

THE SCIENCE THAT CHANGED THE WORLD

*Volume Three — Leaving Earth: Sixteen Inventions That
Took Us Off the Planet, Now in the Public Domain*

By

MARTIN CARR

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TABLE OF CONTENTS

Introduction — The Fence Above the Sky	4
Part One — Escaping the Earth	7
The Rocket Equation	8
Throwing Away the Ladder	12
The Steady Hand	15
Part Two — The Brain That Flew to the Moon	18
The Chip That Went to Space	19
The Program Woven by Hand	22
Part Three — Surviving the Void	26
The Shield of Fire	27
The Gold Blanket	29
A Spaceship You Can Wear	32
Part Four — Unfolding in Orbit	35
The Origami of Spacecraft	36
Power in the Dark	39
The Steady Gaze	42
Part Five — The Sky Full of Satellites	45
The Satellite That Stands Still	46
A Constellation for the Rest of Us	49
Knowing Where You Are	52
Part Six — The Gifts Home	55
The Eye That Came Home	56
The Things That Came Home	59

INTRODUCTION — THE FENCE ABOVE THE SKY

Behind every machine that ever left the Earth there is a document almost nobody reads.

It is dry, defensive, and written in a language built to survive lawyers rather than to be understood. It speaks of "a first deployable member" and "a plurality of thruster means" where you or I would say the satellite unfolded its wings. It numbers its sentences. It repeats itself on purpose. It is a patent — and it is the closest thing we have to the birth certificate of an invention.

A patent is a bargain struck with time. In exchange for telling the world exactly how an invention works — publishing it, in full, for anyone to read — the state grants twenty years of exclusive right. And then, on a specific and unremarkable morning, the clock runs out and the second half of the bargain quietly completes itself: the

monopoly ends, the fence comes down, and the invention becomes the property of everyone, forever.

This book is about the inventions that took us off the planet, and about that morning arriving for each of them.

The great age of leaving Earth — the rockets, the guidance computers, the satellites, the spacesuits, the folding solar wings — happened, for the most part, in the middle of the last century and the decades just after. Which means something quietly remarkable: nearly all of the foundational technology of spaceflight is now old enough that its patents have expired. The specific machinery that carried human beings to the Moon and machines to the planets, once the guarded property of governments and great corporations and the classified programmes of the Cold War, has passed, filing by filing, into the public domain. The knowledge that reached the stars now belongs to everyone alive.

The chapters that follow tell sixteen of those stories — from the rocket equation to the folding solar array, from the computer woven by hand for the journey to the Moon to the constellation of satellites that now knows where you are standing. Some were chosen from the data. In building this book I harvested the entire class of spacecraft patents from the public record and ranked them by how heavily later inventions cited them, letting the numbers surface the deployment mechanisms, the thermal systems, the attitude-control tricks, and the

satellite architectures that the field itself leaned on most. Others — the human-spaceflight stories that no single patent captures, the rocket pioneers, the Moon computer — are told from history. Every patent number, company, and date in these pages is real and freely readable now.

A note on what this book is. It is a history for the curious, not a manual, and nothing in it is engineering advice. Where I have had to choose between precision and readability, I have chosen readability, and the specialist will find simplifications to quarrel with. But the point is not the footnotes. The point is the reach — how humanity built the machines to leave its own world, at what cost, and how the knowledge of it came, in the end, back down to all of us.

Nobody rings a bell on the day a patent expires. The fence just comes down, and almost no one looks up.

This time, look up.

PART ONE — ESCAPING THE EARTH

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CHAPTER 1

THE ROCKET EQUATION

To leave the Earth you must fight, and keep fighting, one merciless fact: everything that goes up must be thrown up, and the throwing costs fuel, and the fuel has weight, and that weight must itself be thrown. This is the tyranny at the heart of all spaceflight, and it was first written down cleanly by a deaf, self-taught Russian schoolteacher named Konstantin Tsiolkovsky at the very end of the nineteenth century.

Tsiolkovsky never built a rocket. He worked it out on paper, in a provincial town, largely alone — and arrived at the equation that still governs every launch. It says, in essence, that a rocket flies by throwing mass backward, and that to go faster you must throw mass faster or throw more of it; and, cruelly, that because the rocket must carry its own unburned fuel, the amount of propellant needed does not grow gently with the speed you want but explosively. To go a

little faster costs a lot more fuel; to reach orbit costs staggeringly more than intuition suggests. The rocket equation is the reason a vehicle the size of an office block is needed to place a small capsule in orbit — most of what you see on the launch pad is fuel to lift fuel to lift fuel.

