Paybacks from Space

By John Benson

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1. Introduction

This paper started when I was in our mountain home at 4,000 ft in the Stanislaus National Forest and the Sierra Nevada Mountains. I was waiting for our dishwasher to finish its cycle before I left for my primary residence in Livermore. I picked up last month's Scientific American and started reading a short article, which ended up being really good, and made a really good point. What our country spends on its space program has a really big payback. Since I've been here almost from the beginning (got my BSEE in 1975), and worked in advanced technology from the beginning, I thought that I could add some "Paybacks…" to the list in the article excerpt, which is in section 2 below.

2. Observations about Space

…The colossally powerful James Webb Space Telescope (JWST) has upended textbook basics several times since its launch in 2021. It has spied galaxies born shortly after the big bang that are far brighter and bigger than scientists thought they had a right to be, seen surprisingly gigantic ancient black holes, and identified life-supporting compounds such as carbon dioxide in the atmospheres of exoplanets for the first time. Its discoveries are corning so fast that scientists sometimes don't know which of its many findings to focus their research on.[1]

These riches are only growing with several other big-ticket observatories that have recently opened or will soon. In 2023 Europe launched its Euclid telescope into space to focus on the dark universe-the mysterious dark energy and dark matter that seem to dominate the cosmos. This year the Vera C. Rubin Observatory in Chile will begin photographing the full sky every few nights, observing moving objects, brief flares and how the universe changes over time. And in 2027 NASA's Nancy Grace Roman Space Telescope will join JWST in viewing space through infrared light, peering back to the earliest epochs of the universe.

With JWST's price tag at $10 billion (it's the most expensive observatory ever built), Euclid's at $1.5 billion, Nancy Grace Roman at $4.3 billion and Vera C. Rubin's at $473 million and counting, why spend this kind of money on space when there are so many problems here on Earth?

Making life on Earth better is a worthy goal, but so is astronomy. Even with these high costs, less than 0.5 percent of the U.S. federal budget goes to NASA every year. And our study of space shows that we humans can still work together across nations and rivalries to accomplish great things. It proves that we can dedicate huge resources and effort to goals that offer no financial gain or material advantage. Knowledge for its own sake is valuable, and its pursuit is justified even if it makes no practical difference here on our planet.

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[1] Board of Editors, January 2025 Scientific American, Pg 70: "Good News from Above." To Order a Copy of a Scientific American Issue: Call (800) 333-1199.

But in fact, astronomy does directly affect people's lives. The need to power spacecraft has pushed development of the solar panel technology we use on Earth. Research on the charge-coupled device (CCD) cameras used in telescopes has enabled the cellphone camera technology in our pockets. Furthermore, viewing Earth from space has helped us understand our changing climate and even drawn humans together in appreciating the fragility of our world.

And what we stand to lose if we divert funding for space research is literally astronomical. The Rubin observatory alone will produce about 20 trillion bytes of raw data per night, and the Roman telescope will add another trillion bytes daily-not to mention the roughly 50 billion bytes coming in from JWST every day. All told, astronomers now have access to a fire hose of celestial information where they once were lucky to get a trickle. Mining these troves will help us understand what happened when the universe was first created. We might figure out how stars and galaxies are born, evolve and die, and we hope we will, possibly, solve some of the biggest mysteries in space: What is dark matter made of? What's the nature of the dark energy pulling apart the cosmos? Is there life beyond us out there somewhere?

The money and work that go toward understanding the universe and our place in it are far from a waste-this project is among the most noble that humanity undertakes. Astronomy serves to remind us that we are part of something much grander than ourselves-that the turmoil of life on Earth both its wonders and its tragedies, isn't all there is. By peering at the stars, we can see that our lives are a small piece of a great and mysterious working.

Just a few hundred years ago we relied on stories to explain what we saw when we looked into the night sky. Today we are more poised than ever to describe our universe the way it really is. This unfolding tale is turning out to be more fascinating than anything humans can invent, and our knowledge of it is worth every penny we spend.

3. Other Developments Caused by the Space Race

The global positioning system (GPS) *was originally developed by the military for precision navigation and weapon targeting purposes. The GPS developers probably did not foresee how this technology would transform almost every industry, as well as day-to-day life, on a global scale. Using maps and travel atlases and stopping to ask for directions are now largely anachronisms. GPS has enabled ride-hailing services, as well as package tracking and delivery. It has improved our fitness by tracking our workouts and our safety by quickly providing our location in emergency situations. GPS will be there in the future to facilitate emerging technologies such as self-driving cars and package deliveries by drone.*[2]

Infrared ear thermometers *— a NASA-derived advancement — measure the amount of energy emitted by the eardrum in the same way the temperature of stars and planets is measured, using infrared astronomy technology.* ***Artificial limbs*** *have drastically improved using advanced space program shock absorbing materials and robotics.*

