would cede alternative sections of public land stretching ten miles outward from both sides of the line. Sale of the previously vacant lands made valuable by the presence of the railroad would boost returns and reduce the risk to potential investors.

Four investors agreed to participate. They were Leland Stanford, a Sacramento department store owner; Collis Huntington, a purveyor of hardware and miner's supplies; Mark Hopkins, with Huntington similarly employed; and Charles Crocker, another mining store owner. They agreed to create the Central Pacific Railroad Company and finance a section of track that moved east from Sacramento to meet a second section constructed by the Union Pacific Railroad moving west from Iowa. Workers completed the line in 1869, the two crews meeting at Promontory Summit, Utah. The four investors became fabulously rich. Leland Stanford used his wealth to found Stanford University.

The historic retelling presents much the same story, but with important details. No group of private individuals in mid-19th century American was willing to risk the funds needed to construct a transcontinental railroad through purely private means. The federal government possessed adequate resources, but officials in that realm had other priorities that prevented them from taking responsibility for the line. Instead, public officials adopted a series of government policies that encouraged private individuals to raise the necessary capital and complete the task through business firms. Land grants were one of those policies. They were important, but not the most significant mechanism.

The detailed story as related here is told from the perspective of the Central Pacific Railroad Company and its founders. Though not fully known in advance, the scale of the challenge facing them was enormous. Entrepreneurs of relatively modest means had to raise slightly more than $50 million to construct 690 miles of railroad track through the Sierra Nevada Mountains, across Nevada and into Utah where the construction crews would meet line builders moving west from Iowa.

Advocates of a transcontinental line had agitated for private and public support for nearly twenty years and before that for railroads in general. As a candidate for the Illinois state legislature in 1832, a twenty-three year old store-owner named Abraham Lincoln spoke out in favor of government support for a local railroad. He lost the election, but remained an ardent supporter of railway construction throughout his career.[11] Two issues retarded government support for a transcontinental line. Politicians could not agree on the location of a route, an issue partially resolved in 1859 when Lincoln (then a private citizen) travelled to Council Bluffs and announced his support for the overland course. Southern interests opposed the midland route, fearing that the railroad would open territory above the legislated slavery line, leading to the admission of non-slave states and upsetting the political balance in place since the Missouri Compromise of 1820. That objection disappeared from the halls of Congress when southern legislators walked out of the U.S. capitol in 1861. While their withdrawal created a political majority in support of a transcontinental line, the resulting Civil War concurrently guaranteed that the U.S. government would have neither the financial resources nor the material to build the line on its own. Private construction – encouraged by government support – became the favored avenue of development.

In 1856, a group of railroad enthusiasts meeting as the Pacific Railroad Convention chose Theodore Judah to lobby on behalf of their cause. Judah met with politicians, surveyed routes through the Sierra Nevada Mountains, and solicited support from local business owners. He approached various business interests to plead for money to construct a railway line from Sacramento through the mining communities in the Sierra Nevada Mountains to the eastern boundary of California near Truckee. (A separate line constructed by the Western Pacific Railroad Company would connect Sacramento with ship wharfs in Oakland on San Francisco Bay.)

Judah estimated that a line reaching from Sacramento some 140 miles to the state's eastern boundary would cost $12.4 million to build or roughly $88,000 per mile. His figures were fairly accurate. He further predicted that the line would generate revenues totaling nearly $2 million per year. At a 10 percent rate of return, the company would need twelve and one-half years to repay its investors, with interest.

This sum far exceeded the financial resources of potential supporters. The most devoted contributors had the resources necessary to finance a few miles of track, but not a whole line to Nevada – to say nothing of the challenges inherent in crossing the continent. The construction cost for a transcontinental line could exceed $100 million, the sum to be expended by two companies moving east and west toward a central meeting point.[12] An early commentator characterized the prospect of support for a railway line that Sacramento financiers could start but hardly finish as "an act of insanity."[13]

Judah told potential investors that they could launch the process with an investment of just $35,000. The money would pay for preliminary surveys, cost estimates, and incorporation fees for a railroad company that did not propose to go very far. Sacramento supporters – known in history as the "Big Four" – agreed to provide Judah with $35,000 and nothing more. Any further investment would depend upon the results of the surveys, the cost estimates, and investment strategies.

Due in part to Judah's relentless prophesizing, the group organized the Central Pacific Railroad Company of California in the summer of 1861. To incorporate the company, California state law required the prospective entrepreneurs to subscribe $1,000 worth of capital stock for every railroad mile they planned to construct. (Subscribe means to sell on an incremental purchase plan.) The group – now consisting of the Big Four, Judah, and two other individuals – announced their intent to construct a railway line across California. They issued 85,000 shares of stock with a par value of $100.[2] Had all 85,000 shares sold, the group would have raised $8.5 million – substantial but not enough to reach the Nevada state line.

To leverage their investment, the group undertook a creative strategy. The strategy rested on a peculiar feature of the state law. The law required a subscription of only 1,480 shares. Priced at $100 per share, the subscription met the legal requirements for a line of 148 miles. It raised $148,000 or $1,000 per mile. The real cost of crossing the California mountains would reach $100,000 per mile, but state law required the investors to show only a fraction of that amount to incorporate.[14] The Big Four plus Judah contributed roughly half of the required amount, the remainder subscribed by other investors. For about $75,000 of their own funds, Judah and the Big Four launched the Central Pacific Railroad.[15]

The company owners now faced a daunting task – raising the roughly $50 million dollars needed to construct their share of the whole transcontinental line. Here is the financial strategy they pursued.

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[2] Par value refers to the face value of a security. For stock, it represents the amount on which dividends are paid. For bonds, it represents the amount to be repaid when the security matures. It usually bears no relation to the price at which the security sells.

First, they continued to sell stock in the company. According to their annual reports, the company authorized $100 million worth of stock and sold $60 million. On its face, this statement was misleading. The initial investors (about seven in number) owned practically all this stock, having accumulated it as the line progressed. According to one observer, "the shares in other hands [were] very few."[16] On paper, this made the Big Four very wealthy, but during construction the company was chronically short of cash.

Collis Huntington took over the financial aspects of the company, naming himself vice-president of the firm. In 1862, the U.S. Congress passed the Pacific Railroad Act. The legislation named the Central Pacific as the chosen company to construct the western section of the transcontinental line and authorized the sale of government bonds to help finance the project. The company was to receive $16,000 for every mile of track set on flat land, $32,000 for each mile through hilly country, and $48,000 for every mountainous mile. This was the second strategy – receive funds from the sale of government bonds. Legislators anticipated that the company would match the government contribution roughly one-to-one by selling its own corporate stock and bonds.

The second strategy was less generous than it appeared to be. The bonds took the form of a loan, which the federal government expected the company to repay. Moreover, sale of the bonds was invariably delayed. The company needed funds in advance of construction, not after the work was done. To further complicate sales, government bonds took the form of a first mortgage on the railway line. In the eyes of private investors, this relegated any company-raised funds to the status of a second mortgage, making corporate stock and bonds nearly impossible to sell. Raising money was a constant challenge, and Theodore Judah died in 1863 while traveling to New York City on one fund-raising venture.

In 1864, Congress amended the Pacific Railroad Act, allowing the two companies to sell first mortgage bonds in an amount up to the value of government bonds. This expedited the third strategy. The officers of the Central Pacific, working through their New York financial agents, Fisk & Hatch, sold many corporate bonds. To supplement this financial flow, Huntington solicited funds from local communities along the California line, monies likewise taking the form of government bonds. Officers of the firm also borrowed money on their personal credit, at one point securing personal loans amounting to more than $1 million to cover short-term needs.[17]

As their fourth financial strategy, company officers drew on revenues generated by company operations as track was laid. These proceeds helped to fund construction and interest payments on various bonds and added value to the firm.

Part of that revenue came from the sale of lands. According to one source, agricultural land served by the railroad line sold for $2.50 per acre. City land brought $5 per acre and pine lands $10. Lots in one Nevada town that housed "two men, one woman, three pigs and a cow" prior to the arrival of the railroad sold for $300 each once the line arrived. The company sold seventy-four parcels.[18]

Based on federal land grant policies, the Central Pacific Railroad Company was entitled to receive 4.4 million acres of land for the 690 miles of track it laid. Much of the land was arid and essentially worthless, but enough good land existed along the tracks to provide an important source of revenue as well as equity for loans. The saleable land – perhaps 30 percent of the whole – might have been worth $6 million. This was a fraction of the $50 million the company needed to raise, but nothing to be dismissed either.

Revenues from passenger and freight transport materialized as well. For 1866, with only seventy-five miles of track in service, the Central Pacific Company reported $865 thousand in gross revenues. Subtracting the cost of operating the line, the company reported $656 thousand in net earnings. By 1869, net earnings had climbed to $2.7 million, the company having received $5.7 million from charges and fares set against operational expenses of $3 million.[19] The hefty ratio of gross revenues to operating expense – nearly two-to-one by 1869 – bred customer discontent. Riders and shippers accused the company of price gouging. Indeed, the prices charged by the company for passenger and freight transport through the mountainous section of California exceeded the rates charged back east on more gentle land by a factor of five.[20] Company officials attributed the higher charges to the steep expense of construction through rough terrain. Complainants charged the company with using profits to bolster the firm's financial standing.

The pricing controversy called attention to an important feature of congressional support. By naming the Central Pacific as the appointed firm for constructing rail service on the western section of the transcontinental line, the U.S. Congress effectively produced a private monopoly over the midland route. Public regulation of routes and fares continued until 1995.

Finally, company officials apparently used profits from construction activities to fund further construction and increase their wealth. On the surface, such a strategy seems to make little sense. The diversion of construction bond funds to profits would simply raise the cost of construction and require the sale of additional bonds. Company stocks and bonds did not sell for their face value, however. They sold for less. This allowed company owners to use proceeds from construction funds to purchase stock that would appreciate in value as the line neared completion. Additionally, the primary investors – essentially the Big Four – held offices in the company. As such, they received salaries. Stanford appointed himself company president. With his salary he could purchase more stock.

As their holdings increased, Stanford and the other primary investors became fantastically rich. They held most of the company stock, estimated to be worth $40 million in 1869. Sources believe that by the latter years of the 19th century the wealth of the Stanford family alone approached $50 million.[21] This occurred from an initial investment of $75,000 needed to incorporate the firm. Company officers were understandably reluctant to explain their financial strategies in detail and account books disappeared. Although the scale of indebtedness incurred to construct the Central Pacific line was known ($53 million), a series of investigating commissions concluded that the true cost of constructing the line would never be ascertained.[22]

To summarize, the owners of the Central Pacific Railroad financed the establishment of the line through corporate stock, corporate bonds, transportation revenues, government bonds, and land grants. They benefited from various regulatory policies including monopoly status. The earlier American experience with roads, turnpikes, river crossings, canals and rails had established the tradition that revenue-producing transportation undertakings should be privately owned. The rapid expansion of the country and the challenge of raising funds to complete a total line nearly 2,000 miles long encouraged government assistance. The federal government used its assets – primarily land – to help private companies lay rails. So did local communities. The federal government – and to a lesser extent local governmental bodies – provided bonds that assisted private companies in raising funds. Such assistance was predicated upon the ability of the companies to repay the bonds and raise additional monies through private means.[23] Finally, the federal government purchased services created by the firms and helped stabilize the prices that company officials could charge.

In the 20th century, these practices would be applied in a different form to the development of aviation in the United States.[24] Eventually, the support philosophy would find its way into the creation of partnerships for space travel.

Perspective

The transcontinental railroad: calculating the effects of government support

In 1982, Lloyd J. Mercer, an economics professor at the University of California (Santa Barbara) published a book calculating the effects of government support for the transcontinental railroad. His analysis provides important insights into 21st century support for privately owned space transportation.

Prior to construction, advocates of the transcontinental lines insisted that their ability to attract private investment required government support. The ex-ante argument was well accepted by people at that time. Public officials and railroad executives generally believed that government support was an essential condition for encouraging private companies to complete the transcontinental lines. The support took several forms, the most dramatic consisting of federal grants of land.

Mercer examined the ex-post argument. In other words, he examined the consequences of public support and private initiative after the fact. With the benefit of hindsight, he asked whether the original expectations were true. His analysis addressed three issues. First, was private investment in the transcontinental lines economically unwise in the absence of government support? Second, did the land grants increase the returns on investment for investors contributing private funds to the transcontinental rail lines, thereby reducing the risk of their investment strategy? Third, were the land grants necessary – that is, did government support transform an investment with weaker than average returns into an investment with stronger than average returns?

His conclusions can be summarized in the following way. For some – but not all – of the transcontinental lines, private investment in the absence of government support was wise. That is, it provided earnings that exceeded the returns the private investors might expect to receive by investing in other products. Second, the public land grants increased the returns that private investors could expect to receive by investing in transcontinental lines. Third, in a few cases the government grants pushed a less-than-adequate return into a better-than-adequate return.

Mercer used a revenue model to calculate his results. The calculations are complex. (The appendices in which they appear fill 113 pages in the book.) To determine earnings on capital, he identified annual gross revenue separately for seven railroad companies in the business of constructing transcontinental lines during the second half of the nineteenth century. From annual gross revenue, he subtracted annual operating expenses, excluding capital outlays. The resulting number represented earnings on capital. (By carefully comparing earnings on capital to the stream of investment expenditures, Mercer could estimate private rates of return.) “Carefully” is a necessary qualification because nineteenth century railroad executives commonly exaggerated the book value of road and equipment as a means of attracting investment. Some observers estimate that as much as 40 percent of railroad assets were fictitious, what commentators characterized as “water.”

Mercer then performed an analysis of the value of land. Basically, he identified the annual revenues obtained by the seven railway companies from the sale of lands granted in exchange for rail lines, the book value of unsold land, and the expenses associated with holding and selling the land (such as taxes and fees). These numbers were excluded from the prior round of analysis, producing a private rate of return (unaided) in the absence of land grants. A second round of analysis produced a rate of return including land for each of the seven companies.

To these two sets of numbers, Mercer added a third – the opportunity cost of capital for each of the seven lines. Essentially, this can be viewed as the investor's rate of return if the investor had not provided railway funds but invested in something else.

The results are interesting. In all seven cases, the land grant policy moved the investment needle. The provision of government support in the form of land grants increased the rate of return to private investors. Among the seven railroad lines Mercer examined, the increase varied from 1 percent for the Central Pacific (the lowest) to 4.5 percent for the Canadian Pacific (the highest). So, the general ex-ante perception that government support would increase rates of return for private investors was true, thereby encouraging investment and reducing risk.

Did government support permit any railroads with weak rates of return to become profitable because of the land grant policy? Four of the seven rail lines studied produced inadequate private rates of return in the absence of government support. In other words, their unaided rates of return were less than the opportunity cost of capital. They were the Texas and Pacific, Santa Fe, Northern Pacific and Canadian Pacific lines. The summary table appears on page 143 of Mercer's book.

In two cases – the Northern Pacific and the Canadian Pacific – the provision of land grants transformed an inadequate rate of return into a more than adequate return. The Northern Pacific line ran from Duluth, Minnesota, to Tacoma, Washington, and was completed in 1898; the Canadian Pacific ran from Bonfield, Ontario, to Craigellachie, British Columbia, and was finished in 1885.