THE MAN WHO LIT THE FIRE

Tsiolkovsky supplied the theory. The first person to make a liquid-fuelled rocket actually fly was an American physicist, Robert Goddard, working in Massachusetts in the early decades of the twentieth century. Goddard was a careful, secretive, much-mocked man — a newspaper once ridiculed him for supposedly not understanding basic physics, an insult the paper corrected, with a straight face, only after the Moon landings decades later. But he was also, crucially for our story, a prolific patenter. Goddard understood that his ideas were valuable and defensible, and he protected them.

In 1914 — years before he flew anything — Goddard was granted two patents that between them sketched the shape of all spaceflight to come. US Patent 1,102,653 covered a multi-stage rocket: the idea of stacking rockets so that spent, empty sections could be dropped away. And US Patent 1,103,503 covered a rocket fuelled by liquid propellants. These were the two foundational moves of the entire field, staked out in law before the technology to realise them properly existed. Goddard would go on to launch the world's first

liquid-fuelled rocket in 1926, a brief, spluttering flight from his aunt's farm that lasted a couple of seconds and rose a few dozen feet, and that began, in a real sense, the road to the Moon. Over his life and after it, more than two hundred patents would bear his name.

THE KNOWLEDGE, NOW FREE

Here is the first appearance of this book's recurring turn, and it is a striking one. Goddard's foundational rocket patents — the multi-stage rocket, the liquid-fuelled rocket — expired the better part of a century ago. They have been in the public domain for longer than most nations have had space programmes. The very ideas that define how you leave the Earth were fenced off, briefly, by one careful man in 1914, and have belonged to all of humanity ever since. Every rocket that has ever flown, from every country, has been free to build on them.

That is worth holding onto as we go. The deepest, oldest foundations of spaceflight are not owned by anyone. They are common inheritance, published and free, exactly as the patent bargain intended. What remained proprietary, and what this book will trace through its expiry, was everything built on those foundations — the guidance, the satellites, the folding structures, the thermal systems — the specific machinery of actually getting it done. The equation and the first patents were only the beginning. The next problem was that a single rocket, however clever its fuel, can barely reach space at

all. To get to orbit, you have to learn to throw away the rocket itself, a piece at a time.

CHAPTER 2

THROWING AWAY THE LADDER

The rocket equation delivers brutal news: no single rocket, burning any fuel humanity can practically carry, can reach orbital speed. The weight of the fuel tanks and engines needed for the whole journey is simply too much dead weight to haul all the way up. If you build one rocket big enough to hold all the propellant, the empty structure to contain that propellant weighs so much that the thing can never reach orbit. The mathematics seems to slam a door.

Goddard's other 1914 patent had already found the way through it, and the idea is so simple to state and so hard to execute that it deserves its own chapter: throw the rocket away as you climb. Build the rocket in stages, stacked one atop another. Fire the first, largest stage until its fuel is spent — and then, instead of dragging its now-empty, useless mass any further, drop it. Let it fall away. Light the next stage, lighter now because it no longer has to carry the dead

weight of the first, and climb on. Drop that too when it is spent, and fire the third. At every step you shed the empty tanks and engines that have done their job, so that the rocket grows lighter exactly as it grows faster, and the punishing arithmetic of the rocket equation is beaten by refusing to carry anything you no longer need.

THE LADDER YOU KICK AWAY BENEATH YOU

It is a strange and almost poignant way to travel — a machine that survives by continuously destroying most of itself, arriving at its destination as a small fraction of what left the ground. The great Saturn V that carried astronauts to the Moon was, by weight, almost entirely fuel and discarded stages; the part that actually reached the Moon and came home was a tiny gleaming remnant at the very top, the last survivor of a vehicle that had thrown away everything else on the way up. Staging is the ladder you kick away beneath you as you climb, rung by rung, because carrying the ladder would stop you ever reaching the top.

Every launch to orbit, to this day, is a staged launch. It is not an optional refinement but the fundamental architecture of reaching space, and it was patented, in its essential form, in 1914 — and has been free for everyone to use for a century. The modern twist, the great project of the current age of spaceflight, is to make some of those discarded stages fly back and land so they can be used again rather than thrown into the sea; but even that is a variation on

Goddard's theme, a way of getting the thrown-away ladder back. The idea of shedding your dead weight to climb higher belongs to everyone now, as it has for longer than living memory.

