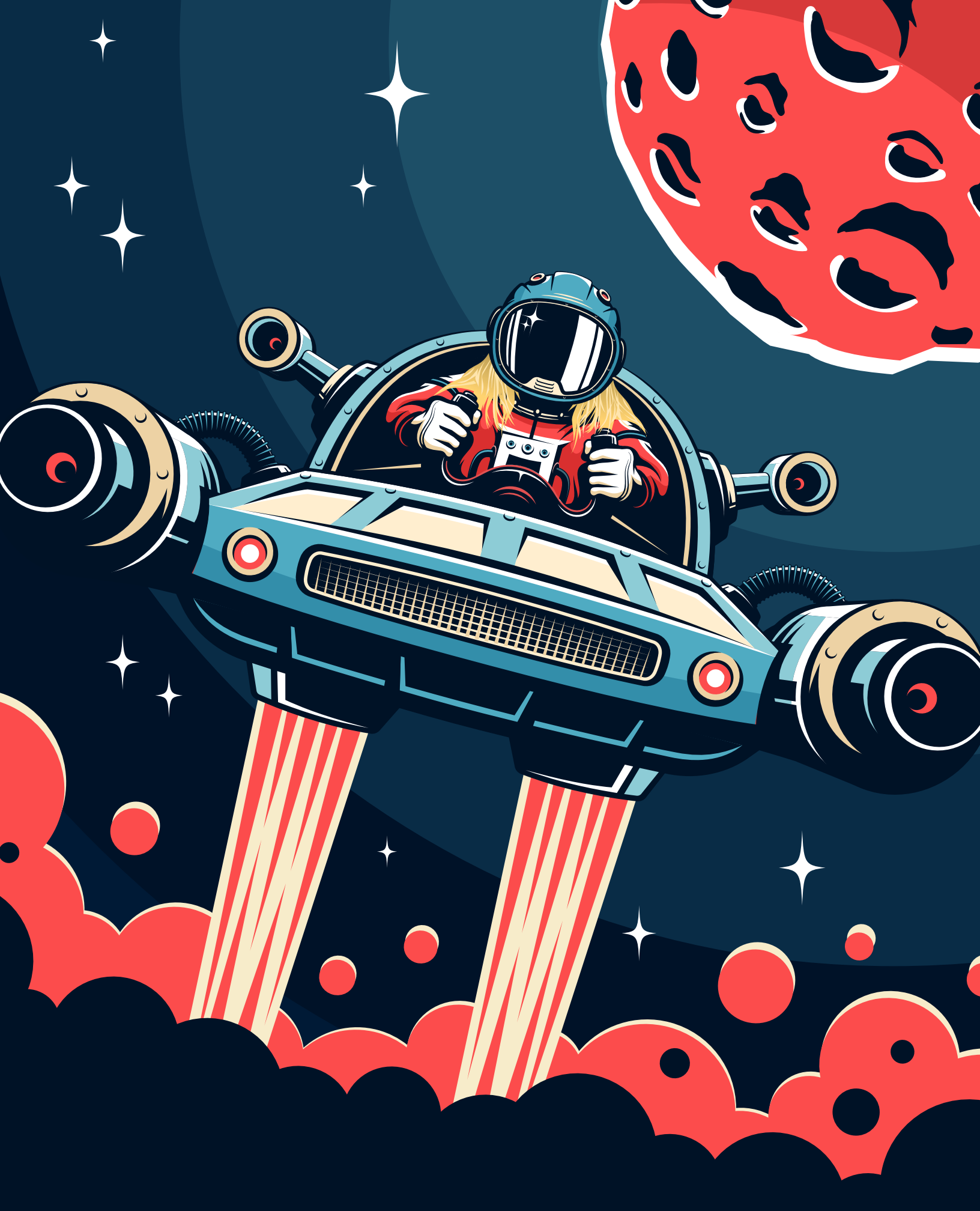

BLAST OFF: The Space Economy Takes Flight

As access to space opens up, there is renewed excitement among investors about the industry's potential.

by A. Agrawal, J. Gans, A. Goldfarb, C. Hadfield and M. Lederman

IN THE MIDST OF THE WORST INFLATION seen in 40 years, not all prices are rising. In the 1970s, the cost of taking a kilogram of water to space was $20,000 in today's dollars. Now, it is more like $2,000 — a tenfold reduction, and as **SpaceX**'s Starship has $20/kg in its sights, there is a real possibility of another hundred-fold reduction in the cost of space access. If this happens, access to space will open up like never before, creating a flood of new business opportunities.