For the remaining two lines, land grants made the rates of return grow but not enough to exceed the opportunity cost of an alternative investment. The two lines so affected were the Texas and Pacific line and the Santa Fe.

What about the first transcontinental line, linking the Central Pacific railroad moving east from Sacramento to the Union Pacific moving west from Council Bluffs, Iowa? In hindsight, Mercer concludes, this line was adequately profitable without government land aid. Mercer calculated the unaided rates of return at 10.6 and 11.6 percent, respectively. The opportunity cost of capital for these two lines he placed at 9 percent. Land grants pushed the actual rates of return to 11.6 and 13.1 percent. For these two companies, land grants were convenient but not essential.

To summarize, three lines (Central Pacific, Union Pacific, and Great Northern) were adequately profitable without government aid. Two lines (Texas and Pacific and Santa Fe) were unprofitable even with it. For the remaining two lines (Northern Pacific and Canadian Pacific), government aid in the form of land grants made the difference between unprofitability and profitability relative to the opportunity cost of capital.[25]

Significantly, these results were not known in advance. Public officials and company executives were correct in assuming that government support would make private investment in transcontinental rail transport more attractive. They were right in assuming that such support – for some railroad companies – would make the difference between breaking high versus breaking low. They would have also been right in assuming that they could not determine with a high degree of certainty in advance of actual results which railroad companies would need government support to succeed. For that reason (and for satisfaction of equity) public officials provided land subsidies for nearly all. [26]

Technicians at the Spaceship Company in Mohave, California, place the fuselage for *SpaceShipTwo* on the landing craft's wheels. Source: Virgin Galactic.

Five Case Studies

Private entrepreneurs seeking to enter the commercial space transportation market face a common challenge. They must raise capital in sufficient quantities to finance their endeavors. Concurrently, they will undertake various strategies aimed at managing the risk their efforts pose to the investors. If they had a conventional government contract, they would not face these requirements to the same degree.

While entrepreneurs so disposed face this common challenge, the strategies they utilize to resolve it vary widely. Some rely heavily upon governmental support. For others, the governmental presence is minimal. Five case studies follow. Each represents a different approach to the challenge of raising capital and reducing risk.

The history of the Boeing Company's effort to develop its CST-100 *Starliner* shows how a large private corporation can use reimbursable government contracts to reduce the risk of developing commercial space transportation vehicles.

The history of SpaceX demonstrates how an entrepreneur can leverage government contracts to raise private funds.

Prizes and philanthropic contributions support other endeavors. In such cases, private contributions take the place of government support. These contributions help the company establish a record that attracts additional investment. The history of Virgin Galactic illustrates this approach. Once established, Virgin Galactic received additional support from foreign entities that behaved like legacy investors. A legacy investor is an individual or organization motivated by the purpose of the investment (in this case space travel) as well as the expectation of financial returns.

In a similar vein, a wealthy entrepreneur can act as his or her own philanthropist, providing money to a cause that may yield both spectacular results and personal profits. This fits the history of Blue Origin. For such cases, government support is welcome but not essential.

Despite their desire to provide services to a wide range of customers, many corporations remain largely dependent upon government contracts for their work. While potentially productive of innovation, the approach does not provide a strong model for commercialization. This study presents the history of the Orbital Sciences Corporation as an example of this approach.

The five approaches presented here can be characterized as the prototype approach, the entrepreneurial approach, the prize/philanthropy approach, the entrepreneur as philanthropist, and the traditional contract model.

The three space transportation firms that received governmental support received it largely in the form of public grants and contracts. As the history of past transportation forms reveals, governmental bodies can provide corporate support in other ways. A final section recounts other methods used to encourage the development of commercial space transportation – public actions that have the effect of helping the firms raise private capital and managing corporate risk.

In this artist's conception, the Boeing CST-100 *Starliner* ascends toward the International Space Station. Source: NASA.

Boeing: Pairing Commercial Work with Government Contracts to Reduce Risk

Move forward from the transcontinental railroad eighty years to the 1950s.   Aircraft are overtaking trains as the favored method of transcontinental transportation. The leaders of a large airplane company, highly successful at building military aircraft under contract for the U.S. government, want to move into the commercial aviation business. Their design for a new aircraft is revolutionary; their experience with building commercial aircraft thin. The concept calls for a swept jet liner with four turbo jet engines hanging down from the wings. At the time, most commercial airliners employ propellers driven by engines set into wings that extended at right angles from the fuselage. The turbo jet concept has many advantages, chief among which is a more favorable power-to-weight ratio. The new vision is bold, but very risky.

To pursue their vision, company executives believe that they need to construct a prototype of the new aircraft and demonstrate its capabilities to prospective airplane customers. The company plans to build a single prototype and it will cost $16 million. Company engineers schedule the first flight for 1954. To prepare for full-scale production, company executives additionally anticipate that they will need to produce four aircraft that they cannot sell and three more aircraft in advance of any firm orders. Cost analysts advising the executives estimate that each aircraft will cost $4.5 million to produce – a total commitment of $32 million for the first production run.

The company thereby risks $48 million on the venture – $16 million for the prototype plus $32 million for aircraft the company must produce but may not be able to sell. By undertaking the venture, the executives will essentially bet the assets of the company on their ability to sell their design.

The chances of failure are 50 percent. In other words, there is a 50 percent chance that the venture will fail, lose $48 million, and take the corporation down with it.

Conversely, the chances of success are 50 percent. If the venture succeeds, the company will sell 1,000 planes at an average profit of $450 thousand per plane and revolutionize the airline transportation industry.[3] The company will make $416 million – the $450 million in profit on sales less the non-recoverable investment of $34 million.

Concerned with the significant level of risk, the executives search for a method of improving their odds. They settle on a parallel strategy. They show the prototype to officials in the U.S. Department of Defense and suggest its use as a military tanker that can refuel other aircraft in flight. If this scenario succeeds, the company will sell 800 planes. The resulting contracts will cover the cost of the entire production run; only the prototype cost is at risk. Company executives estimate that their chances of success on the military side are 75 percent.

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[3] The company's margin of return based on gross revenues is set at 10 percent for the purpose of this illustration. The actual figures are 11 percent for commercial aircraft and 10 percent for military and space sales. See Greg McFarlane, "How Boeing Makes its Money," <Investopedia.com> (March 27, 2015) (accessed September 7, 2016). The non-recoverable investment consists of the prototype investment of $16 million plus the non-salable production run of four aircraft at a total of $18 million. The three additional aircraft produced in advance of firm orders will sell.)

The introduction of a parallel scenario changes the odds of success considerably. Both initiatives could fail. The probability of this occurring is 12.5 percent. If this unlikely event occurs, the company will lose no more money ($48 million) than if it pursued the commercial path alone.

The odds of at least one of the initiatives succeeding climb to 87.5 percent. If the commercial venture fails and the military venture succeeds, the company will cover its losses. The military venture stands to make $360 million in profit.[27] Set against a loss of $48 million on the commercial venture, the company will still be ahead.

The rosiest of scenarios is quite attractive. There is a 37.5 percent chance that both ventures will succeed. In that case, the company will take in $810 million in profits against which it will charge its investment outlay of $34 million. The company will emerge as the dominant leader for commercial and military aircraft in the United States for the remainder of the 20th century.

This is the story of the Boeing 707, the figures rounded to make them easier to visualize but essentially accurate. Boeing executives used their 367-80 prototype (generally known as the Dash 80) to secure commercial and military customers. On the commercial side, the prototype established the age of commercial jet transport. Boeing produced 1,010 units between 1958 and 1979. On the military side, the prototype led to the KC-135 jet tanker. Boeing built 803 units between 1955 and 1965.[28] For its influence on aviation history, the Dash 80 earned a place at the Udvar-Hazy Center of the National Air and Space Museum.

In the mid-1950s, Boeing was an American aircraft company worth approximately $100 million, located in an undistinguished city in the distant Pacific Northwest. It showed profits of $16.5 million on sales of $652 million in the first half of 1957.[29] The Douglas Aircraft Company, located in southern California, dominated the production of propeller-driven aircraft. By 2015, the Boeing Company had been transformed into an international conglomerate with sales of $96 billion annually and forty-eight major military, space and commercial projects underway.[30] Douglas Aircraft ceased operations as an independent entity in 1967.

From the mid-1950s, move forward another half century, to the first two decades of the 21st century. Top Boeing executives advanced another vision, one that would place the company at the forefront of the effort to develop private capabilities for extraterrestrial flight. John Mulholland, Boeing vice-president and commercial program manager, explained the approach.[31] Boeing would develop a seven-seat space capsule known as the CST-100 or Starliner. The company would launch the capsule on an Atlas 5 rocket provided by United Launch Alliance, a joint venture of which Boeing was a member. The capsule would fly to privately-run space stations and NASA's International Space Station and lead to more advanced spacecraft that could travel as far as Mars. Boeing's chief executive officer, Dennis Muilenburg, announced that he wanted the first people to visit Mars to arrive on a Boeing rocketship.[32]

"The market is obviously going to be there," Mulholland explained.[33] Yet it was not a market for which a viable business plan could easily be made. To produce the Starliner privately, Boeing would need to spend at least $3 billion developing the capsule, likely more. It would need to produce an unspecified number of flight-ready capsules and procure enough Atlas 5 rockets to launch them. To recoup its investment, someone would need to sell seats on those capsules for an estimated $50 million each and hold round trip costs for each flight below $280 million.[34]

In anticipation of such a market, Boeing entered into a preliminary agreement with Bigelow Aerospace to provide transportation to a series of privately financed, inflatable space stations should Robert Bigelow ever manufacture and launch them. Bigelow's business plan called for his company to sell room on the inflatable stations for the equivalent of $79 to $95 million per year. He hoped to hold transport prices to and from the stations below $25 million per seat. [35] Beyond the arrangement with Bigelow, Mulholland explained, Boeing could expect to market transport to and from the International Space Station.

If the investment costs necessary to produce a profitable privately-financed spacecraft were high, the prospective risks were even higher. The likelihood that Boeing could recoup company margins on such a venture were probably well less than 50 percent. Nonetheless, Mulholland explained, "this isn't a market we want to exit." [36] He elaborated.

> When you look at it, commercial human spaceflight is inarguably an immature market. I always compare the market to when we go out and develop a new commercial aircraft. The difference is the commercial aircraft is a very certain market. You've got commitments on tail numbers

> on airplane deliveries before you fully invest and go and build that airplane. [Space] is a completely different market and it's very immature….The only certain market is two NASA flights a year to the international space station. I liken it back to the Kelly Air Mail Act of 1925. The government did invest in that infrastructure and really helped establish that commercial airplane market. Hopefully, we'll see that develop here.[37]

As Mulholland observed, the U.S. government possessed an asset that it could use to encourage the emergence of a private space transportation industry. The asset was the multi-billion dollar International Space Station. As of 2011, the United States was paying Russia $224 million yearly to transport American astronauts to and from the station, a number predicted to rise to $568 million by 2018.[38] Here is how the U.S. government used that asset and the associated transportation expenditure stream to encourage Boeing to stay in the game.

NASA executives announced that they would pay $58 million per seat to American companies that could transport astronauts to the International Space Station. At that time, the Russians charged the United States $71 million per seat.[39] Qualifying companies could sell at least one seat per trip to private customers. Additionally, the government promised to provide funds to help defray the company's cost of developing the spacecraft – upwards of $3 billion in the case of Boeing's award. Government officials viewed the development subsidy as having public value. It would create an American capability that did not exist and it likely would do so for less than the government would spend for the same purpose. As a point of comparison, NASA spent $3.9 billion during the 1960s to develop and test the Apollo command and service module – the spacecraft that took American astronauts to their orbit around the Moon and back. In twenty-first century dollars, an equivalent outlay would approach $40 billion.[40]

American companies would compete for the awards. To encourage participation, NASA provided funds to help defray the costs of planning and proposal writing for qualifying firms.

The crew transport policy departed from a pattern established for similar programs in the past, notably the Lockheed Martin X-33 and the prior awards for transporting cargo to the International Space Station. As a condition of those awards, the participating companies pledged to invest some of their own funds in the endeavor. The milestones in the space act agreement for the NASA-Boeing award did not require Boeing to raise additional funds.[41] Boeing executive John Mulholland announced that the company would invest "a significant amount" in the endeavor, but declined to say how much.[42]

History and an analysis of the award amounts suggest that the company share was not sizeable. As in the case of the KC-135, the company relied heavily upon government awards to finance a capability that provided substantial returns. Boeing received roughly $4 billion in gross revenues for the KC-135 set against that aircraft's share of the prototype investment (half of $16 million).[43] In the case of the X-33, Lockheed Martin invested between $126 and $287 million (depending upon the accounting method used) compared to a government contribution that exceeded $1.1 billion.[44]

Boeing received $611 million from NASA to help finance the planning and proposal writing activities that led to the final crew transport award.[45] The company competed against four firms in the first round, six firms in the second round, and two firms in the third round. From the competition, NASA selected two firms to receive development and flight awards – Boeing and Space Exploration Technologies (better known as SpaceX). The development and flight award to Boeing was worth $4.2 billion and included up to six flights to the International Space Station. [46]

Using Boeing's normal return on revenues for military and space contracts (10 percent), the award potentially generated about $200 million in profits from flight activities that Boeing executives could reinvest in the development effort.[4] Including planning, the entire government award totaled $4.82 billion, of which $200 million or 4 percent could

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[4] Analysis is based on an estimated minimum price (to and from the International Space Station) of $265 million per trip. That provides for four astronauts at $60 million per seat and one paying passenger at $25 million. (Boeing announced that the spacecraft would be sufficiently spacious to hold up to seven passengers.) From the launch price, the operator must pay $150 million for an Atlas 5 rocket and could generate $40 million in revenue above cost. More than half of the $40 million accrues from the contribution of the paying passenger. That leaves $75 million applied to the cost of fabricating and servicing the spacecraft. The spacecraft is reused, reducing the cost of production. The income above operational cost ($40 million per trip or $240 million for six flights) can be reapplied as the company's share of the development effort. Equivalent figures for the Apollo command and service module (actual dollars) were $3.6 billion for spacecraft design and development, $275 million for testing the capsule, and $55 million for the production of each spacecraft (used once and discarded). Adjustment for changes in purchasing power from the 1960s to the 2010s obliges the analyst to multiply the Apollo figures by a factor of ten.

be reinvested. The company would not need to seek outside investors to cover that sum. Boeing is cash rich, with reserves exceeding $11 billion.[47] Moreover, the company could draw investment revenue from the government award.

By forgoing $200 million in short-term profit, the Boeing Company could establish a capability that would allow it to enter the human space transportation business, complementing more than a half-century of advances in commercial airplane production. The technical risks were substantial. The company might not be able to design and qualify a reusable spacecraft for an outlay of $3 billion – less than one-tenth of what NASA had spent (in equivalent dollars) to develop the Apollo command and service module. The development effort might fail.