Staging solved how to get up. But a rocket that merely goes up, blindly, is a firework. To go somewhere — to reach a precise orbit, to hit the Moon, to point at a planet — a rocket must know, at every instant, exactly where it is pointing and how fast it is going, with no help from the ground and nothing outside to look at. It must, in the truest sense, find its own way. And that turned out to require one of the most beautiful instruments ever built.

CHAPTER 3

THE STEADY HAND

Imagine being sealed inside a windowless box, in the dark, and asked to know — precisely, continuously, without looking outside — which way you are facing and how fast you are moving. No landmarks, no horizon, no stars to sight, nothing external to check yourself against. This is very nearly the situation of a rocket climbing through the atmosphere and out into space: it must know its own orientation and motion exactly, from the inside, in order to steer, and it cannot simply look out of a window and get its bearings. The instrument that solved this problem is called an inertial guidance system, and it is one of the quiet marvels of the twentieth century.

THE SPINNING HEART

At its core lies the gyroscope — a wheel spun at high speed, which, by a deep law of physics, resists having its axis turned and so tends

to keep pointing in the same direction no matter how the vehicle around it twists and rolls. Mount such spinning wheels carefully, and they become a fixed reference held inside the moving machine: a memory of which way is which, maintained purely by spinning mass, needing nothing from outside. Add accelerometers — instruments that sense every push and shove, every change in speed — and you can, in principle, track your own motion completely from within. Start from a known position, then continuously add up every acceleration and every turn the gyroscopes and accelerometers report, and at any instant you can calculate exactly where you are and where you are pointing, having watched nothing but your own insides. It is called dead reckoning, and inertial guidance is dead reckoning raised to an art.

The development of practical inertial guidance is bound up with one institution above all, the Instrumentation Laboratory at the Massachusetts Institute of Technology, and with the driven engineer who led it, Charles Stark Draper. Draper's laboratory turned the gyroscope from a physics-lecture curiosity into a precision instrument accurate enough first to guide missiles and then to guide human beings to the Moon and back. The same fundamental technology — a self-contained system that knows its own motion without reference to the outside world — steered the great rockets, the nuclear submarines that could not surface to navigate, and the Apollo spacecraft on its quarter-million-mile journey.

THE ART OF KNOWING WHERE YOU ARE

There is something almost philosophical in inertial guidance, and it is worth pausing on. It is a machine that navigates by pure introspection — that knows where it is entirely by remembering where it started and paying perfect attention to every motion since. It needs no satellites, no ground stations, no view of the sky; it cannot be jammed or spoofed, because it listens only to itself. That self-reliance is exactly why it remains, decades later and even in the age of satellite navigation, the bedrock of how rockets and spacecraft and submarines find their way. The foundational work is long since public, its patents expired, its principles taught in every aerospace course; the specific mastery of building gyroscopes and accelerometers precise enough to trust with a human life stayed, like so much in this book, a harder and more guarded thing.

Staging got the rocket up; inertial guidance told it where it was pointing. But steering a rocket, and later landing on the Moon, required more than knowing your position — it required computing what to do about it, continuously, in real time, faster than any human could. And that demand, more than almost anything else, drove the invention of the machine that now runs the world: the computer small enough to fly.

PART TWO — THE BRAIN THAT FLEW TO THE MOON

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CHAPTER 4

THE CHIP THAT WENT TO SPACE

In the early 1960s, a computer was a piece of furniture. It filled a room, drew the power of a house, and was tended by specialists in white coats. The idea of a computer small enough and light enough and reliable enough to bolt into a spacecraft and trust with human lives was, to most people, faintly absurd. And yet reaching the Moon demanded exactly that: a machine to run the guidance, to solve the equations of the journey continuously, in real time, in a box an astronaut could reach — because the alternative, doing all the computing on the ground and radioing up the answers, was too slow and too fragile for the split-second business of flying and landing.

The technology that made it possible had been invented only a few years before, and the Moon programme became its first great proving ground and its first great customer.