[2] Aldo Spadoni, Northrop Grumman, "How Technology From the Space Race Changed the World," Dec. 2, 2022, https://now.northropgrumman.com/how-technology-from-the-space-race-changed-the-world

*Deep space exploration missions depend on excellent **digital image processing** technology developed by the Jet Propulsion Laboratory (JPL). JPL adapted this technology to help create modern CAT scanners and radiography.*

*The list of technology from the space race goes on. Consumer products like **wireless headsets**, **LED lighting**, **portable cordless vacuums**, **freeze-dried foods**, **memory foam**, **scratch-resistant eyeglass lenses** and many other familiar products have all benefited from space technology research and development.*

***Modern laptop computers** are direct descendants of The Shuttle Portable Onboard Computer (SPOC), which was developed in the early 1980s for the space shuttle program.*

*Technology from the space race has also been applied to directly improve public safety and reduce the risk of accident and injury. **Anti-icing systems allow aircraft to safely fly in cold weather**. **Safety grooving**, which first was used to reduce aircraft accidents on wet runways, is now also used on our roadways to prevent car accidents. **Smoke and carbon monoxide detectors** were first developed for the NASA Skylab program in the 1970s. **Modern firefighting equipment** widely used throughout the United States is based on NASA-developed lightweight fireproof materials.*

*One of the most important spinoff technologies is in the area of food safety. NASA was faced with the problem of feeding astronauts in confined environments under weightless conditions. They also could not tolerate potentially disastrous crumbs, bacteria or toxins. **NASA teamed with the Pillsbury Company to develop the Hazard Analysis and Critical Control Point (HACCP)** concept. HACCP is designed to prevent food safety problems during production, rather than catching them after they have occurred. The U.S. Food and Drug Administration has used HACCP guidelines for the safe handling of seafood, juice and dairy products since the early 1990s.*

For more than half a century, the NASA Technology Transfer Program has provided private industry with a connection to its vast resources to support commercial product improvement development. To date, NASA says that about 2,000 "spinoff" commercial products have been successfully developed in many fields. But, despite what you might have heard, NASA didn't invent Tang, Velcro or Teflon frying pans.

*One of the earliest and most significant advancements was the development of the **integrated circuit**, the foundation of modern electronics. NASA's need for compact, reliable electronics propelled this technology forward, eventually leading to the widespread use of microchips in everything from personal computers to smartphones.*[3]

Satellite technology also saw meteoric advancements. The launch of Sputnik was followed by a series of American satellites, culminating in the development of communications satellites. These satellites revolutionized global communications, enabling real-time telecommunication across continents and paving the way for the globalized world we live in today…

The Space Race significantly influenced educational reforms, particularly in the United States, igniting intense focus on science, technology, engineering, and mathematics (STEM) education. The launch of Sputnik was a wake-up call, highlighting a perceived gap in scientific capabilities between the US and the USSR.

[3] SocialStudiesHelp.com, "The Space Race: Technological Advancement and Cultural Impact," https://socialstudieshelp.com/the-space-race-technological-advancement-and-cultural-impact/

Furthermore, NASA itself became a beacon of educational outreach. The agency developed educational resources to inspire young minds, including educational television programs and classroom materials centered on space exploration and science. These efforts aimed to cultivate a new generation of scientists and engineers…

Understanding Earth's atmosphere and environment also benefitted from the Space Race. Satellites launched during this period vastly enhanced weather forecasting capabilities and provided the first comprehensive data on Earth's sun and radiation environment.

4. Machine Intelligence

Since the early days of the space race, advanced computers have been an integral part of space travel. Without innovative computer systems, satellites would not orbit the Earth, robotic explorers would not roam Mars, and astronauts would not have made that "giant leap" onto the lunar surface. Space-computers have enabled remarkable feats of exploration across the solar system and beyond.

Prior to 1965, American crewed spacecraft relied solely on analog technology. Complex calculations for essential functions like rocket burn timing, altitude adjustments, and reentry angle were tediously done by hand. The stakes were high – minor mistakes could greatly amplify into mission-ending disasters.

The Gemini program broke new ground as the first capsule to include a digital computer. This milestone IBM system boosted crew safety with rapid number crunching. Its programs automated routine tasks, freeing the astronauts to focus more on scientific experiments. The streamlined Gemini flights proved out key capabilities like spacewalking and rendezvous critical for the Apollo moon missions.

Despite its pioneering status, the Gemini computer was quite limited. Its tiny core memory stored just 1024 16-bit words. Over 20 of Gemini's 30 programs were written in complex assembly language. Software was still in its infancy – during Gemini 8, a faulty thruster led to a harrowing emergency, made much worse by the limited computer.[4]

Yet this modest beginning ushered in the modern era of space computing. Lessons learned directly fed into Apollo's computers as digital flight control came into its own.