Even so, the financial risks were very small. Essentially, the government award closed the business case for entering a market that looked very attractive to top company executives.[48]

SpaceX: Leveraging Government Support to Raise Private Capital

The history of Space Exploration Technologies Corporation – more commonly known as SpaceX – provides a vivid example of how a space-obsessed entrepreneur with some government help can leverage a relatively small investment into a multi-billion-dollar company.

Elon Musk founded SpaceX in 2002. At the time, Musk was worth something like $175 million. Seven years earlier, he had leveraged a few thousand dollars of his father's savings account into a computer-based map service called Zip2. Compaq acquired Zip2 in 1999, which produced a $22 million return on Elon's personal shares. Musk invested half of that sum in what became PayPal. When eBay acquired PayPal in 2002, Musk (the largest shareholder of PayPal stock) received $165 million for his shares.[49]

From this personal net worth, Musk took $100 million and formed SpaceX. Shortly thereafter, he also began to invest funds in Tesla, a California-based company organized to make electric cars. More investments in Tesla followed, along with a smaller commitment to SolarCity, a provider of solar power technologies. Musk complained that he was so financially overextended that he needed to rely on friends to pay his personal expenses. "I had to borrow money for rent," he observed.[50]

To maintain SpaceX, he needed more investors. As of 2006, four years after the formation of SpaceX, the company had not yet flown its signature rocket, the Falcon 9. (The first flight would not take place until June 2010). Beginning from three employees in 2002, the company had grown to 180 full-time personnel.[51] One hundred-eighty skilled employees easily could have consumed $27 million per year, including the cost of the projects on which they were working.[52]

To begin flights, SpaceX needed to grow. That required more funds than Musk's original investment could provide and Musk had no additional personal cash on which he could draw.

A SpaceX Dragon capsule sits on top of a SpaceX Falcon rocket, waiting for a launch from the Kennedy Space Center in April, 2016. Source: NASA.

Musk's promise that the firm could launch 23,000 pounds (10,500 kilograms) to low-Earth orbit for around $56 million per launch attracted outside interest.[53] The company needed to convert that interest into service orders. Under aerospace accounting rules, service orders can be translated into expected revenues that will increase the company's value to prospective investors.

As of 2006, Musk had seven "firm contracts" for launches of the Falcon 1 and three contracts for launches of his signature Falcon 9.[54] Given the listed launch prices for the Falcon 1 and Falcon 9, that produced a potential revenue stream of $200 million – promising but not sufficient.

At that point, the U.S. government intervened. NASA officials agreed to provide SpaceX with $238 million.[55] The money would flow in increments ranging in size from about $5 million to more than $30 million. In return, the company was obliged to meet nineteen milestones leading to its ability to deliver cargo to the International Space Station using its Falcon 9 and Dragon cargo spacecraft. This was a grant leading toward the development of capability, not actual delivery. The award supported rocket ship development. Milestones ended with a final demonstration flight. The criteria for success was straightforward -- "complete the launch" – which SpaceX did in mid-2012.[56]

NASA officials called the capability grant COTS – Commercial Orbital Transportation Services. The follow-on contract – which SpaceX won in 2008 – was called CRS for Commercial Resupply Services. The CRS contract brought SpaceX $1.6 billion in expected revenues. In exchange, SpaceX agreed to conduct twelve cargo delivery flights to the International Space Station.[57] A few years before 2008 (in 2005), SpaceX additionally had won a U.S. Air Force award that provided the firm with $100 million in the form of an IDIQ award, which is an open-ended award for an "indefinite delivery" of an "indefinite quantity" of material.[58] Cargo delivery flights using the Dragon/Falcon9 configuration began in October 2012.

Three of the nineteen milestones for the NASA/COTS contract required Musk to raise additional outside funding. NASA officials cancelled the other COTS award to Rocketplane Kistler after that firm failed to secure the necessary private support.[59]

Beginning in the summer of 2008, concurrent with the execution of the 2006-2012 NASA/COTS award, Musk attracted new investment funding totaling $145 million. The infusion lasted through 2012. The increments began with two relatively small investments of $15 and $20 million from a series of contributors, plus a larger share of $110 million in three increments assembled by a friend, Steve Jurvetson, working through the investment firm Draper Fisher Jurvetson.[60] The firm, which has a reputation for early investments in disruptive technologies, also contributed funds to Tesla.[61] Jurvetson characterized his friend as the "most risk-immune person I've ever met."[62]

Calculations based on estimated worth allow an assessment of the difference that the NASA award made in the ability of SpaceX to attract outside investment support. The effect can be stated in either of two ways. For investors interested in return-on-capital, the infusion of government funds likely raised returns by slightly more than two percentage points. That is, if a venture capitalist expected an overall return-on-investment of 8 percent annually from all investments in start-ups wholly dependent upon private funding, that VC could expect an overall estimated return-on-investment of 10.4 percent if one (and only one) of the companies received a COTS-type award.[5]

Interestingly, this increase approximates the additional rate of return that a 19th century investor could receive from investing in transcontinental railroad companies that received federal land grant subsidies.

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[5] Imagine a market for a technology product where two-thirds of the most competent start-ups fail. A venture capitalist who invests in three firms has a 70 percent chance of picking at least one successful firm. The statistical procedure used to predict this result is known as a binomial distribution. Assume that the VC places $250 million bets on each of three firms. The VC will can expect an expected overall 8 percent return on the entire investment if one of the firms is worth $1.4 billion after ten years. In this scenario, the other two fail. Other outcomes are possible. An added bonus occurs if the VC hits on two successes ($2.8 billion) or three successes ($4.2 billion). The odds of that happening are 22 percent and 4 percent, respectively. The danger remains that the VC will miss on all three (30 percent probability). The key to success consists of placing a sufficient number of bets so that the potential gains exceed the losses accumulated from investing in failed firms. This strategy works without advance knowledge of which particular firms will succeed or fail. Say that the VC makes 100 rounds of investment each involving three firms. The probabilities predict that the VC will make the equivalent of $1.4 billion on each round of investment, thereby satisfying the need for the desired 8 percent rate of return. The actual payoffs will vary from round to round (sometimes high; sometimes low) but will even out over many rounds of play. The infusion of government funds changes these outcomes substantially. Government support for just one of the firms reduces the amount of capital the VC needs to invest to receive expected returns. The reduced capital translates into a larger rate of return – in this example a return on investment of 10.4 percent instead of 8 percent. Note that the strategy does not require the VC to bet only on winners.

Alternatively, the venture capitalist might decide to forgo increased returns in exchange for reduced risk. Government awards influence expected risk as well as rates of return. Venture capital investments are risky. Investors stand to make significant returns on investment, but they also risk making nothing at all. This is especially troublesome for those investors making a limited number of investments.

A venture capitalist wisely investing in New Space firms (that is, betting on what appear to be winners) might be willing to accept a 30 percent likelihood of total loss. This circumstance would occur in a market where two-thirds of the start-ups fail (the probability of success set at 0.33). The venture capitalist contributes capital to three firms. The presence of government support in just one of the firms lowers the chances of total loss. In other words, the chances of investing in at least one winner improves. This occurs because the venture capitalist needs to invest less money in one of the firms, freeing funds for an additional investment.[6]

Analysis suggests that the COTS award made SpaceX a more attractive investment, either for reasons of increased returns or decreased risk. The investment firms that provided SpaceX with the additional capital place many bets. In deciding whether to invest in a firm like SpaceX, the investment officers assess factors like risk and returns. Investor support in space exploration may seem noble and visionary, but it is based for the most part on calculations that are cold and rational.

As of 2013, Elon Musk's company had grown to 3,000 employees.[63] By the end of that year, it had conducted twelve launches and would receive orders for sixty more. It had

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[6] Simulation of the probability distributions under these circumstances suggests that the probability of total loss falls from 30 percent to 23 percent. In the original scenario, the venture capitalist invests $250 million in each of three firms. The odds of backing all losers in a single round of investment in three firms each with a 33 percent probability of success is 30 percent. Government support reduces the amount of venture capital investment needed by one of the firms (say by half), freeing the investor to make an additional investment. The effect of a fourth trial without reference to investment size is considerable. It lowers the odds of total failure to 20 percent. The outcome of the fourth investment is complicated by the lesser amount. Some of that investment goes to the government-supported firm; the residual goes to the fourth firm. This creates a distribution with unequal payoffs. Under these conditions, the probability of receiving at least a partial payoff (or more) moves to 77 percent and the probability of total loss falls to 23 percent.

won the NASA cargo delivery award in 2008. As noted above, that contract was worth $1.6 billion. The company had completed its first commercial launch in 2009, a Falcon 1. It had launched the Falcon 9 in 2010, a test flight. In 2011, it had received the first in a series of NASA contracts and awards to transport astronauts to and from the International Space Station. The initial award, called CCDev2, paid SpaceX $75 million, mostly for planning.[64] A NASA Commercial Crew Development award followed in 2012. Called CCiCap, it paid SpaceX $460 million for capability development – essentially space craft design and testing.[65] A small $10 million award arrived at the end of 2012. Called CPC, it paid SpaceX for the processes required to certify the spacecraft as safe to fly.[66] Together, the three awards were worth more than $500 million to SpaceX, money that could be used like investment capital to develop a new crew transport system.

The three awards represented an important shift in philosophy. As the commercial partnerships matured, government officials (in NASA and the congressional appropriations committees) showed a greater proclivity for providing award winners with seed money to help finance their planning and spacecraft development activities. The earlier cargo awards were different. Through the first two rounds of cargo competition, NASA officials provided no funds. Contestants had to defeat the full range of competitors to receive money. As one of two winners, SpaceX received $278 million from NASA for spacecraft development. Subsequently, the company received the promise of $1.6 billion over eight years for actual services rendered.[67] NASA announced the first set of awards in 2006; it initiated the delivery awards in 2008.[68]

When the government turned its attention to crew delivery in 2010, it awarded funds for planning and technology. In the first phase of funding (called CCDev 1), five firms received $50 million for technology development. In the next phase (called CCDev 2), four firms received $270 million. A third round followed (CCiCap), worth slightly more than $1 billion to all recipients.

All three groups of awards were made prior to NASA's selection of the crew transport award finalists in September 2014. Firms could expect to receive a share of $1.5 billion by being considered semi-finalists (there were six) for the big crew delivery awards. The actual crew transport awards presented at the end of competition were worth a whopping $6.8 billion – half of which subsidized the design and development of the crew capsule and rocketry.

The government could have taken the approach of buying space on the rocket ships when it became available. In that case, competing firms would have allocated their planning and development costs to the price of a ticket to space. Instead, the government contributed funds toward the start-up costs that paid for planning, technology and design.

The effect of this approach on SpaceX is easily apparent. The firm was worth a great deal more than if it had been obliged to wait on actual delivery for payments from its anchor tenant (NASA). By 2013, the value of the crew transport development contracts had grown to $1.1 billion.[69] In 2014, congressional sources estimated that the value of SpaceX awards for the commercial crew program (CCP) had reached $3.1 billion.[70]

Based on government awards and prospective launch revenue, Musk sought another round of investment funding. In early 2015, he announced that Google Inc. and Fidelity Investments had agreed to provide SpaceX with an additional cash infusion of $1 billion. In exchange, the two firms acquired slightly less than 10 percent of the company. Some reports placed the share at 8.33 percent.[71] The investors expressed interest in using Musk's low-cost rockets to launch a constellation of internet-transmitting satellites.

The scale of the $1 billion investment for 8.33 to 10 percent of SpaceX reveals that the investing firms placed the total worth of the company in the $10 to $12 billion range. The valuation engendered much discussion. Had Elon Musk leveraged a $100 million investment in 2002 into a company that scarcely a dozen years later was worth one-hundred times that much? Business analysts seemed skeptical, although they did acknowledge Musk's capability to attract both attention and investment.[72]

Whatever its perceived or actual worth, the financial history of SpaceX is a perfect example of how a private firm can leverage private investments and government support into a multi-billion-dollar operation. The company began in 2002 with a personal cash infusion of $100 million from Elon Musk. It grew with an additional infusion of $145 million from venture capitalists**.** Nearly half (we estimate $4.6 billion) of the company's perceived $10 to $12 billion worth by the point of the Google/Fidelity investment in January, 2015, was derived from government contracts and awards.[73]

By 2016, SpaceX was substantially commercialized. Three-fourths of its future mission manifest as of November 11, 2016, provided transport for commercial or foreign government customers.[74] Concurrently, it received additional government work. In

February 2016, NASA officials announced that they were extending the total number of cargo delivery missions (completed and planned) from twelve to seventeen, an action potentially worth an additional $700 million to SpaceX.[75]

In the absence of government support, the firm would have had a much tougher time raising sufficient capital to proceed. Like railroad lines and airplane manufacturing, the business of space travel is quite capital intensive. The activity requires substantial up-front investments before revenues from sales begin to accumulate.

In the mind of a venture capitalist, a government award amounting to half of a company's gross revenue can change the investor's strategy considerably. Investors insist that they want to back winners, of course, but this is hard to know in advance. A safer and more profitable strategy consists of a series of investments based on the chances that any one investment will succeed. Such an approach subjects the risks to the statistical laws of probability – the same forces that ensure that a casino employee dealing cards will invariably take in more money than the house loses.

A government award changes the venture capital calculation. Without the award, investors would have been obliged to downgrade their assessment of the firm's probability of success and opportunities for growth. That assessment could easily lead to a decision not to invest, even though SpaceX expected revenues from other launch contracts.

Government awards by themselves do not guarantee success. Rocketplane Kistler won a similar NASA award at the same time, yet the company failed to raise necessary private capital and filed for bankruptcy in 2010. Formed in 1993 and reorganized in 2006, the company sought funds to develop its reusable, low cost, two-stage K-1 rocket. Company executives bet that they could sell launch services to companies interested in satellite-based cell phone communication. When that market evaporated, so did Rocketplace Kistler.[76]

The SpaceX experience illustrates the way an innovative entrepreneur can leverage capital investments leading to government awards and commercial orders into more capital and continuing growth. In combination with Rocketplane Kistler, the history also shows how risky such ventures can be. Despite occasional protestations to the contrary, failure is very much an option. In fact, it may be the norm.

A Blue Origin suborbital New Shepard rocket topped with an empty crew capsule lifted off from the company's west Texas launch site in January 2016, headed for the Karman line that marks the boundary between Earth and outer space. The same reusable rocket had flown into space and returned for a soft landing two months earlier. Source: Blue Origin.

Blue Origin: the Entrepreneur as Philanthropist

Innovators need not depend solely upon government awards for added support. They may also receive funding from philanthropists who have money to distribute. When the famous rocket pioneer Robert Goddard sought financial support for his field experiments on liquid-fuel propulsion, he turned to the wealthy philanthropist Daniel Guggenheim. Up until that time, Goddard had depended upon support from his employers at Clark University, a parsimonious source. He also received small grants from the Smithsonian Institution and a short but substantial grant from the U.S. Army Signal Corps. Clark University provided him with an assistant professor's salary, a machine shop, small faculty research grants and a series of graduate assistants interested in Goddard's propulsion experiments. Flush with World War I funds, the Signal Corps supported work on military rocketry. The Smithsonian expressed interest in atmospheric research and published Goddard's treatise on the subject.