The space industry includes a wide range of markets: space hardware (e.g. satellite manufacturers and modules), launch services, flight and delivery, space tugs, satellite operators (remote sensing, connectivity), drones and unmanned aerial vehicles, ground terminals, security and storage, data platforms, location and mapping and space infrastructure — to name a few. The thread that connects all of these markets is that they each depend, directly or indirectly, on access to space.

Achieving a lower-cost access for **Elon Musk**'s **SpaceX** is one thing; making access cost-effective for other new business opportunities is another matter. Innovators will care not just about costs that are achieved in the near term for SpaceX, but whether they will remain there over the long haul. At the outset, when there is capacity to spare, a company like SpaceX may use its technology to set prices close to its own costs of $20 per kilogram; but as more and more opportunities arise and capacity becomes scarce, launch companies will find it easier to charge more. Faced with the expectation that SpaceX may become a bottleneck, far-sighted entrepreneurs and investors may decide that it is too risky to innovate in the first place. Without some way to guarantee prices will stay reasonable, the potential of low-cost access may go unexploited. Savvy investors and entrepreneurs must also monitor the state of competition and ask whether those providing access are pre-emptively taking actions that suggest costs will remain low enough in the future to warrant investment today.

Cost Reductions and Technological Change

Economists recognize that at its essence, radical technological change boils down to one thing: a large reduction in the cost of doing something. The 1800s were not so much an Industrial Revolution as a drop in the cost of energy to power machines; and the late 1900s Information Technology Revolution was really just a fall in the cost of arithmetic (through better semiconductors). More recently, the Internet Revolution is just a drop in the cost of communication and connecting the world. And recent developments in artificial intelligence are just a set of statistical techniques that will dramatically lower the cost of prediction.

In each case, the cost reduction has resulted in an input to production that was once scarce or expensive becoming abundant and cheap. If you recall Econ 101, this represents a

As the cost of accessing space falls, we could see entirely new space industries emerge.

movement outwards in supply which results in that very input being used more intensively across many areas. For radical technological change, the move outwards can be so large that economies are transformed.

The current reduction in the cost of transport into space has the potential to do the same. Just as railroads opened up frontier lands, access to space is on the precipice of a similar cascade. And with that change comes opportunity for entrepreneurs and investors.

As the cost of accessing space falls, we could well see the creation of entirely new space industries — everything from energy production to space mining to space manufacturing. Whether the next decade of the commercial space industry results in incremental or radical innovation depends, in part, on the development and deployment of 'complementary innovations' that are necessary to take advantage of the falling cost of accessing space. Cheap power only transformed the global economy after hundreds of smaller complementary innovations were developed and deployed, including the mechanical looms that transformed the textile industry and the rail tracks and locomotives that transformed transportation, and machine tools that used steam power to shape metal. These machine tools, in turn, enabled more powerful steam engines.

In other words, cheap steam power transformed the world economy because inventors in other industries, from textiles to railways, could rely on continued access to the steam engine on terms that made their investments in complementary innovations likely to generate a positive return. The lesson is this: Reducing the cost of accessing space alone is not enough. Since it seems likely that there will be few substitutes for SpaceX perhaps for a decade or more, can the space industry depend on continued access? Will we have to wait for patents and trade secrets owned by SpaceX and others to become open before the industry can truly take off?

More of the Same, But Better

Science and exploration are already reaping the benefits of lower-cost access to space. As costs fall, exploration is giving way to space tourism, whereby wealthy people pay to spend time in space. But cheap access also means more science and exploration. We are already starting to see some of the new opportunities that a lower cost of space access can bring. Following are some examples.

TELECOMMUNICATIONS: Satellite television and telephones have existed for decades. Weather and geological mapping satellites help us forecast the path of hurricanes, find valuable minerals and navigate our way around the earth. In each case, the technologies take advantage of being above the earth to provide information services to those of us who remain here. As launch costs fall, a new set of entrepreneurs will be able to put satellites in space. In doing so, they are providing a wider variety of telecommunications and mapping services than were previously possible.