THE TYRANNY OF THE WIRE

The problem with old computers was not really the size of their parts but the number of their connections. A complex circuit meant thousands upon thousands of individual components — transistors, resistors, capacitors — each of which had to be wired to its neighbours by hand, by the thousand. Every joint was a chance to fail, and in a machine with hundreds of thousands of joints, something was always failing. This "tyranny of numbers" put a hard ceiling on how complex, and how reliable, a computer could be. You could not simply build a bigger brain, because the wiring to connect it would defeat you.

The breakthrough, arrived at around 1958 to 1959 by Jack Kilby at Texas Instruments and, independently and in the form that would win, Robert Noyce at Fairchild Semiconductor, was the integrated circuit: the idea of building many components, and the connections between them, together, all at once, on a single small slice of semiconductor. Instead of wiring a thousand parts together by hand, you made the thousand parts and their wiring as one object, printed into the material itself. It collapsed the tyranny of numbers at a stroke. Suddenly a great deal of circuitry could be made small, light, and — because there were no hand-made joints to fail — reliable.

THE MOON AS CUSTOMER

The integrated circuit was new, unproven, and expensive, and in its earliest days it badly needed a customer willing to pay for it and to trust it. The Apollo programme became that customer. The computer built to guide the Apollo spacecraft was one of the very first machines designed around integrated circuits, and for a period the Moon programme was buying a significant share of all the integrated circuits produced in the United States. That guaranteed demand, and the ferocious reliability standards that came with putting the chips where lives depended on them, helped drive the young industry forward — pushing the price down, the quality up, and the manufacturers toward the mass production that would, within two decades, put a computer on every desk and eventually in every pocket.

There is a genuine and under-told line of descent here. The relentless miniaturisation of computing — the whole road from the room-sized machine to the smartphone — was pushed hard, in its fragile infancy, by the demand of spaceflight for something small enough to fly. The chip in your pocket is a distant descendant of the chip built to go to the Moon. And the foundational patents of the integrated circuit, Kilby's and Noyce's, expired decades ago; the founding idea of the modern world sits, like Goddard's rockets, in the public domain. But a chip is only hardware. To fly to the Moon it needed a mind — and that mind had to be woven, by hand, into copper and magnetism.

CHAPTER 5

THE PROGRAM WOVEN BY HAND

The computer that guided Apollo to the Moon was a miracle of its age: around seventy pounds, smaller than a cubic foot, built from those new integrated circuits, holding roughly five thousand seven hundred logic gates. By the standards of today it was almost unimaginably feeble — a modern phone outclasses it by factors too large to be meaningful. And yet it flew human beings to another world and landed them and brought them home, and it did so with a reliability that shames many far mightier machines. How it stored its program is one of the most extraordinary and moving stories in all of computing.

SOFTWARE WOVEN INTO WIRE

The Apollo Guidance Computer's permanent memory — the program itself, the irreplaceable code that would fly the mission —

was not written to any chip or disk. It was woven. The technology was called core rope memory, and it worked like this: a wire threaded through a tiny magnetic ring counted as a one; a wire routed around the outside of that ring counted as a zero. To store the program, then, you had to physically thread wires through or around tens of thousands of minuscule magnetic cores, in exactly the right pattern, by hand — encoding the software, bit by literal bit, into a woven mesh of copper and iron.

This weaving was done, at the Raytheon factory, by teams of women skilled in precise handwork — women who were sometimes called, with the casual condescension of the time, the "Little Old Ladies," even as they held in their hands the only copy of the only program that could land human beings on the Moon. Once woven, each memory module was sealed in epoxy, entombed forever, utterly unchangeable. And this is the detail that stops you cold: the program could not be patched. Whatever was woven was what flew. If a bug had been found the week before launch, there would have been no software update, no quick fix — only weeks of unpicking and re-threading by hand. The code that went to the Moon was a physical object, sewn by human fingers, and it had to be perfect because it could not be changed.

THE MOTHER OF THE ROPE

Presiding over the software that would be woven into that rope was

Margaret Hamilton, who in her early thirties led the software engineering team at the MIT Instrumentation Laboratory. Hamilton and her team wrote the flight software — the real-time operating system, the priority scheduling that let the computer drop less urgent tasks to handle critical ones, the error-recovery routines that could catch a problem and keep flying. That last capability was not academic. During the final descent of the first Moon landing, the guidance computer was overwhelmed with more work than it could do and began throwing alarms — and because Hamilton's team had designed it to recognise overload and shed its lowest-priority tasks rather than freeze or crash, it kept doing the essential job of landing while shedding the inessential. The software noticed it was drowning and saved itself, and the landing continued. It is not too much to say that this design choice helped save the first Moon landing.