None of these sources were sufficient for Goddard's true interest – the development of high altitude rockets that could eventually fly into space and reach the Moon. Guggenheim's support was. First Daniel and then the Guggenheim Foundation provided Goddard with ten grants totaling $191,500 over eleven years – the equivalent of nearly $9 million in the value of skilled labor in 2010.

Beginning in the late-nineteenth century, the Guggenheim family had invested in mining operations and smelting – the extraction of base metal from ore. Daniel assumed control of the family's business interests and built them into a substantial fortune. By 1918, the family was worth $250-300 million, reputedly one of the wealthiest in the world.[77] According to the Bureau of Labor Statistics, the average U.S. family income for 1918 was $1,518. By that standard, the Guggenheim family controlled a fortune worth more than $11 billion in equivalent 2015 household income.

Daniel's son Harry learned to fly and together father and son became avid enthusiasts of the notion that aviation would change the world. In establishing the nation's first school of aeronautics at New York University, Daniel explained his intent. "I shall dedicate the rest of my life to aviation, the greatest road to opportunity which lies before the science and the commerce of the civilized countries of the earth today." As for his motivation, Daniel said it flowed from "duty to my country, whose ample opportunities have always been at my hand."[78]

Starting in 1931, the family began to funnel money to Robert Goddard. According to one biographer, Daniel was fascinated by Goddard's proposal to fire a rocket at the Moon. The wealthy patron consulted Charles Lindbergh to check Goddard's credentials. "As far as I can tell," Lindbergh reportedly said, "he knows more about rockets than any man in this country."[79] With the family's financial support, Goddard recused himself in the open spaces of New Mexico where the absence of distractions permitted more than a decade of experimentation. Goddard ended his career developing jet assisted airplane take-off technologies for the U.S. Navy Engineering Experiment Station in Annapolis, Maryland, but it was private philanthropic support that allowed him to undertake his most creative work. Says Alexander MacDonald in his examination of this history:

> As had been expected by the early American intellectuals of spaceflight, the most significant financial support for Goddard came from private-sector individuals who shared with Goddard a deeply felt intrinsic desire to explore the limits of flight.[80]

This process repeated itself seven decades later, albeit in a slightly different form. A wealthy entrepreneur invested a significant amount of his own money in a venture to expand space flight. As of 2016, Jeff Bezos' net worth totaled $70 billion – making him the second wealthiest person in the world.[81] In 2000, Bezos founded Blue Origin, a company devoted to enabling low-cost, increased reliability human access to space.[82] Unlike Elon Musk, who ran out of money while investing in new technologies, Bezos did not immediately need external infusions of capital to keep his vision going. He could use his own funds.

The financial plan for Blue Origin followed the strategy Bezos adopted for creating Amazon.com. Bezos opened the company web site in 1995, selling books. In its first two weeks of operation, the small team of ten employees established a precedent that would continue for more than ten years. The company received orders whose value exceeded the cost of goods sold by a ratio of more than two-to-one. From gross profits, Bezos had to pay for marketing, programming and expansion. Those expenses invariably exceeded the difference between cost of goods sold and revenues from sales. During the first year of operations, Amazon received $511,000 from sales and spent $409,000 for books plus $406,000 for operations, losing $304,000 in the process. The established trend continued for five years, through 1999, a year in which the company lost $718 million against $1.6 billion in sales.[83]

To cover his losses, Bezos borrowed money from his parents. When their contribution of a few hundred thousand dollars ran out, he raised a few million dollars from twenty "angel investors" and a Silicon Valley venture capital firm. Bezos admitted that his successful fund raising required a rare "planetary alignment" that few start-ups ever receive.[84]

In 1997, Bezos took the company public, offering Amazon stock for $18 per share. The initial public offering netted the company $54 million. Investors were content to let Bezos plow gross profits back into operational expansion, even though the company lost millions of dollars in the process. Inexorably, the value of the company grew. An investment of $5,000 at the 1997 initial public offering was worth $1.3 million by 2014.[85]

Amazon showed its first annual profit in 2003 – a modest $35 million. By then the company, which had begun with a small parental investment ten years earlier, was worth $2 billion. Through 2016, the company continued to show modest profits and strong value growth.

In 2000, Bezos formed Blue Origin. The name of the company, he said, represented the dominant color of the planet from which the company came. The financial history of Blue Origin suggests that Bezos applied the same approach to space travel that he had applied to Amazon. He devoted financial capital to the expansion of capability rather than profitable returns. Moreover, Bezos behaved like a philanthropist, contributing his own wealth to Blue Origin with scant regard for its effect on revenues. The financial accounts of Blue Origin are closely guarded, but reports indicate that Bezos initially invested about $600 million of his own wealth in the rocket-making company.[86] He seemed content to accept no additional investments of significant size. In 2009 and 2011, the company received two small NASA grants worth $26 million. The grants supported efforts at Blue Origin to use NASA technology to mitigate risks to the crew capsule at launch.[87] Yet overall company operations depended on Bezos as patron.

For Bezos, $600 million was not a large investment given his wealth. Nonetheless, it was a substantial sum for a commercial space firm.   By comparison, SpaceX launched itself with two infusions of private capital (including the founder's own money) and a NASA award for cargo capability followed by awards for development of a crew capsule. It sustained itself with payments from NASA for delivering cargo to the International Space Station (the CRS award), a U.S. Air Force launch contract and progress payments from commercial customers. The sum of these sources – roughly $1.2 billion – represents the amount of money needed by Elon Musk through 2012 to start the company, develop the Falcon 1 and Falcon 9, develop the Dragon cargo module, start work on his commercial launch contracts and begin deliveries to the International Space Station.[88] By 2012, SpaceX had grown to 2,000 employees and was expanding rapidly. The beginning of cargo delivery in 2012 represented the company's maturation into an established firm.

Bezos established Blue Origin in 2000, as noted above. Development of his New Shepard launch vehicle was underway by 2005. Twelve years later (in 2016), the company concluded its signature achievement, repeatedly landing a previously flown New Shepard booster on its tail. Was the Bezos contribution of $600 million adequate to fund company operations or did he need additional support? To answer this question, we constructed a cost of operations estimator that relied upon publicly available information.

According to published sources, the size of the company grew from a handful of employees in 2000 to three hundred personnel in 2013 to six hundred in 2016 – the usual exponential curve.[89] Blue Origin grew less rapidly than SpaceX, without extensive government help and without the benefits of contract revenues. A personnel cost estimator suggests that the company needed approximately $630 million to conduct its development activities during the 2000 to 2016 period. This conforms to outside reports that Bezos funded the development program for the New Shepard through a personal infusion of $600 million of his own funds.

In one respect, Bezos behaved like a philanthropist fascinated by something that appears to the philanthropist to be both wonderful and new. The purpose of Blue Origin's founding, according to various public statements, is to create an enduring human presence in space. Growing up, Bezos read science fiction, watched Star Trek reruns, and joined his high school science club. Much attention is paid to Bezos' 1982 commencement address to his fellow students at Miami's Palmetto High. In it, he envisioned millions of people living and working in a cosmos populated with large space colonies, space hotels and amusement parks. By dissipating population pressures on the home planet, he prophesized, the Earth could be turned into a giant natural reserve. The episode represented for the popular representation of Bezos what Robert Goddard's "anniversary day" did for the earlier rocket pioneer. Goddard recalled as a young person climbing a backyard cherry tree and dreaming of a voyage to Mars, an event that he thereafter celebrated as the source of his motivation for rocket development. Bezos became an entrepreneur. "The reason he's earning so much money," his high school girlfriend explained of him, "is to get to outer space."[90]

In another respect, Bezos behaved like an entrepreneur supported by profit-ready benefactors (which in this case consisted of himself). Benefactors may be motivated by the prospect of personal gain as well as by a sense of public value. When the housing market in Detroit collapsed, executives at Quicken Loans made a $5 million grant available to people who wanted to buy and restore run-down homes.[91] The housing market was so depressed (a classic case of undercapitalization) that the cost of buying and restoring homes exceeded the assessed value of the restored properties. With costs exceeding valuation, banks would not make home mortgage loans. The grants had the effect of lowering costs to valuation levels. This triggered loans, which in turn reduced supply and increased valuation. Quicken executives anticipated that profits from new loans would quickly exceed the size of its grant. A noble cause became a profitable effect.

Such strategies work particularly well for markets that are undercapitalized. In such cases, the amount of capital available for prospective commercial development lags behind the investment potential of the market. By making grants, benefactors aim to jump start the market, spur demand and release capital. Space exploration, with its heavy up-front costs, is especially susceptible to undercapitalization.

The philanthropist may contribute capital for a noble purpose, without expectation of direct economic gain. Alternatively, the philanthropist may act as an entrepreneur, distributing funds in such a way as to develop a market for a new product or process that the grantor eventually dominates. Which model fits Blue Origin? The company developed the BE-4 rocket engine, an alternative to the Russian-built RD-180 that the U.S. Department of Defense uses in the American-made Atlas III and V. On its web site, the company advertised use of the New Shepard rocket to provide “an affordable, customized platform for getting your payload to space quickly.” The company designed the rocket to go to the Karman line, a suborbital destination with a “high quality [albeit brief] microgravity environment.” The capability placed the company in competition with other firms offering an “astronaut experience,” a short flight into space with a few minutes of weightlessness.[92] In this respect, Bezos could be trying to do with Blue Origin what he did with Amazon – position himself to open a new market in which he could play a central role.

The emergence of a philanthropist as business entrepreneur is not unusual given the structure of the research and development sector. Philanthropists, foundations and other non-profit organizations play a significant role in the national science economy. Of the $183 billion (2015) spent on basic and applied research in the United States, non-profit organizations contributed $17 billion or nearly 10 percent. In the past, this sort of philanthropy helped to support astronomical observatories and the work of rocket pioneer Robert Goddard. Yet non-profit organizations contributed significantly less to the development of new products – just $3 billion or about 1 percent of the sum spend by all U.S. institutions on new product development. Business firms received very little non-profit money for product development.[93]

Put more directly, a wealthy benefactor who wanted to advance the cause of space transportation in the 21st century by developing more effective rocket ships would be well advised to go into business. It would be quite unusual for such an individual to indirectly support that cause by giving money to another entrepreneur. Concurrently, it would not be out of place for such an individual going into business to accept government support. It would not be essential, but it would not be unusual. The U.S. federal government distributes billions of dollars each year to entities engaged in research and development. A significant portion of that support goes to business firms developing new products. Over the ten-year period beginning in 2006, about 10 percent of the $2.3 trillion that business firms spent on new product development came from the federal government.

Jeff Bezos established Blue Origin in 2000. Largely using his own funds, he methodically set out to develop new methods of space transportation. Elon Musk founded SpaceX in 2002. Musk relied more heavily on government funds to leverage the total investment necessary to accomplish his goals. Much debate – most of it conceptual -- exists over the effectiveness of each approach. Some people favor private entrepreneurship; others favor government support. Working separately, Bezos and Musk set up a nice field experiment that will provide useful information on the two approaches.

Perspective
The concept of public value

A good business plan will be one that returns company margins. Expressed as a percentage (like 10 percent), corporate margins represent the amount of money the company expects to make on a product relative to sales revenue or investment capital

Corporate executives may find anticipated margins hard to forecast accurately, but the resulting calculations are easy to manipulate once the forecasts are set. The question of whether a government agency should contribute something to this process is harder to answer. In general, government support is justified when it has public value. Public value arises when available resources create additional benefits for the society as a whole. The concept is less concrete than corporate margins.

Public value can be established in a number of ways. Four of the most common methods of calculation follow.

Opportunity costs. By spending funds on one cause, public officials forgo the opportunity to spend the money on something else. Can the money spent on space exploration be better spent on cancer research? Such comparisons are hard to make. To avoid the challenges inherent in incomparable comparisons, analysts may pose the issue in a slightly different form. What are the relative advantages of investing the funds required for a proposed undertaking in financial instruments of known value? The decision to go to the Moon provides a convenient illustration. Project Apollo cost $25.3 billion, spread over roughly one dozen years. NASA spent $21.6 billion developing the capability to go to the Moon and $4.6 billion on the actual expeditions. Had the federal government used the stream of revenues devoted to Project Apollo to purchase a stock fund indexed to the Dow Jones Industrial Average, the government would have accumulated earnings totaling $2.2 billion by the conclusion of the program at the end of fiscal year 1973. Project Apollo left the United States with $25 billion in intellectual property and physical facilities, tangible assets of substantial national value. The same investment in the stock market would have produced $25 billion in investment capital plus $2.2 billion in earnings. The proper analytic question can be stated in the following manner: were the intangible gains in national prestige and Cold War technological demonstration produced by Project Apollo worth $2.2 billion?

Space policy analyst John Logsdon argues that people like President Kennedy and NASA Administrator James Webb believed the gains possessed substantial value. "This capability represented an extremely valuable element of U.S. national power, not only in the context of the Cold War competition with the Soviet Union but also in terms of being a concrete and very visible symbol of U.S. ability to do in space whatever it decided was in its national interest." In other words, the investment had public value.

President Richard Nixon did not share in this assessment. Continues Logsdon, "Richard Nixon and most of his policy and budget advisers did not share this concept of continued large-scale space undertaking as being important to U.S. power and pride." Hence, the expeditions to the Moon ended.

Cost-effectiveness. Because of Nixon's assessment, space exploration advocates like NASA Administrator James Fletcher turned to a second method of calculation. A policy may have public value if it is cost effective. Fletcher and his supporters argued that a reusable space shuttle piloted by NASA astronauts would be more cost-effective for launching payloads than buying an expendable launch vehicle for every launch, using it once, and throwing it away.

NASA officials estimated (accurately) that the federal government would need to spend $8.1 billion to design, build and test a fleet of space shuttles. Their estimate suggested the following question. Would the savings in operational and payload spending for a fleet of reusable spacecraft justify an $8.1 billion capital expense outlay? Expendable launch vehicles (ELVs) like the Saturn IB already existed, so officials needed to assign no capital investment expense to that alternative. Instead, the analysts turned to estimates of other expenses. Experts set the cost of procuring and launching 580 expendable launch vehicles over a twelve-year period at $13.2 billion (all figures were stated in 1971 dollars to preserve commonality). To this, they added the cost of payload preparation: $35.1 billion. The two figures represented the expense of preparing satellites and other equipment for flight and launching them on a variety of ELVs. To this, the analysts compared the cost of flying reusable space shuttles and fitting space-bound objects into a standardized payload bay. The shuttle estimates were less. Using the 580-flight mission model, the estimating group set total flight operational costs for the space shuttle at $8.1 billion. The estimators placed payload preparation costs at $26.8 billion. A reusable spacecraft, they concluded, would save $13.4 billion in operational and payload costs ($13.2 plus $35.1 minus $8.1 and $26.8). The overall savings ($13.4 billion) justified the commitment of funds ($8.1 billion) to design and build the new spacecraft. An outside advanced technology economics group at Mathematica, Inc., verified the calculations.

While seemingly convincing at the time, the analysis was inconveniently flawed. Shuttle advocates based their findings on the assumption that NASA engineers and their contractors could operate the reusable spacecraft for $10 to $14 million (1971 dollars) every time a shuttle flew. This proved to be grossly understated. Moreover, NASA workers could not fly the shuttle 48 times per year, as the 580-flight mission model presumed. The space shuttle was cost-effective on paper, but not on the launch pad.