Take **Kepler Communications**. Founded in 2015 by four graduate students from the University of Toronto, Kepler is building a constellation of small satellites to provide near real-time data exchange to businesses and governments that operate in remote parts of Earth. For example, the Polarstar research vessel used for arctic research uses Kepler's services to transfer the data it collects in the Arctic to the research centres housing their computational resources. Six years after starting the company, Kepler has more satellites in orbit than any other company in Canada.

Another organization aiming to improve communication and take advantage of the falling cost of access to space is SpaceX's own Starlink. It has launched over 1,000 satellites and plans to launch tens of thousands more with an aim to bridge the digital divide, reducing the wealth gap between rich and poor by providing the rural poor with better information.

Intra-Orbit Transportation Services: Starlink didn't just require access to space, it also required services in space. Consider the January 24, 2021 SpaceX mission Transporter-1, which deployed 143 satellites in a single rocket. The mission did not end once the satellites were in space, however. The launch also put all the satellites at a similar altitude and orbit. Satellite launches have a last mile problem: Each one needs to get to a specific location and altitude after the rocket gets them to a lower earth orbit.

A new industry is developing to solve this problem: space tugs, or 'orbital transfer vehicles,' which carry satellites and other equipment to their final destination orbit. Transporter-1 carried two such tugs. In our language above, space tugs are a complementary innovation.

MANUFACTURING. If the cost of sending things to space and back falls by enough, then — as with historical frontiers — resources

can be *brought back* from space. It may even be feasible to beam down clean energy if we can get heavy equipment into orbit. And there may be resources worth mining on the Moon or on asteroids, either because they are valuable on earth (such as gold, platinum or rare Earth elements) or because they are valuable to other space activities (such as water for fuel and for human consumption).

Space is a distinctive environment because of microgravity and because it is a large vacuum. Many manufacturing processes on earth require a vacuum in order to create high-quality technology parts. This is an expensive process and limits the size of parts manufactured in the vacuum. Still, it remains much less expensive to create the vacuum on Earth than to manufacture one in space. Microgravity is not possible to produce on Earth and it appears to have advantages in manufacturing certain materials, such as pure fibre. If the costs of getting to lower Earth orbit, operating there and returning fall enough, new manufacturing processes that take advantage of the vacuum of space and microgravity become possible.

Even once rockets can carry heavy equipment into space, space tugs can transport them within space, and re-entry vehicles can safely send large quantities of resources or manufactured products back to Earth, a number of additional technologies will be needed. For example, mining the Moon might require specially designed bulldozers and other mining equipment.

Creating thriving new space industries will require thousands of such innovations in both products and services, many of which may result in the creation of entirely new industries. However, these enabling industries will only develop if the commercial incentives are strong enough. The entrepreneurs and investors developing these industries need some assurance that, as the industry grows and they contribute to its growth, they will be able to capture a portion of the profits.

RESOURCE EXTRACTION. The main opportunities over the next 10 years likely relate to mining and manufacturing of materials in space for use in space. **NASA**'s Artemis Program — which has the goal of establishing a sustainable presence on the Moon to prepare for missions to Mars — has been an important source of funding for space mining and manufacturing projects. For example, the Japanese company **ispace** raised tens of millions of dollars to fund its vision of creating a lunar city by 2040 by extracting building materials, water and energy from the Moon itself. Along with two other companies, ispace won a recent NASA competition, as part of the Artemis Program, to collect material from the Moon and bring it back to Earth.

Of the 56 leading space companies identified by **SpacePolicyOnline**, 24 mention mining, resource extraction or in-space manufacturing on their websites or in press releases. In some cases, these connections are superficial: **Maxar**'s robotic arms can "dig, drill, sample, and explore the Martian surface." However, in many cases, the business model is directly related to mining or manufacturing. For example, **Axiom Space** offers in-space manufacturing processes as central to its plans for a commercial space station. The 'big three' U.S. aerospace companies (**Boeing**, **Lockheed Martin** and **Northrup Grumman**) have all publicly commented on space mining in the past few years, while **Moon Express** raised $65.5 million with the explicit goal of mining the Moon.