Hamilton is often credited with popularising the very term "software engineering," insisting, against the prejudices of an age that saw code as an afterthought to hardware, that building software was a rigorous engineering discipline in its own right. She was right, and the whole modern world of software has grown from that insistence. The computer that flew to the Moon, and the woven program that ran it, and the engineering discipline that made that program trustworthy, are all now part of history and public knowledge — the machine long since declassified and documented, its code published for anyone to read. The brain that flew to the Moon is, like everything else in this book, ours now. But a mind and a rocket are not enough

to survive out there. Space itself is trying to kill you, and the next problem was simply staying alive in it.

PART THREE — SURVIVING THE VOID

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CHAPTER 6

THE SHIELD OF FIRE

Getting to space is only half the journey. Coming home is, in one specific way, far more violent — and for the entire history of human spaceflight it has depended on a technology that works by deliberately, controllably destroying itself.

A spacecraft returning from orbit is travelling at enormous speed, and all of that speed is energy that has to go somewhere before the vehicle can safely touch the ground. As the capsule plunges back into the thickening atmosphere, it slams into the air so fast that the air cannot get out of the way; it compresses violently in front of the vehicle, and that compression heats it to thousands of degrees, hot enough to glow, hot enough to melt or vaporise almost any material. The returning spacecraft is wrapped in a sheath of superheated plasma. The problem of re-entry is the problem of not being burned alive inside it.

BURNING ON PURPOSE

The solution that carried every early astronaut home, and carries capsules home to this day, is the ablative heat shield, and its logic is beautifully counterintuitive: do not try to resist the heat — spend it. An ablative shield is made of a material designed to char, melt, and vaporise in a controlled way, and as it does so it carries the heat away with it. The outer layer burns off and streams away behind the vehicle, taking its enormous heat energy with it into the wake, while the sacrifice of that outer layer keeps the surface beneath cool enough to protect the astronauts within. The shield saves the crew by burning away in their place. A capsule that has returned from space has a heat shield that is scorched, eroded, and partly consumed — it did its job by being destroyed, exactly as designed.

There is a deep kinship here with the ablative logic we will meet nowhere else so purely: a technology that protects by controlled self-destruction, spending itself so that what it shields survives. It is the same spirit as the crumple zone of a car or the sacrificial anode on a ship's hull — the deliberate ruin of one part to save the whole. The materials science of ablative heat shields, refined through the early space programmes, is now long-established public knowledge, its foundational work decades old. And it remains, even now, how we come home: for all our advances, the surest way to survive the fire of re-entry is still to carry a shield built to burn.

CHAPTER 7

THE GOLD BLANKET

Space is not simply cold, though it is that. Space is thermally violent in a way that is hard to imagine from the surface of a temperate planet. A spacecraft in orbit is roasted on the side facing the Sun, where there is no air to carry heat away and temperatures can climb far above boiling, and simultaneously frozen on the side facing away, radiating its warmth into a void near absolute zero. The same object, at the same moment, is being cooked and frozen, and the difference between its sunlit and shadowed faces can be hundreds of degrees. Keeping the delicate machinery of a spacecraft — and, on crewed missions, the fragile human beings — within the narrow band of temperatures they can survive is one of the central, unglamorous, unrelenting problems of spaceflight.

THE BLANKET THAT ISN'T WARM

The most visible answer is the shimmering gold and silver foil that wraps so many spacecraft, giving them their distinctive treasure-chest glint. It is called multi-layer insulation, and, despite appearances, it is not a warm blanket in any earthly sense. It is many, many layers of thin reflective film, separated by the near-vacuum of space, and it works precisely because there is no air. On Earth, heat moves mostly by conduction and convection — through direct contact and moving air — but in the vacuum of space, heat can only move by radiation, by glowing it away. Multi-layer insulation attacks radiation with reflection: each shiny layer bounces heat back, and with dozens of layers stacked up, the flow of heat is choked almost to nothing. The gold foil does not keep a spacecraft warm; it keeps it thermally isolated, slowing the roasting and the freezing alike so that the vehicle's own systems can manage the balance.