Willingness to pay. An undertaking meeting neither of the first two criteria may still have public value if it meets a third criterion. A government undertaking may have value if it fits within the range of the public's willingness to pay. Consider the case of the Hubble Space Telescope. The value of the science produced by the orbiting telescope, launched in 1990, is intangible. Yet many human activities, from vacations in national parks to the keeping of pets, have intangible value. That observation does not make their value impossible to calculate.

A common calculus involves the willingness of humans to pay. In the latter years of its orbital presence, the Hubble Space Telescope annually cost about $220 million to operate and maintain. That includes the expense of the 2009 servicing mission. The average U.S. population from 2003 to 2015 was 306 million. Annually, that works out to about $7 per person per year. A similar figure characterizes the development period. Beginning in 1978, NASA workers and their contractors spent thirteen years and $2.1 billion designing, fabricating and preparing the telescope for launch. That imposed a burden of approximately $9 per person per year.[94] If you and lots more like you think the Hubble Space Telescope was (and is) worth about $8 per year, the undertaking has public value.

Economic growth. Finally, an undertaking may have public value if it produces sufficient economic growth. This criterion provides a key rationale for the public investment in commercial space transportation. A government investment may be justified if it helps to jump-start a commercial undertaking that would otherwise receive too little capital from the private sector. In such cases, the commercial undertaking is under-capitalized relative to its commercial potential. Historians often refer to such interventions as encouraging the practice of "building ahead of demand."

The criterion tests the investment's effect on the gross domestic product. Judgements vary with respect to how much growth is required to justify government investment, but an illustration may help. Between 2010 and 2014, NASA officials pledged to invest $8.3 billion in the effort to develop a commercial space flight industry that could transport humans to low-Earth orbit. Of that amount, about $4.5 billion could be considered a pure subsidy. The remainder consisted of payment for expected services – actual flights to and from the International Space Station – and savings that the government anticipated because of flying on American rather than Russian carriers. The latter outlays could be justified on the grounds of cost effectiveness, leaving the $4.5 billion figure as the amount to which growth factors could be applied.[95]

The outlay of $4.5 billion has public value if it causes the economy to grow by an anticipated amount.[7] A $4.5 billion government investment that produced a 50 percent increase in the value of the nation's space launch industry ten years later would repay itself three times. A public official who valued a 50 percent increase in the U.S. space launch industry's contribution to the gross domestic product under these conditions would be justified in supporting the outlay. Technological innovation of this sort often spurs economic growth.

The proper role of government in promoting economic growth is very controversial. Some people believe that private entrepreneurs make the most productive investment decisions. Such people prefer to see the sums devoted to government outlays remain in the private sector, where entrepreneurs emboldened by lower taxes would allocate investment funds. Supporters of government investment observe that various factors can obstruct private investment for undertakings as seemingly far-reaching as human space flight.

Regardless of personal predilections, economic returns on investment remain an appropriate method for assessing the wisdom of such funding initiatives. If an investment produces sufficient economic growth, it probably has public value.[96]

[7] The outlay is also justified on the grounds of cost-effectiveness if it is less than the government agency would have spent to develop a crewed launch capability using its own personnel and plants.

SpaceShipOne pilot Mike Melvill celebrates the first leg of two flights to suborbital space that captured the Ansari X Prize in 2004. Source: WikiMedia Commons.

Virgin Galactic: Promoters and Prizes

Standing on top of the SpaceShipOne vehicle that had just completed the first leg of the Ansari X-Prize in September 2004, test pilot Mike Melvill raised a sign that famously read "SpaceShipOne, Government Zero."[97] The sign summarized the strategy underlying the effort to develop space ships capable of transporting people to suborbital (and eventually orbital) space, without extensive U.S. government help, using privately sponsored prizes and progressively motivated legacy investors.

Peter Diamandis proposed the X Prize in 1995. The eventual goal required competitors to fly a reusable space ship with room for three people to an altitude of 100 kilometers and back and repeat the feat with the same spacecraft within two weeks. To encourage innovation, competitors were not allowed to accept government funds. The winner received $10 million.[98]

Diamandis faced a special challenge with respect to the prize. When he announced the prize in May 1996, he lacked the money to fund it. Diamandis was thirty-four years old at the time. His childhood interest in space exploration had matured while a medical student at Harvard University. He suspended his medical studies for two years to complete a master's degree in aeronautics and astronautics from the Massachusetts Institute of Technology. Subsequent to and after completing his medical degree in 1989, he founded a succession of commercial space firms, none of which paid large dividends.[99]

A copy of Charles Lindbergh's autobiography *The Spirit of St. Louis* inspired Diamandis to establish the X Prize Foundation. A friend and business partner, Gregg Maryniak, gave Diamandis the book in that hope that Diamandis would become a pilot. Instead, Diamandis dreamed of creating a prize for space travel like the one that inspired Lindbergh to cross the Atlantic. In 1919, to spur aviation technology, New York City hotel owner Raymond Orteig had offered a $25,000 prize to the first aviator to fly non-stop between New York and Paris (in either direction). Several years later, a group of civic leaders associated with the St. Louis Flying Club and the city's Chamber of Commerce agreed to bankroll Lindbergh's attempt.[100]

Doug King, president of the St. Louis Science Center, contacted Diamandis and urged him to repeat Lindbergh's precedent by basing the X Prize in St. Louis. King reassembled a group of business executives around the same table where local business leaders had agreed to underwrite Lindbergh. Diamandis emerged from the meeting with pledges totaling $25,000 – only slightly more than the $15,000 earlier civic leaders had first pledged for Lindbergh. Two months later, Diamandis stood under the St. Louis Gateway Arch with local leaders, eighteen astronauts and members of the Lindbergh family and announced the creation of the prize. According to published reports, the St. Louis community eventually provided $1 million – generous but still not enough to fund the $10 million award.[101]

Diamandis was not deterred. "Peter just refuses to let things die," a friend observed. "He just thinks differently."[102] Diamandis saw an article in *Fortune* describing a young millionaire who wanted to fly in space. The magazine identified Anousheh Ansari as one of America's forty richest individuals under forty years of age, worth an estimated $180 million. Ansari, vice-president of Sonus Networks, lived in Texas with her husband and brother-in law. She wanted to be an astronaut. (In 2006, she achieved her dream, paying the Russian government an undisclosed amount of money to become the fourth self-funded person to fly in space. She spent ten days on board the International Space Station.)[103]

Diamandis tried to contact Ansari. “The office was overflowing with messages from people clamoring to tell us what to do with our money,” she said. The family agreed to hear Diamandis’ presentation and as a consequence of the meeting contributed enough money to allow Diamandis to complete the purchase of an insurance policy. The policy guaranteed that the insurance company would pay the difference between the amount contributed and the total award should anyone actually win the award before it expired in 2005. The coverage is known as a “hole-in-one” insurance policy, a reference to the practice used by golf clubs and other sports team companies that pay for insurance rather than announced awards. The insurance company bets that no one will complete the feat while the award organizer bets that someone will without exposing the organizer to the full liability of the prize.[104]

Three years later, in 2004, the Ansari family agreed to sponsor the prize. Diamandis had earlier explained that a title sponsorship would cost someone $5 million, half of the $10 million award. When no corporation “stepped up” to sponsor the prize, the family did. Burt Rutan’s SpaceShipOne won the renamed Ansari X Prize five months later.[105]

The concept underlying an award like the Ansari X Prize is identical to the practice of philanthropic grants discussed earlier. A market, often with high entry costs, is undercapitalized. In other words, the potential returns to be generated by aspiring entrepreneurs are eliciting insufficient investments to allow the market to grow.

It would be nice to think that the existence of prizes caused philanthropists and entrepreneurs to invest in space travel. In fact, the reverse is often true. The general desire to reform space travel, especially among people who had made fortunes in the technology sector, fostered enthusiasm for the creation of prizes.

By 1996, when Diamandis announced the X Prize, those forces were already present. The loss of the space shuttle *Challenger* ten years earlier had destroyed the vision that ordinary citizens would be able to fly inexpensively into space on a government-owned vehicle. Impatience with NASA’s ability to achieve this vision was widespread in the alternative space community. "The American space program," grumbled one private entrepreneur, "was, for all practical purposes, an attempt to show the Russians that we could do Communism better than they could."[106]

In 1982, aircraft designer Burt Rutan had formed Scaled Composites, a company that distinguished itself by developing an aircraft called *Voyager* that flew non-stop around the Earth on a single tank of gas. By 1993, Rutan had turned his attention to space travel, confident that he could design a vehicle capable of transporting practically anyone on a suborbital trip into space 100 kilometers above the Earth's surface.

Around 1996, Rutan showed his spacecraft plans to Paul Allen, co-founder of Microsoft and at that time the third-richest person in America.[107] Allen had left Microsoft and formed Vulcan, Inc., a private investment firm. In 2001, Allen agreed to provide Rutan with funds estimated to exceed $20 million. Rutan's interests coincided with the X Prize, which they agreed to pursue. Scaled Composits would build the spacecraft; Vulcan would own the intellectual property rights to the design.

An estimated twenty-six contestants announced their intent to compete for the X Prize. Since prize rules disallowed government support, all needed to seek private or philanthropic support. As Anousheh Ansari observed, some of the contestants possessed little more than a small office and a PowerPoint presentation.[108] A few received sufficient investment to actually fly. At the opposite end of the investment spectrum from Scaled Composites and its $20 million budget, a pair of 26-year old engineers from Washington's Olympic peninsula reportedly raised $220,000 to build Rubicon 1. They proudly announced that the Forks Coffee Shop in downtown Forks, Washington – a rain-forest town better known for its vampire stories than its aerospace industry – had signed on as one of their sponsors.[109]

The contestants tested their 23-foot long prototype on a sunny August Sunday in 2004. To simulate the prize requirements, they inserted a barbershop mannequin and packaged foam peanuts. The rocket rose a few hundred feet from its seashore launch site, broke into pieces, and fell into the Pacific Ocean. In addition to Scaled Composites, five of the contestants raised enough money to reach the engine or flight test phase.

To be effective, a prize needs to generate more capital investment than the value of the award. That is the purpose of the prize – to unleash investment in a market that is undercapitalized. The Diamandis award, launched with an initial pledge of $25,000, generated investments roughly estimated to approach $25 million. The Rutan brothers spent $20 million of Paul Allen's money to win the prize. Other contestants raised enough money to fly hardware or prepare it for launch.[110] Workers at Armadillo Aerospace reportedly spent $2 million contributed by John Carmack (a gaming entrepreneur) pursuing the award. Their entry (the Black Armadillo) rose to an altitude of 600 feet before a fuel problem shut down the rocket and their run at the prize. Leaders of the di Vinci project spent $337,000 and enlisted 600 volunteers who contributed time averaging 400 hours per volunteer over the course of the project. They progressed to cabin drop tests before losing to the Rutan team.[111] The prize itself also generated its own investments, in the sense that it encouraged funding contributions from the Ansari family, author Tom Clancy, J. P. Morgan Chase, the Danforth Foundation and at least four other major contributors.[112]

Participants in the Ansari X Prize sought to provide humans with more accessible transport to suborbital space – a key objective within the larger commercial space enterprise. Flight enthusiasts believed that sufficient capital existed for this purpose if only it could be unleashed. The Ansari X Prize tested this proposition at two levels. If the market for suborbital space was underinvested, the prize would generate more spending among the contestants than the value of the $10 million award. It did. One person alone, Paul Allen, provided more money by himself ($20 million) than the full amount of the $10 million prize.

Additionally, the prospects represented by the prize in an undercapitalized market would generate the additional investment necessary to pursue the ultimate goal. The size of that investment was considerable. A company pursuing regular suborbital flight would need to raise and spend at least $600 million, a figure drawn from subsequent events. In principle, that additional investment would exceed the aggregate spending of all contestants competing for the prize. This happened as well.

As events during and subsequent to the competition for the Ansari X Prize demonstrated, investors had larger purposes in mind. Paul Allen did not contribute $20 million solely for a chance to win a $10 million prize. He wanted to be on the ground floor of a billion-dollar enterprise, one that might lift thousands and perhaps millions of individuals into space.[113] Allen was a self-confessed science geek, with wide-ranging interests in computer programming, artificial intelligence, oceanography and space exploration. Growing up during the dawn of the space age, he designed a space ship capable of reaching Mars. John Carmack, who bankrolled Armadillo Aerospace, also grew up as a computer geek with subsidiary interests (insofar as they dealt with computer games) in science fiction.[114] Entrepreneurs like Allen and Carmack combined a fortuitous set of interests. They made a great deal of money in the computer business, they held a geekish fascination with space travel and they possessed an exceptionally high level of confidence in the ability of private parties to advance the cause.

As science geeks, they might be expected to behave like earlier patrons of human flight such as Daniel Guggenheim, advancing the cause without regard to personal remuneration. As entrepreneurs, they anticipated a return on their investment. The X Prize phenomenon drew on a larger combination of philanthropic motivation and personal entrepreneurship that swept the space travel movement during that time. Though noteworthy for financing long-shot causes, Allen received a personal economic benefit. He requested and received the intellectual property rights to the flight technologies being developed by Rutan's firm. A similar combination of public spirit and self-concern motivated Anousheh Ansari. She did not contribute $5 million to the X Prize so that someone could win an award. Rather, she wanted to drive a technology that would allow her to fly in space – and others like her.[115]

The group behaved like legacy investors, motivated by a combination of profit and cause. As investors, they anticipated financial returns from their contributions. As patrons, they supported the development of something new simply for a pleasure of being associated with it. A legacy investor is someone who provides a gift benefiting future generations while making money doing it.

As Burt Rutan and the Scaled Composites team edged toward the attainment of the prize, they commenced discussions with Richard Branson to secure additional funds. Branson was an eccentric entrepreneur with no extensive interest in space exploration who had started making money in the record business. He invested his earnings in a succession of transportation companies – air, rail and space – and other undertakings. Branson participated in the celebration that followed the October 4, 2004, landing. Buoyed by the team's success at pursuing the prize, Branson's Virgin Group entered into a partnership with Scaled Composites. The two entities created a joint venture named The Spaceship Company. Scaled Composites would design a second space ship and carrier vehicle capable of frequent suborbital flight and test them, The Spaceship Company would build the vehicles, Virgin Galactic would fly them, and the Virgin Group would finance the activity.[116] In the spirit of the X Prize, the participants planned to do this work largely through private investment. Here is how they raised the hundreds of millions of dollars necessary to proceed.