For both mining and manufacturing, complementary innovations are already occurring, and many of the necessary innovations are not technical. For instance, the potential for space resource extraction has led to new laws and international agreements around access and ownership of space resources. The U.S., Luxembourg, the UAE and Japan have already passed legislation permitting the private sector to engage in resource extraction in space. There is also innovation in education. Scholars at the Colorado School of Mines have noted that "the era of commercial space mining has begun," and the school has created an undergraduate minor in Space Mining.

For manufacturing, there has been progress in technological innovation. In 2018, the company **Made in Space** (now part of **Redwire**) proved the feasibility of producing high-quality ZBLAN optical fibre in microgravity through an experiment on the International Space Station. In a March 2021 investment call, Redwire noted, "To really emphasize our unique positioning in developing the next generation of space infrastructure, I would like to highlight our market leading position in in-space manufacturing and robotic assembly." They emphasize in-space manufacturing as a complementary innovation to other space activities, including satellites.

Houston, Do We Have a Market Power Problem?

A transformative space industry requires more than the small equipment that can currently be sent into space, and only one company seems close to providing low-cost access to space for

The promise of (monopoly) profits tomorrow can incentivize a firm to innovate today.

heavy equipment: SpaceX. If Starship proves to be the only cost-efficient launch vehicle for the heavy equipment needed to build large-scale industry in space, how can entrepreneurs looking to develop these new opportunities trust that all their profits will not be dissipated at launch?

As in every industry, monopolies cause problems: They price too high and produce too little. However, in innovative industries, monopolies also have advantages. The promise of (monopoly) profits tomorrow can incentivize a firm to innovate today. Indeed, the purpose of the patent system is to grant temporary monopolies to incentivize firms to undertake risky innovation.

But, while a monopoly can be good for providing incentives to innovate, the concentration of power can limit the incentives for others to invest in complementary innovation. In particular, a potential co-innovator will worry that — after they invest to build a business that relies on access to the monopolist's service — the monopolist will raise their price. At that point, the innovating firm will have no choice but to accept the higher price. This concern is particularly salient when the firm's investments cannot be easily redeployed to another application. For instance, there aren't many uses for space tugs outside of the space industry.

Contractual commitments by the monopolist do not necessarily solve this problem as contracts over highly novel and hard-to-describe (or not-yet-invented) technologies will rarely be complete, leaving ample opportunity for the monopolist to renegotiate the terms (or, as we say in Economics, 'behave opportunistically'). Economists call this the 'hold-up problem.'

Preventing the Chill

Space is cold and has been notoriously difficult to warm up to entrepreneurial opportunities — and the chilling effect of a monopoly provider will not help matters. But SpaceX will benefit from transformative new industries. Its challenge is how to incentivize rapid investment by others, and to overcome the temptation to raise prices once they have made the investments, or shut them out once profitable opportunities are identified. Economists have recognized four broad approaches to overcoming this chilling effect. Each has its own benefits and costs.

DO IT YOURSELF. The chilling effect on complementary innovations to low-cost space access arises because the space transport provider and complementary innovator face conflicting incentives once the investment has been sunk. A straightforward way to remove this conflict is through common ownership. That is, the transport provider should also undertake the necessary complementary innovations. An example is Starlink, SpaceX's planned constellation of thousands of small satellites in low Earth orbit that communicate with ground transceivers, designed to provide satellite Internet access.

The benefit of such integration is that it directly removes any conflicting incentives. The cost is that it requires the transportation provider to do it all. There are limits to that. For starters, the transportation provider only has a certain amount of capacity to undertake different activities. But more critically, for a frontier, there is no reason to suppose that the transportation provider has a monopoly on imagination. In that case, those who have that imagination have to still work through a bottleneck. In that sense, integration does not resolve the fundamental problem.

MAKE A PROMISE. The primary reason for the chill is that when a future conflict arises, it will be resolved in favour of the monopolist. Eliminating the chill can be achieved by the monopolist tying their own hands to prevent the ex-post price squeeze entrepreneurs fear. This strategy was used to open up the Canadian Prairies to farming. The **Canadian Pacific Railway**'s transcontinental line was completed in 1885. It went through potentially rich farmland in Saskatchewan, but frontier settlement remained limited for over a decade. Farmers didn't move to the frontier because of fears that the price of transporting crops to the cities and ports of the east would be too high and the price of equipment and finished goods coming from the east would be too high.