When the bold decision was made to land humans on the Moon before the end of the 1960s, the massive Apollo spacecraft grew to accommodate three astronauts. Along for the legendary ride was the Apollo Guidance Computer (AGC) – compact yet ingeniously designed by MIT engineers.

Housed in a 24-pound navigation box, the AGC boasted a 2.048 MHz clock paired with 4 KB of RAM and 72 KB of ROM. This does not sound impressive compared to today's gigahertz mobile phones with gigabytes of memory! But the AGC achieved remarkable reliability through core rope memory – durable magnetic woven wire that stored data as tiny analog rings.

From launch to lunar touchdown, the AGC handled vital tasks: engine burns, abort guidance, trajectory corrections, star sightings, and the final descent to the alien landscape. The software effort was monumental – over 3 million lines of code were written and thoroughly checked. Commands came via a numeric keypad called DSKY (Display Keyboard) with illuminating Verb and Noun two-word combinations.

[4] https://www.americaspace.com/2021/03/17/serious-problems-here-remembering-gemini-viii-otd-in-1966-part-2/

During each successful Apollo mission, the AGC steered a true course despite any equipment issues or flight anomalies. Without the AGC integrating complex sensors and making swift corrections, Neil and Buzz's giant leap would have remained out of reach.

With milestones like lunar landings and Mars flybys achieved, space programs set their sights on more ambitious destinations like the outer planets. But trips like Jupiter and beyond were over a billion miles away – requiring nuclear-powered probes capable of decade-plus journeys.

Weight constraints ruled out lifting bulky state-of-the-art computers aboard long cruise probes. However, leveraging both lightweight space computers and significantly more powerful ground systems enabled remarkable missions:

Voyager I and II – launched in 1977, the far-traveling probes each have three IBM 32-bit computers with just 4 MB of memory. But Earth-bound computers handle intensive image processing and route plotting computations.

Galileo – The 1989 Jupiter orbiter contains an adaptable array of 10 microchips realizing over 100,000 gates for command and data handling. Its journeys were coordinated via ground stations.

Cassini – The Saturn probe launched in 1997 boasts two Harris radiation-hardened 32-bit CPUs running at 25 MHz, but relies on Earth to crunch its voluminous sensor telemetry.

New Horizons – The tiny probe's integrated circuits contain just over 100,000 gates, on par with 1990's era Macintosh computers. Launched in 2006, ground stations guide this Pluto and Kuiper Belt explorer.

5. Reverse Design-Flow

In the above time-line, something interesting happened. The demands of space-launch computer systems were paralleled by demands for robustness as are common industrial computer applications. Thus, suddenly, designs for large-volume industrial applications were suitable for space applications.

Since 1981, NASA has thoroughly flight-tested and employed Lenovo ThinkPad laptops aboard Space Shuttle and International Space Station missions. Why does this particular line of commercial computer hardware qualify for space travel?

It turns out ThinkPad engineering closely aligns with the rigorous quality standards spacecraft demand. Their case uses lightweight yet strong magnesium alloy, well suited for shock and vibration. ThinkPad design emphasizes effective cooling despite zero-gravity conditions. Each key component is secured firmly to handle pounding launch forces.

On top of that sturdy construction, NASA opted for high-reliability solid state drives versus mechanical hard disks more prone to cosmic ray disruption. Good display legibility helped under cramped sleeping quarters conditions, and spill-proof keyboards guarded against wayward drops of coffee in weightlessness.

By selecting ThinkPad hardware, adapting them for space environments, and working closely with Lenovo on ongoing improvements, NASA balanced cost-effectiveness with essential reliability. Laptops lent versatility across station activities like systems monitoring, science experiment support, and communication with ground control.

5.1. Martians are now Solid-State

Tirelessly roaming the Martian surface since 2004, NASA's twin plutonium-energized rovers Spirit and Opportunity probed craters and canyons for evidence these harsh plains once ran wet. Each rover carries hardened PowerPC CPUs tested to withstand intense cold along with radiation bombardment. Their 256 MB of DRAM and 256 MB of flash memory seem meager. However, smart algorithms help the rovers recognize geological clues and navigate unpredictable terrain.

In 2012 the car-sized Curiosity rover landed via an audacious sky-crane maneuver. Its main flight computer actually dates back to the early 2000's, based on a 20 MHz RAD750 radiation-hardened PowerPC chip with 256 MB of DRAM. Despite its outdated brain, Curiosity leverages numerous self-correcting mechanisms to explore over 11 miles while assessing Mars past habitability.

These robotic pioneers relayed findings to eager scientists back on Earth via local orbiters. Their discoveries collectively indicated Mars once sustained surface lakes, ponds and streams – marking it as a prime candidate for evidence of ancient microbial life. Someday, human colonists may tread the same ancient lakebeds the rovers explored thanks to their reliable onboard computers.