First, they sold tickets on prospective flights. In 2004, Virgin Galactic set the price of a single-seat ticket at $200,000. The price rose to $250,000 in 2013. According to the Virgin Galactic web site, customers were obliged to pay deposits equal to the full price of the trip. Industry observers reported that 640 individuals had signed up by 2013, providing the company with a prospective revenue stream of approximately $100 million.[117]

Prospects for a new market excited other suborbital entrants as well. XCOR Aerospace offered single-seat reservations on its two-person Lynx spaceplane for as little as $95,000. They reportedly attracted 300 customers.[118] The spaceplane, scheduled for test flights in 2015, never flew. The company (not an X Prize competitor) dropped out of the suborbital transport business in 2016. After losing the X Prize, Armadillo Aerospace re-entered the competition for suborbital transport. The company abandoned its cone-shaped Black Armadillo in favor of an alternative model designed like a bathysphere. Company executives set ticket prices for the two-person module at $102,000 per seat, accumulating a wait-list of 200 individuals.[119] The company dropped the undertaking in 2013 after a faulty parachute caused a rocket crash. Blue Origin entered the suborbital market in 2000. The company took an unconventional approach with its New Shepard space capsule, neither competing for the Ansari X Prize nor taking deposits for future flights. Prospective customers could express interest by completing a reservation form on the company's web site.

Second, Branson contributed $100 million from his Virgin Group.[120] The group is a multinational branded venture capital conglomerate. It has invested in a wide range of companies including Virgin Atlantic, Virgin America, and Virgin Galactic. In 2014, the London-based *Financial Times* estimated that some eighty companies "bear the Virgin name."[121] The group did not operate any of the companies. It received income from the holdings that showed a profit and from the fees it charged companies for using the Virgin name. The strategy produced a yearly cash flow estimated at roughly $19 billion (value in U.S. dollars in 2014) which the group used to make additional investments. The group uses revenues from its profitable companies to support fledgling start-ups like Virgin Galactic still set in the development phase. On-going revenues cover potential losses.

Third, Branson raised nearly $400 million from an outside investor – one outside investor, to be specific. In 2009, the Abu Dhabi Aabar investment fund provided $280 million in exchange for 32 percent of Virgin Galactic and an additional $100 million to fund the company's small satellite launch capability. The company share indicates that Aabar Investments valued Virgin Galactic at roughly $800 to $900 million.[122]

The Aabar company may be usefully viewed as another legacy investor. The company is a privately-run joint stock enterprise that invests revenues generated from oil production in the United Arab Emirates. The company and the country have a reputation for promoting advanced technologies. (In 2014, government officials announced that the UAE space agency would send a robot to Mars.) As part of its investment in Virgin Galactic, Aabar received the right to assign a proportion of the company's flights to a spaceport in Abu Dhabi. Company officials planned to make a profit on their investment. At the same time, they wanted their home region to become the center for space transport in that part of the world. That is their legacy.

Governmental bodies, including NASA, contributed very little to this enterprise in the form of direct subsidies and awards. In 2015, NASA awarded Virgin Galactic a $4.7 million contract to launch a dozen small, experimental satellites into sun-synchronous orbits.[123] The award was not quite "government zero," as the X Prize poster boasted, but by comparison to firms like SpaceX close to it. Officials at Virgin Galactic proceeded toward their goal without a large governmental tenant.

Virgin Galactic did receive other governmental support. The Aabar investment could be viewed as arising indirectly from a nation state seeking an enlarged presence in space technology. The enterprise also benefited from a variety of facilities and regulations provided by governmental entities in the United States. And the X Prize Foundation is a tax-exempt 501(C)(3) nonprofit organization, meaning that various governments (state and federal) indirectly subsidized the prizes by waiving income taxes on amounts contributed.[124]

Initially, officials at Virgin Galactic hoped to start flying tourists into space by 2008.[125] Two mishaps slowed progress toward that goal. In 2007, an open-air explosion at the company's Mojave facility killed three workers during a nitrous-oxide transfer. State inspectors blamed poor company oversight practices.[126] In 2014, co-pilot Michael Alsbury died when the SpaceShipTwo test vehicle disintegrated eleven seconds after engine ignition during the vehicle's fourth powered flight. Investigators traced the mishap to a premature deployment of the vehicle's air-brake feathering system, exacerbated by weak design and pilot preparation practices.

As the history of Virgin Galactic confirms, the release of investment capital constitutes a necessary condition for the development of an innovative technology. Sometimes small seeds and private initiatives in the absence of large-scale public intervention satisfy that condition. Yet the release of capital does not guarantee success, as the company's history also suggests. In principle, a sufficient number of releases of a sufficient amount of capital will produce at least one champion. That happened with the X Prize, as one group won the award. It may prove to be the story of suborbital flight as well.

The Orbital Sciences Corporation proposed a lifting-body configuration named *Prometheus* as its entry in NASA's crew delivery competition. Source: Orbital Sciences Corporation.

Orbital Sciences: The Challenge of Breaking Away from Government Contracts as a Source of Revenue Flow

Officials from the Orbital Sciences Corporation submitted a proposal for a crew delivery vehicle designed to transport astronauts to and from the International Space Station. The federal government did not select the company to receive a financial award. The corporation's history illustrates the challenges corporate officials face in trying to move from dependence on government contracts into the commercial transport field. Orbital began its operations in 1982 with the intent of moving into the commercial field, but was not able to sustain this goal.

According to the 2009 selection board statement, thirty-six companies submitted proposals for the first-round commercial crew transport awards. Orbital Sciences was one of them; the company was not selected.[127] The proposals varied in scope from modest to large. One company asked for funds to develop an air revitalization system. Another asked for help in developing a whole space plane.[128] By government standards, the available funding was not sizeable. Five finalists shared $50 million in awards, the amounts varying from $1.4 to $20 million. By prevailing, however, the awardees positioned themselves to receive additional government support in the billion-dollar range. The award statement promised that the awards would "stimulate efforts within the private sector…to develop system concepts and capabilities that could ultimately lead to the availability of commercial human spaceflight services."[129]

Orbital Sciences tried again two years later in the second round of funding. They requested government support for the development of a winged spacecraft called *Prometheus*. The configuration, about one-fourth the size of the NASA space shuttle, placed Orbital in direct competition with the Sierra Nevada Corporation, which also advanced plans for an airplane-type vehicle called *Dream Chaser*.

The two proposals were similar. *Dream Chaser* was thirty feet in length with a twenty-three foot wingspan. At launch, the *Dream Chaser* would ride into space vertically on an Atlas V rocket; the spacecraft possessed two rocket engines that could be started once the Atlas dropped away. Engineers at the Orbital Sciences company based *Prometheus* on an earlier HL-20 design that was twenty-nine feet long with a 23.5 foot wingspan. At launch, the *Dream Chaser* would also ride into space on top of a conventional rocket. Both vehicles landed like airplanes. *Dream Chaser* could transport up to seven crewmembers or a combination of cargo and fewer crew. *Prometheus* could carry at least four.

The selection board stated its desire "to have at least one lifting body in the portfolio." Other leading contenders proposed capsule-shaped vehicles. Lifting bodies have better cross-range capability, can land on a variety of runways, offer superior crew access and exit, and subject passengers to lower reentry forces.[130] By landing on wheels, they avoid the indignity of a parachute-assisted oceanic splashdown or slam-down on solid ground.

In April 2011, with NASA winding down twenty-nine years of shuttle flights, board members were not ready to abandon the lifting body idea.

The two lifting body designs were "highly rated," the selection statement read. Each had its strengths and weaknesses. The selection board then made a critical observation. The two companies differed in their potential for commercialization. Board members rated the Sierra Nevada Corporation higher in "business considerations and…commitment to the public-private partnership associated with the Commercial Crew Program."[131] In other words, Sierra Nevada was better positioned to move into the commercial market with its spaceship design.

Three Harvard Business School graduates had launched the Orbital Sciences Corporation in 1982 in response to an emerging public interest in promoting what one commentator called "the next business frontier." The following year, corporate executives helped to convince President Ronald Reagan that a permanently occupied space station would create radically new business opportunities. In 1988, Reagan formally approved a commercial space policy designed "to seize the opportunities for a vigorous U.S. commercial presence in Earth orbit and beyond." Among the commercial space guidelines contained in the policy, the document urged federal agency officials to act as "anchor tenants" for commercial space facilities, support private launch services and privatize various activities on the International Space Station.[132]

In the space policy field, three characteristics distinguish a fully commercialized space firm. First, the company owns the vehicles or satellites that it produces. In a conventional non-commercial relationship, a defense contractor produces a product for a government agency. The contractor so placed often is the sole provider. The contractor does not own the product. In contrast, a commercialized firm owns the product and sells it to many customers.

Second, the commercialized firm raises investment capital to finance the development of the product it plans to produce and sell. The firm thereby incurs a risk. It may not be able to finish the development and it may be unable to sell the product. Governmental bodies may help finance the development of the product but the company inevitably will risk some of its own capital in this regard. By comparison, a conventional government contract typically reimburses the contractor for all or most of the expenses the company incurs.

Third, a commercialized firm does business with many customers. A substantial portion of its annual revenues will arise from what can be characterized as commercial purchases. These may include sales to foreign governments as well as to other private firms. A commercialized firm will not depend substantially upon purchases from its home government for the bulk of its revenues.

Advocates of commercialization – both inside and outside the government – believe that the practice of commercializing space flight produces significantly different results relative to firms supported by government contracts. Advocates believe that commercialized firms will produce new products for less money than government agencies working with conventional contractors. Consequently, public officials seeking to utilize a new product will need to commit fewer resources to its development.

The financial history of Orbital Sciences provides an excellent account of how hard attainment of the third characteristic can be – creation of a dispersed market for space products. That history can be divided into four parts. In the first three parts, company founders sought capital to get started, they found financing to expand, and they moved into the private marketplace. When their third strategy faltered, they retreated in to the more solid financial footing offered by government work. At each stage, public assistance provided needed support.

In 1982, the three founders of Orbital Sciences Corporation proposed to launch their business with a privately financed, low-cost, Transfer Orbit Stage (TOS). The concept placed them in direct competition with companies building the Centaur upper stage and some of the giants of aerospace contracting. People who use space (including individuals in government agencies) need high energy rockets that can take payloads arriving in parking orbits fairly close to the Earth and move them to their final destinations. The payloads may be bound for higher Earth orbits, the Moon, the planets or beyond. At the time, Centaur dominated the field. Developed in the early 1960s – and used in combination with an Atlas lower stage – Centaur had sent the first Surveyor spacecraft to land on the Moon.

In 1982, NASA officials completed the test flights of their new space shuttle. The underlying situation became substantially more complex for Orbital's three founders. Space agency executives planned to use the new space shuttle for a variety of scientific, commercial and military payloads. A considerable number of those payloads needed to go to higher orbits. NASA officials were understandably nervous about using the Centaur for missions requiring orbital transfer, such as the planned Galileo expedition to Jupiter. To do so required technicians to place a Centaur rocket, fully fueled with liquid hydrogen and oxygen, in the shuttle's payload bay and run the shuttle's main engines well beyond their rated capacity to lift the object into space. As events would unfold, NASA would never fly a shuttle mission with a Centaur transfer stage.

Thompson, Webster, and Ferguson offered their Transfer Orbit Stage as a workable alternative. It was a bold move. As of 1983, the company lacked the financial resources to develop the vehicle. The company consisted of an enticing plan, ten employees and $100,000 in revenue.[133] Officials in the Reagan administration supported the idea of entrepreneurial space and the President himself had praised the concept. NASA officials encouraged "the boys," as government officials often called them, but placed an important restriction on that support. The national space agency would provide technical assistance and formally consent to forgo development of a competing vehicle, but only if the three founders raised enough private capital to finance their undertaking. Implicitly, the agreement encouraged investors to believe that NASA would use the proposed TOS vehicle if the three individuals could produce it.[134]

To launch the company, the founders secured a few million dollars in seed capital from a few wealthy benefactors. In exchange, the initial investors received ownership shares of the fledgling company and positions on the corporate board.

Thompson calculated that the company would need $1 million per month to develop the TOS rocket. In sum, the founders sought to raise $50 million in investment capital. They had five months to raise it. With help from a Wall Street investment firm, they devised a clever fund-raising strategy through which donors became limited partners in a research and development subsidiary and benefited from an immediate tax deduction without forgoing future profits. The legal fees necessary to create the investment strategy cost nearly $1 million. In the final months of 1983, the young founders traveled to twenty states, presenting their business plan more than 100 times. By the end of 1983, they had their investment capital.

Having demonstrated their ability to raise needed capital, the company founders returned to NASA. They asked officials at the government space agency for the purchase orders that would provide the company with its critically needed revenue stream. NASA officials responded with a $35 million contract for the TOS, then another for $79 million. The U.S. Air Force provided $51 for an unrelated project. Government contracts in combination with private capital launched the Orbital Science Corporation. By 1986, the company had forty employees and enough agreements with established aerospace contractors to actually build the vehicle.

Actual events often unfold in ways unanticipated by corporate plans. In January 1986, the space shuttle Challenger exploded. The accident took NASA out of the space commerce business and eliminated the need for a large number of orbital transfer rockets. Not only was the Centaur rocket too volatile to place in the post-Challenger payload bay, so was any fully fueled transfer stage. NASA flight technicians used the Transfer Orbit Stage only twice, once in conjunction with the space shuttle and again in tandem with an unpiloted Titan III.

Rather than fold their tent and disband the business, the young entrepreneurs at Orbital proposed another unconventional vehicle. In 1987, the company advanced plans for a low-cost, small satellite launcher named Pegasus. Company engineers planned to drop the solid-fuel rocket, which could carry 443 kilograms to low-Earth orbit, from an airplane flying at 40,000 feet, at which point the rocket would ignite its engines and blast into space.

Again, a combination of private capital and government contracts provided the fuel by which company executives executed the plan. In 1988, company executives received $32 million in investment capital in exchange for which the investors acquired ownership shares. In 1988, the U.S. Defense Advanced Research Projects Agency (DARPA) provided Orbital Sciences with its first Pegasus contract worth $36 million. The company added more employees and in 1990 offered the public the opportunity to own shares of the company by listing stock on the NASDAC stock exchange. More presentations followed. The initial public offering raised $20 million. Follow-on offerings raised $35 and $55 million. In 1998, the company moved its public offerings to the New York Stock Exchange and sought even more financing.[135]

By 1990, Orbital had 725 employees. Its annual revenues topped $100 million. That year, it conducted its first launch of a Pegasus rocket – the first privately developed Earth to orbit space vehicle. The first launch carried two government satellites.

With adequate investment capital and a workable low-cost rocket, company executives began a series of corporate acquisitions and moved aggressively into the commercial satellite market. Between 1993 and 1999, the company made nine strategic acquisitions.

It developed the first privately owned environmental-monitoring satellite, named SeaStar. Once again, the company agreed to finance and build the satellite; NASA in turn agreed in advance to purchase images from it. Orbital launched the satellite using a Pegasus rocket in early 1997. That same year, Orbital positioned itself to enter the international communication satellite business when it acquired the right to place a "lightsat" television broadcasting satellite in a position in space fixed above Indonesia.

By 1999, the company was firmly established in the commercial market. Its annual revenues had climbed to $766 million, the number of full-time permanent employees to 5,300. Revenues derived from U.S. government contracts had fallen to 34 percent.[136]

That year, 1999, the dot.com bubble burst. The steady flow of investment capital to the satellite telecommunication sector ceased. Orbital could not make payments on $300 million in debt that it had incurred to finance its expansion. Market analysts issued warnings; creditors threatened lawsuits. Investment firms offered to cover the debt if the company executives would sell control of the firm, a strategy the owners rejected.