The issue was resolved with the Crow's Nest Pass Agreement of 1897. In order to get access to British Columbia and to receive funds to build more rail in Canada's west, CP Rail signed an agreement with the government committing to keep prices low. This price commitment induced settlers to move to Saskatchewan and start farms. Importantly, this in turn prompted further investment by the railway. More settlers led to increased investment in trunk lines, which in turn led to more settlers. The railway ended up benefiting from allowing the government to constrain its ability to raise prices in the future.

The long-term contract, in this case facilitated by the government, offered settlers on Canada's frontier assurance that their investments could be recouped. Similarly, space transport providers can try to lock-in a price to a venture for many years

with a long-term contract. Perhaps, they can also find a third party (or other mechanism) to commit themselves not to act on the temptation to renegotiate that price.

The problem with this approach is that it requires you to anticipate a lot about the future. It is difficult to write long-term contracts when there is considerable uncertainty about the economic environment in which that contract will operate. Eventually, the Crow's Nest Pass Agreement became an anachronism, limiting economic opportunities in the Canadian west by incentivizing farmers to send unprocessed grain east, rather than processing it locally.

For nascent space industries, anticipating the future environment is particularly difficult. Conditions for space transportation may change in unanticipated ways; fuel prices may fluctuate; new technologies may emerge; regulation may impact economic activity; or there may be other factors that alter the costs or benefits of operating over the term of the long-term contract. After all, it was precisely these changes in cost that drove our present inquiry.

CREATE YOUR COMPETITOR. When the profitability of a monopolist's business depends on the extent to which complementary innovations are developed, it is more important to create the conditions for those innovations to flourish than to create barriers to your own potential competitors.

This has arisen before when intellectual property has created conditions that might lead to a chilling of complementary investments. **Xerox**, which developed Ethernet, offered an open licence for the technology at a nominal charge. This spurred **Intel** and others to develop chips that would allow Ethernet to be used in local computer networks. And more recently, **Tesla** committed to not enforce any of its patents over electrical vehicles. This was done to create a platform to drive further investment in EVs by other manufacturers — and incentivize investment in complementary assets, such as charging stations, parts and repairs.

CREATE SURPLUS CAPACITY. One of the implicit drivers of launch costs is the lack of availability of capacity to slot launches in a timely manner — like an overbooked airline route that allows prices to rise as a way of rebalancing demand with limited supply. But this also works in reverse: if there is plenty of available capacity, there are incentives to utilize it, creating pressure to drop prices to fill loads.

There is a way a provider can mitigate those fears: visibly invest in a large amount of capacity — a long row of gleaming starships, for example. Having that capacity available means that it will be less profitable to raise prices later on, even when there is higher demand for launch. Since the rockets already exist, more rockets means more commitment to more launches, which, in turn, keeps those launches cost effective.

In closing

We hope this article provides some principles for identifying real progress in the space economy. First of all, any progress toward reducing the cost of accessing space matters, because it makes accessing the frontier easier. And second of all, commitments to reducing the hold-up problem matter.

Announcements by SpaceX around licensing of launch technology or decisions to oversupply capacity suggest that the holdup problem will be overcome, and that investments in complementary innovations will pay off. Transformative growth will depend on whether those looking to invest in complementary industries can be assured of continued low-cost access to space. ***RM***





Ajay Agrawal, C.M., is the founder of the Creative Destruction Lab (CDL), headquartered at the Rotman School of Management with 12 locations worldwide. He is also the Geoffrey Taber Chair in Entrepreneurship and Professor of Strategic Management at Rotman. **Joshua Gans** is the Jeffrey Skoll Chair of Technical Innovation and Entrepreneurship and Professor of Strategic Management at the Rotman School. **Avi Goldfarb** is the Rotman Chair in Artificial Intelligence and Healthcare and Professor of Marketing at the Rotman School. The three are co-authors of *Power and Prediction: The Disruptive Economics of Artificial Intelligence* (HBR Press, 2022.) **Chris Hadfield**, O.O.C., O.Ont., MSC, CD, is a retired Canadian astronaut, engineer, fighter pilot and musician who has flown two space shuttle missions and served as Commander of the International Space Station. He is a Fellow of the CDL. **Mara Lederman** is Co-founder and COO of Signal 1, which is transforming healthcare with AI. She was the Site Lead for CDL Toronto and a professor at the Rotman School for nearly 20 years.