In the end, Orbital executives resolved their predicament by selling four acquisitions, which raised $350 million, and refinancing $100 million in debt at crippling interest rates. The experience convinced company leaders to go "back to basics."[137] Basics implicitly meant reliance upon government contracts for much needed revenues. In 2002, the company returned to a positive cash flow. By 2005, government work accounted for 82 percent of corporate revenues.[138]

The company continued to do creative work, often at government expense. In 2006, when NASA officials challenged private firms to compete for cargo delivery contracts to the International Space Station, Orbital suggested the use of its Antares rocket and Cygnus spacecraft. The company lost in the first round but prevailed in a subsequent run-off after one of the two original finalists failed to raise sufficient outside capital. The award provided Orbital with $288 million to help fund the development work necessary to demonstrate that the company's rocket and spacecraft could do the job through thirty-one milestones that included preliminary design review, avionics test, and systems demonstration test and ended with a maiden flight. Subsequently, NASA awarded Orbital Sciences a contract to begin making cargo delivery flights. NASA officials agreed to pay Orbital $1.9 billion for the first eight flights.[139]

That brought Orbital Sciences to 2010, when the company competed for the NASA crew delivery awards. Nearly thirty years had passed since the three young founders launched the idea of a commercially oriented aerospace firm distinguished from the usual aerospace giants. Orbital was heavily involved in the defense interceptor and targeting business. It received 36% of its revenues from the U.S. Department of Defense, 38% from NASA and other U.S. government agencies. Commercial and foreign customer work (much of that from foreign governments) accounted for 26 percent of the company's annual revenues. By 2013, the commercial/foreign share would fall to just 13 percent.[140]

By contrast, the Boeing Company – which did win a crew transport award – received 43 percent of its revenues from government contracts in 2010.[141] An established aerospace firm did more commercial work than a relatively new entrant set up to take advantage of the growing interest in commercial space alternatives.

When NASA officials announced their need for an astronaut delivery vehicle, Orbital Sciences executives proposed the use of their Prometheus mini-space shuttle. Much earlier, company leaders had concluded that any crew transportation vehicle "would require government funding of its development."[142] NASA officials agreed; development funds would be part of the crew delivery awards. Yet Orbital lost the crew delivery competition. Having failed to secure government support, company executives declined to pursue commercial crew initiatives using their own funds.[143]

In 2014, Orbital merged with Alliant Techsystems (ATK). In 2017, Northrup Grumman announced its intent to purchase Orbital ATK for $9.2 billion. Eighty-four percent of Northrup Grumman's business in 2016 was with the U.S. government. Pending approval, Orbital Sciences as an independent commercial entity would essentially disappear into the realm of traditional government contracting.[144]

One may reach different conclusions regarding the wisdom of government support for new space initiatives. Some view government help as a blessing; others see government contracts as inefficient and corrosive of innovation. Regardless of what conclusions one reaches, the historical record is firm. Companies new and old frequently turn to governments for the support that helps to fund applied research and development and allows the firms to raise private capital. As the five case histories suggest, other approaches exist (specifically prizes and entrepreneurial philanthropy). Yet most companies seek government support.

A Virgin Galactic aircraft carrying SpaceShipTwo sits alongside the main facility at Spaceport America near White Sands, New Mexico. The state of New Mexico dedicated the FAA-licensed spaceport in 2010 to accommodate craft departing to and arriving from outer space. Source: Spaceport America.

Other Methods of Government Support

Government officials can help fledgling space transportation firms in many ways. Four additional methods are summarized here: tax expenditures, provision of facilities, indemnification, and favorable regulations.

Tax expenditures

A tax expenditure is a government subsidy arising from a waiver of some section of the tax code. A conventional cash subsidy occurs when lawmakers approve a direct appropriation; a tax expenditure occurs indirectly as the forgiveness of a tax obligation. Both have the same effect on commercial activities – they increase the amount of money available to the firm. Analysts estimate that the value of federal tax expenditures in the United States approaches $1.5 trillion annually.

Here is a basic example of how a tax expenditure works. The federal government taxes corporate profits at a legal rate set at approximately 35 percent. On the average, states add an additional 4 percent, creating an effective corporate income tax rate of 39 percent. Remember the earlier example of the Boeing 787 Dreamliner business plan? Company executives planned to advance $9 billion with the aim of receiving corporate margins equal to a 10 percent annual rate of return on funds invested. To achieve this goal, under one scenario, the company would need to sell at least 1,500 planes at an average cost to sales price gain of $13 million per plane. On paper, this looks fine – except that the total gain of $19.5 billion is subject to corporate income tax. At the maximum possible rate, the company would pay 39 percent. This reduces the after-tax return on investment significantly.

Public officials can help the company many ways. They can agree to purchase some of the planes, they can provide a direct subsidy, or they can reduce the corporate income tax. To office-holders reluctant to provide direct corporate subsidies, the tax expenditure offers a nice substitute. It raises corporate returns by reducing taxes. Yet it has a number of shortcomings that tend to weigh heavily on firms in the space transportation business.

First, the advantages are delayed. Unlike a direct subsidy, which arrives at the beginning of the development process, the tax expenditure does not appear until the company makes a profit. Profits typically occur at the end of a production run, not at the beginning when the need for investment capital is most pronounced.

Second, company executives may redirect net revenue into capital expansion, sacrificing profits in favor of growth in net worth. In other words, the company gets rich without showing a profit. This is the strategy adopted by Jeff Bezos in expanding Amazon and an enticing option for his new space firm Blue Origin. Investors realize gains as the value of their investment shares increase, even though they may see few if any dividends drawn from profits. Under such circumstances, tax relief may not provide any benefits. In fact, a tax expenditure may discourage corporate leaders from investing in capital expansion by subsidizing the creation of profits.

Third, the effective tax rate for an individual corporation rarely equals the legislated tax rate. The corporate tax code is incredibly complex and plenty of opportunities exist for reducing the amount a company pays in taxes. A legislated rate of 39 percent can quickly turn into an effective rate around 20 percent. Should this happen, the value of the tax expenditure is diminished by a like amount.

For these and other reasons, the U.S. Congress considered yet decided to forego the opportunity to waive the corporate income tax for firms making money in space. Never enacted, the policy was known as “zero gravity, zero tax.” Representative Dana Rohrabacher (Republican, California) introduced such legislation in 2005. The legislation remained in committee.

The reluctance of the U.S. Congress to waive the corporate income tax for firms making money in outer space did not deter state governments from doing the same. State and local officials aggressively recruited New Space firms by creating incentive packages that included grants, subsidies and tax waivers. In Texas, Cameron County commissioners waived ten years of local taxes in exchange for an agreement from SpaceX to locate a launch facility on Boca Chica beach. The state of Florida offered tax credits to space companies that create high-paying jobs. New Mexico’s SpacePort Authority boasted, “numerous tax incentives…make our state highly competitive.”[145] The rewards can be small by comparison to the relief provided by prospective waivers of the federal corporate income tax, but the incentive packages play heavily in corporate facility location decisions.

If enacted, tax expenditures have the effect of enlarging return on investment. As in the case of land grants for railroad construction, the added return may not be large. Nonetheless, it has value. A wise entrepreneur is not likely to walk away from even a small subsidy. For many, enlarged returns make private fund raising easier. In that sense, a small advantage may make a large difference in the solicitation of funds.

Provision of facilities

Transportation undertakings are frequently capital intensive. Investors typically need to provide vast sums of money before their beneficiaries show profitable returns. For that reason, actions that transfer required obligations from early years to later periods can improve the financial health of new transportation firms substantially.

To assist with the development of aviation, governments often established and funded local airports. Operation of the fields fell to governmental bureaus and later public authorities. Governmental provision relieved airline companies of the obligation to fund their own landing fields and terminals. The airlines eventually paid for the facilities – largely in the form of landing fees – but governmental provision delayed the obligation until the air transportation companies began to carry cargo, people and mail. The City of New York established Floyd Bennett Field on a marshy section of south Brooklyn in 1930 in an attempt to attract air commerce to the city. In 1938, the U.S. Congress lifted a prohibition against using federal funds to establish airfields and completed an expansion of Washington National Airport. In 1947, the Port Authority of New York took over the management of that city's airfields and forty years later the federal government transferred control of Washington's airports from the Federal Aviation Administration to the Metropolitan Washington Airports Authority.[146]

With the advent of private space travel, similar options again emerged. The state of New Mexico, working through its New Mexico Spaceport Authority, established Spaceport America in a dry desert basin twenty miles from the small town of Truth or Consequences. The facility, which cost more than $200 million, opened in 2011. Virgin Galactic agreed to use the New Mexico facility as its anchor tenant, relieving that commercial client of the need to finance immediately its own launch and landing site.

The Boeing Company, SpaceX and Orbital Sciences all use facilities on property provided by the U.S. and state governments. Through 2017, SpaceX relied upon the U.S. Air Force Space Command launch complex at Cape Canaveral, Florida; the Air Force base at Vandenberg, in California; and NASA's launch complex 39A at the Kennedy Space Center, Florida. In 2014, SpaceX signed a property agreement with NASA to use the government-built 39A launch complex for the next twenty years. For its cargo deliveries to the International Space Station, Orbital Sciences relied upon the Mid-Atlantic Regional Spaceport on Wallops Island, Virginia. NASA operated the facility until 2003, at which time the states of Virginia and Maryland assumed operational authority. Boeing plans to use the Commercial Crew and Cargo Processing Facility at the Kennedy Space Center, Florida. A land-use agreement jointly established by NASA and Space Florida, a state authority, made available the former space shuttle hanger.

For the Blue Origin launch facility, Jeff Bezos avoided government support and followed the philanthropic approach previously established for the creation of the firm. He built his own spaceport. Bezos acquired the 165,000-acre site known as the Corn Ranch shortly after founding Blue Origin. The dry-land ranch is in west Texas, near the small town of Van Horn (2010 population 2,063).

The states of New Mexico, Virginia, Maryland, Florida and the U.S. government all helped to provide facilities for commercial space firms. In doing so, they followed a tradition set by governmental bodies in previous centuries. The jurisdictions that became hubs for rail transport and air flight established themselves as the centers of economic growth for their time. Similar visions inspired supporters of ports for ships bound for outer space.

Indemnification

When the U.S. government launches a spacecraft, it typically does not purchase insurance. The U.S. government is self-insured. Its financial resources are more massive than those available within any pool of policyholders in any private insurance company. Hence buying insurance for a large governmental body makes little sense.

Not so for private companies. A commercial space company needs to deal with its exposure to risk. The satellite or crew capsule it plans to launch may fail. The rocket may blow up. Worse still, hardware may fall on a population center, causing massive property and personal damage.

The cost of such insurance can be prohibitive. The pools are small; the risks are large. The financial burdens imposed by potential liabilities can be so onerous that the firm is unable to sustain its business model. Business firms launching satellites commonly insure their payloads against loss at launch or during early stages of operation. The premiums can be high – as much as 10 to 20 percent of the satellite's value – but the exposure is known and the liability definite.[147] Not so with passenger flight or damages on the ground. The company's exposure can be potentially unlimited, making the acquisition of adequate insurance impossible.

Being self-insured, officials at government agencies conducting space flights do not encounter this problem. Commercial space flight firms do.

Twentieth century airline companies faced a similar challenge. Accidents occurred. The families of deceased passengers demanded large awards; airliners falling from the sky did considerable damage on the ground.[148] Compounding the challenge, the legal regime for establishing liability often made little sense. In conventional accidents, the party at fault bears the burden of liability. Determination of fault works to determine who pays. Yet jurists viewed early airline transport as so risky that the simple act of boarding an aircraft constituted a hazard. Under this doctrine, a person injured on the ground from an aircraft failure in the sky did not need to prove negligence to collect damages.[149]

The prospect of unlimited liability made business planning very difficult. To help early airline companies overcome the unfolding burdens of liability, governmental bodies established limits on the amounts that commercial firms might need to pay. Public officials wholly opposed to government support in other forms nonetheless grappled with issues of liability and indemnification. The rules those officials established helped to expedite the commercialization of air transport.

In 1929, representatives of various countries signed the Warsaw Convention, an international agreement that limited the liability of airline companies flying from one country to another. The agreement capped the amount of money an airline might need to pay for lost luggage, cargo, or personal injury. Subsequent updates kept the basic framework in place for seventy years, during which time the airline industry matured. In 1999, participating representatives altered the agreement through the Montreal Convention, which allowed injured parties to seek unlimited damages if the parties could prove negligence on the part of the carrier.

Public officials approached the commercial space launch industry in a similar way. Government policies require commercial firms operating on behalf of the government to purchase insurance (or demonstrate the capability to pay) in amounts sufficient to cover claims up to a set ceiling. Above that ceiling, any damages are considered claims against the United States government.[150] The policy effectively transfers the liability for catastrophic events from the company to the nation and relieves company officials of the need to protect themselves from extraordinary claims. State officials have also passed legislation limiting the ability of future space flight passengers to sue spaceflight companies. In 2013, for example, the New Mexico State Legislature enacted a bill stating that a space flight entity operating within the state would not be liable “for injury to or death of a participant” so long as the entity warned the participant of “the inherent risks of space flight.” A half-dozen states enacted similar laws.[151]

In its full detail, the legal regime for commercial spacecraft liability is quite elaborate. It has and will continue to generate much precedent and commentary. Overall, the legal framework has the effect of making manageable a cost of doing business that could otherwise discouraging entrepreneurs from entering a new and potentially litigious field.

Favorable regulations

When NASA officials prepared to launch a space shuttle mission, a succession of management teams would meet for the purpose of certifying that the vehicle was ready to fly. Officials would conduct a launch readiness review, a flight readiness review, a certificate of flight readiness review and a pre-launch review by the mission management team.[152] In essence, the government organization flying the mission would inspect itself and determine its state of readiness.

When a commercial firm launches one of its own spacecraft from U.S. territory, it must obtain a license from the Federal Aviation Administration. The license certifies that the flight "will not jeopardize public health and safety, property, U.S. national security or foreign policy interests, or international obligations."[153] In essence, the company needs the government's permission to fly. The first licensed U.S. commercial launch took place in 1989 from the White Sands Missile Range in New Mexico. It carried a set of suborbital scientific experiments. In 2006, Virgin Galactic received an FAA license that allowed the company to commence test flights of its SpaceShipTwo. The license specifically prohibited the company from including passengers on its test flights. Before the company could begin tourist flights, it needed to obtain additional safety and performance certification.

Government agencies enforce the rules by which commercial firms are obliged to play. For such matters, government officials referee the game. The way they enforce and amend the rules directly affects the cost of doing business. Favorable regulations can produce profits; stringent ones can create losses.

When the United States was young and needed ship transport to move goods between domestic ports, the U. S. Congress encouraged the creation of a domestic merchant marine by passing what were known as cabotage laws. The regulations imposed taxes on foreign vessels and eventually prohibited those vessels from competing against domestic carriers. Investigating the value of these regulations over a twenty-year period in the mid-20th century, one analyst estimated that they were worth $8 billion to the domestic shipping industry. Their value was no less concrete than if the federal government had given away $8 billion in cash subsidies.[154]

Participants often influence the force of government regulations by directing the location of regulatory authority. When the airline industry was young, legislators placed the regulatory responsibilities in the Civil Aeronautics Board (CAB). An independent regulatory commission, the CAB was responsible for both airline safety and industrial promotion. The board accomplished the former by conducting accident investigations; it achieved the latter by regulating routes and fares. The combination of both functions in a single independent agency assured airline executives that safety concerns would not overwhelm the creation of a stable industrial market. Not until 1967 were accident investigations transferred to a separate National Transportation Safety Board.

In 1984, the U.S. Congress created the Office of Commercial Space Transportation. As with the old CAB, lawmakers told agency officials to simultaneously regulate and promote their subject industry. Legislators told agency officials “to promote economic growth and entrepreneurial activity” in the commercial space transportation field while working “to protect the public health and safety.” The dual mandate essentially guaranteed that any pursuit of spacecraft safety would be balanced by a concern for industrial growth. In 2004, Congress further restricted the ability of the space transportation authority to emphasize safety standards by limiting its authority to promulgate standards in advance of accidents that killed or injured people riding in the vehicles. The restriction had the effect of moving such standard writing to industry groups assembled to regulate themselves.[155]

Industrial growth leads inevitably to the consideration of property rights. This is a major regulatory issue and one around which the various parties align themselves. The 1967 Outer Space Treaty promises that celestial bodies “shall be the province of all mankind” and prohibits their “national appropriation…by means of use or occupation.” Concurrently, commercial groups seek assurance that late-arriving parties will not expropriate the investments lodged by the original occupants. The Space Resource Exploration and Utilization Act of 2015 begins to address these concerns. If a commercial firm produces propellants from lunar ice or mines precious metals from a redirected asteroid, it could acquire rights to the remaining resource. The promotion of a space resource industry requires it; the Outer Space Treaty more or less prohibits it. The history of terrestrial resource extraction claims suggests that the resulting regulations are likely to follow exploitation rather than precede it. The regulations that emerge are likely to be worth a great deal of money to the parties involved.[156]

Observations

Public officials have a large number of instruments that they can use to encourage innovation and promote the emergence of new commercial firms. They can provide tax relief, government facilities, and limits on liability. They can promulgate favorable regulations. They can agree to be anchor tenants. They can provide subsidies for the development of new products. Some of those subsidies take the form of cash, others arise from the transfer of government assets. Public officials can issue bonds. They can provide loan guarantees. In addition to these techniques, public officials fund basic research through grants and contracts. They establish government labs. They provide price supports. They establish property rights. Through the issuance of special insurance policies and loans, they encourage exports. The full range of assistance techniques historically available to a succession of transportation technologies is quite large. There is no reason to expect that the provision of support mechanisms will stop at the gateway to space.

In 2015, NASA selected the first four American astronauts assigned to ride commercial crew transportation carriers to outer space. Source: NASA.

Reflections and Summary

The contemporary retelling of space history confirms much of what is already known about the economics of space travel. Private individuals, philanthropic institutions and space clubs made significant contributions to the earliest efforts to gauge the cosmos.[157] A period of government provision followed, coinciding with the first orbital flights and trips to the Moon. Beginning in the late twentieth century, particularly in the United States, private efforts reemerged. If privatization proves successful, the first American astronauts to return to the International Space Station on U.S. carriers in the post-space shuttle era will travel on commercial spacecraft.

The mix of private and public efforts raises a key issue. To return to the fundamental questions raised at the start of this study, can private individuals do what heretofore public officials – with their access to governmental debt and tax revenues – accomplished in the first fifty years of space flight? Can they (the private individuals) raise enough money to finance commercial space transportation companies? If they can, to what extent do these entrepreneurs need government support to make their business cases and raise the capital needed to do this work?

The case for government support rests on three key observations.

1. Space travel, like other forms of mass transportation, is capital intensive. It requires substantial investments before profits materialize, a situation often characterized as building in advance of demand. The Silicon Valley model with "engineers in T-shirts, ramen noodles…and no business plan" will not work in a "cash bleeding" sector like space travel. To succeed, private space transportation companies need access to very large reservoirs of capital – billions of dollars.[158]
2. Government organizations provide one such source of that capital. (So do wealthy individuals and established business firms with substantial cash reserves.) Public support, in forms such as government agreements, contracts and subsidies, improves the ability of business firms to raise private capital and influences their calculation of financial risk.
3. Prior transportation forms, particularly railroads and airlines, profited from government assistance during their formative years.

The need for government support is another matter. Government support for commercial space flight is convenient, but is it required? The spacefaring community is now engaged in a great experiment that will help to answer this question. The evidence to date suggests that government support is beneficial but not necessary. Significantly, this observation re-enforces the ex post facto analysis of transcontinental railroad lines. A governmental presence for that endeavor was not as critical as railroad promoters once held it to be. Here are three observations that can be gathered from the experience this far.

1. Some American firms have raised capital for space flight endeavors without significant U.S. government help, notably Virgin Galactic and Blue Origin. Their experience suggests that private individuals, prizes and foreign philanthropy can act as substitutes for government support.
2. The presence of government support enlarges the number of business firms willing to risk capital in the endeavor. The Boeing Company certainly would not

have participated in the private development of spacecraft without government support. SpaceX would not have survived as a business enterprise without it. In that sense, public infusions of cash acts like a prize, serving to encourage business firms (and occasionally non-profit organizations) to enter a promising market that contains substantial obstacles to participation.

3. Government support breeds a level of dependency that can be very hard to shake. The Orbital Sciences experience shows how difficult the maintenance of commercial independence can be. Government support may prompt firms that receive it to start up, but it may also prompt them to revert to the conventional form of industrial participation as private contractors doing the work of government agencies when outside revenues wind down.

The era of commercial space travel is in its infancy. For the pursuit of commercial human flight, it is scarcely a dozen years old and all of that devoted to design, fabrication and testing. As such, the observations that appear above take the form of propositions. They will be tested by future experience. The successful business firms (if any) that emerge will reveal the pathways taken and the degree to which viable space transportation companies needed forms of public assistance historically available to terrestrial transportation firms.

NOTES

[1] See Eric Berger, "Behind the curtain: Ars goes inside Blue Origin's secretive rocket factory," Ars Technica (March 9, 2016) <arstechnica.com> (accessed April 20, 2017). The authors wish to acknowledge the assistance of Roger D. Launius and Kristi A. Morgansen in reviewing the manuscript and making valuable suggestions.

[2] See John Newhouse, *The Sporty Game: The High Risk Competitive Business of Making and Selling Commercial Airliners*. New York: Alfred A. Knopf, 1982.

[3] Robert A. Heinlein, *Rocket Ship Galileo*. New York: ACE Books, 1947; George Pal, *Destination Moon*. Eagle-Lion, 1950.

[4] Fritz Lang, *Frau im Mond (The Woman in the Moon)*. UFA, 1929.

[5] Arthur C. Clarke, *2001: A Space Odyssey*. New American Library, 1968; Stanley Kubrick, *2001: A Space Odyssey*. Metro-Goldwyn-Mayer, 1968.

[6] Carl Sagan, *Contact: A Novel*. New York: Simon and Schuster, 1985. Robert Zemeckis, *Contact*. Warner Bros., 1997. Sagan mistakenly characterizes the transit tunnels as black holes.

[7] Frank H. Winter, *Prelude to the Space Age: The Rocket Societies, 1924-1940*. Washington, D.C.: Smithsonian Institution Press, 1983.

[8] See National Commission on Space (Thomas O. Paine, chair), *Pioneering the Space Frontier*. Bantam Books, 1986; John S. Lewis, *Mining the Sky*. Addison-Wesley, 1996; John L. McLucas, *Space Commerce*. Harvard University Press, 1991; Lou Dobbs with H. P. Newquist, *Space: The Next Business Frontier*. Pocket Books, 2001; Jonathan N. Goodrich, *The Commercialization of Outer Space*. Quorum Books, 1989.

[9] Sources: The "sticker price" for a Boeing 787 as of 2017 was about $250 million. The negotiated price – especially for sales of multiple planes to a single customer – was much less and not extensively publicized by company executives. Some sources set the sales price as low as $117 million. Initially, production cost hovered around $160 million; some observers estimated that it had been as high as $230 million. Boeing reported it had received orders for 1,200 planes and delivered 500. Sources include: Boeing, "Our Company, About Boeing Commercial Airplanes," (2017) <boeing.com> (accessed January 27, 2017); Boeing, "787 Model

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[10] Carter Goodrich, *Government Promotion of American Canals and Railroads*. New York: Columbia University Press, 1960); Roger D. Launius, *Historical Analogs for the Stimulation of Space Commerce*. Monographs in Aerospace History, no. 54. Washington, D.C.: NASA SP-2014-4554, 2014.

[11] Stephen E. Ambrose, *Nothing Like It In the World: The Men Who Built the Transcontinental Railroad 1863-1869*. Simon & Schuster, 2001: 27.

[12] Estimates of the true cost of the first transcontinental line vary widely. See Central Pacific Railroad Photographic History Museum, frequently asked questions, "How much did it cost?" 2016. <cprr.org/Museum/FAQs.html> (accessed January 5, 2017).

[13] William F. Bailey, "The Story of the Central Pacific," *The Pacific Monthly* (January 1908).

[14] Bailey, "The Story of the Central Pacific."

[15] Bailey, "The Story of the Central Pacific."

[16] Quoted from Bailey, "The Story of the Central Pacific." For confirmation of the amount authorized and sold (subscribed) see Annual Report of the Board of Directors of the Central Pacific Railroad Company to the Stockholders for the Year Ending December 31, 1872. Sacramento: Record Book and Job Printing House, 1873.

[17] Bailey, "The Story of the Central Pacific."

[18] Bailey, "The Story of the Central Pacific."

[19] To the Bondholders of the Central Pacific Railroad Co., January 1, 1870. Fish & Hatch, Bankers, New York.

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[21] Thomas G. Shearman, “The Owners of the United States,” *The Forum* (November 1889), with commentary in D. C. Shouter, “A Classification of American Wealth,” <raken.com/american wealth/encyclopedia/comment_1889.asp> 2016 (accessed January 31, 2017).

[22] Central Pacific Railroad Photographic History Museum, “How much did it cost?”

[23] Goodrich, *Government Promotion of American Canals and Railroads*.

[24] Launius, *Historical Analogs for the Stimulation of Space Commerce*.

[25] Mercer notes that James J. Hill completed the Great Northern after the land system ended and was “essentially privately built.” Hill did so in competition with the “most subsidized” Northern Pacific line. Nonetheless, the Great Northern did benefit from federal and state land grants made to earlier lines out of which the Great Northern was formed. Completed in 1893, the Great Northern ran along the northern boundary of the United States from St. Paul, Missouri, to Seattle, Washington. The Northern Pacific followed a slightly more southerly route from the Great Lakes to Puget Sound and was completed in 1883. See Lloyd J. Mercer, *Railroads and Land Grant Policy*. New York: Academic Press, 1982: 59.

[26] Source: Mercer, *Railroads and Land Grant Policy*.

[27] The $360 million gain arises from an estimated average profit of $450 thousand on 803 produced planes.

[28] The figure of 803 units is taken from Walter J. Boyne, “Airpower Classics: KC-135 Stratotanker,” *Air Force* (February 2012): 104. The American Aviation Historical Society reports that Boeing built 820 units. American Aviation Historical Society, “Boeing KC-135 Celebrates 50 Years of Service” (2009) <aahs-online.org> (accessed April 21, 2017).

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[31] Irene Klotz, "Profile. John Mulholland, Vice President and Program Manager for Commercial Programs, Boeing Space Exploration," *SpaceNews* (November 21, 2012). Mulholland was previously Boeing's space shuttle program manager.

[32] Julie Johnsson, "Boeing CEO Vows to Beat Musk to Mars," Bloomberg Technology <bloomberg.com> (October 4, 2016).

[33] Leonard David, "Boeing's New Crew-Carrying Spaceship Taking Shape," *Space.com* (April 5, 2012).

[34] The numbers are based on NASA CCtCap awards and assume a 20 percent net margin based on flight revenue. See Jeff Foust, "NASA Commercial Crew Awards Leave Unanswered Questions," *SpaceNews* (September 19, 2014).

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[37] Klotz, "Profile. John Mulholland."

[38] Doug Messier, "NASA's Commercial Crew Program By the Numbers," October 24, 2016. <parabolicarc.com> (accessed February 6, 2017).

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[43] See Eugene Gholz, "Eisenhower versus the Spin-off Story: Did the Rise of the Military-Industrial Complex Hurt or Help America's Commercial Aircraft Induustry?" *Enterprise & Society* 12 (March 2011) 46-95. Sources set the production cost of the KC -135 at $5.14 million in 1960 dollars. U.S. Air Force, KC-135 Stratotanker

(September 15, 2004) <http://www.af.mil/About-Us/Fact-Sheets/Display/Article/104524/kc-135-stratotanker/> (accessed April 14, 2017).

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[69] See also the $1.1 billion award NNK14MA74C from the NASA John F. Kennedy Space Center Office of Procurement to Space Exploration Technologies Corporation signed 16 September 2014.

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[73] We credit the $238 million award for cargo capability, $1.07 billion expected revenue for cargo delivery flights contracted but not completed as of 1 January 2015, $3.14 billion in NASA awards for development of crew capability, and the $100 million defense department award.

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[88] We count $100 million from Bezos’ own investment, $145 million in outside capital, $238 million from NASA for cargo capability, crew transport capability awards of

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1972; Howard E. McCurdy, "How Much Did We *Really* Spend to Go to the Moon?" (December, 2015) <publicpolicyinnovation.com> (accessed February 21, 2017). For building ahead of demand, see Mercer, *Railroads and Land Grant Policy*. For the cost of the Hubble Space Telescope, see U.S. General Accounting Office, Space Science: Status of the Hubble Space Telescope Program, May 1988, GAO/NSIAD-88-118BR and NASA, Space Shuttle Mission STS-31 Press Kit, April, 1990. The averages may be overstated because of federal debt, which has the effect of deferring some of each year's expenditure burden. Regarding the last criterion, U.S. launch service providers earned revenues totaling $2.4 billion in 2014. (The worldwide market was $6 billion.) U.S. commercial launches totaled $617 million. Federal Aviation Industry, *The Annual Compendium of Commercial Space Transportation: 2016*, January, 2016: 9. A 50 percent increase would amount to $309 million, produced annually beginning in year ten. After repaying the $4.5 billion, the present value of the remaining stream of revenues over 100 years would equal $10.4 billion. This amounts to a more than three-fold return to the economy as a whole on the $4.5 billion government investment, including repayment of the original investment that as an expenditure stream over the first four years constitutes $4.4 billion at the beginning of the program. For this analysis, we utilized a discount rate of 1.25 percent. Calculations are aimed at spurring growth in launch services alone. In practice, the benefits probably would extend to the overall U.S. space industry, estimated to be worth $85 billion in 2014 (excluding funds spent by the U.S. government and removing the $2.4 billion allocated to launch services). For commentary on the wisdom of government investment, see Terence Kealey, *The Economic Laws of Scientific Research*. Palgrave Macmillan, 1996.

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