Behind the foil lies a whole hidden discipline of moving heat around a spacecraft — carrying it away from hot electronics, spreading it, dumping it into space through radiators. When I harvested the class of spacecraft patents from the public record and ranked them by influence, this quiet field surfaced strongly. Among the most-cited was Midwest Research Institute's "compact vacuum insulation" (US 5,175,975, granted 1993) — foundational work on the vacuum-based insulation that keeps heat where it belongs. Another, from Isothermal Systems Research, covered "high heat flux evaporative spray cooling" (US 5,220,804, also 1993) — a technique for pulling large amounts of heat away from densely packed, powerful electronics by

spraying them with an evaporating liquid, the same basic principle by which sweat cools a body, adapted for the fierce concentrated heat of modern space hardware. Both patents are long expired, their citation counts among the highest in the spacecraft field, their methods now free for anyone to build upon.

THE INVISIBLE ART

Thermal control is the kind of engineering that never makes a headline and never gets a statue, and yet nothing survives in space without it. Every satellite, every probe, every crewed vehicle lives or dies by its ability to manage the savage thermal swing between sunlight and shadow, and the shimmering foil and the hidden cooling systems are what make the difference between a working spacecraft and a frozen or roasted ruin. The founding techniques, surfaced by the data and confirmed by their influence, are now common property. The gold blanket, and the quieter art beneath it, belong to everyone who would keep a machine alive in the void.

CHAPTER 8

A SPACESHIP YOU CAN WEAR

Of all the machines in this book, the strangest and the most intimate is the one a human being climbs inside and wears. A spacesuit is not clothing. It is a spacecraft shaped like a person — a self-contained, wearable vehicle that must do, around a single fragile body, everything a spaceship does around a crew: hold in air at survivable pressure against the hard vacuum outside, supply oxygen, remove the carbon dioxide the wearer exhales, and manage the same brutal thermal extremes that the gold blanket fights on the vehicle itself. To step outside into space, or to walk on the Moon, a person must carry their entire life-support world with them, wrapped around their skin.

THE PROBLEM OF A WORKING BODY

The hardest and least obvious of these problems is heat — and specifically the heat the astronaut's own body makes. A person

working hard inside a sealed, airtight suit generates a surprising amount of warmth, and in the vacuum of space that heat has nowhere to go. There is no breeze, no air to carry it off; the suit that keeps the vacuum out also keeps the body's heat in. An astronaut labouring on a spacewalk or hauling equipment across the lunar surface would, without some active means of cooling, quickly overheat inside their own sealed shell, drenched and dangerously hot, the visor fogging, the body cooking in its own exertion. Solving this was essential to doing any real work in space at all.

When the spacecraft-patent data surfaced its most-cited inventions, this deeply human problem was among them. United Technologies' "space suit cooling apparatus" (US 5,092,129, granted 1992) addresses exactly it — the machinery of drawing a working astronaut's body heat away and keeping them cool and functional inside a sealed suit in the thermal hostility of space. The classic approach, refined over decades of spacewalks, threads a garment worn against the skin with a network of fine tubes carrying cooling water, which absorbs the body's heat and carries it away to be shed — a wearable radiator, in effect, laid against the body. It is unglamorous plumbing in the service of something profound: letting a human being work, in comfort and safety, in a place that would otherwise kill them in moments.

CARRYING A WORLD

There is something quietly staggering in the whole idea of the spacesuit — that to survive outside, a person must become, in effect, their own smallest possible spacecraft, carrying a breathable atmosphere and a cooling system and a pressure hull as a second skin. Every spacewalk is a human being sealed inside a personal, wearable world, tethered to nothing but their own supplies. The technologies that make it possible — the pressure garment, the life support, the cooling — were developed at enormous effort through the early space programmes, and the foundational patents, like United Technologies' cooling apparatus, have expired into the public domain. The knowledge of how to build a spaceship a person can wear is now, in its essentials, freely available. The suit that let human beings walk on the Moon is, in the end, ours too.

PART FOUR — UNFOLDING IN ORBIT

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CHAPTER 9

THE ORIGAMI OF SPACECRAFT

Here is a problem you would never think of until you faced it, and it turns out to be one of the defining challenges of spacecraft engineering. A rocket's nose is small — a narrow cylinder, a few metres across at most. But the things a spacecraft needs to do its job are often large: solar arrays the size of tennis courts, antennas like great dishes, booms and masts and radiators reaching out many metres. How do you fit something enormous inside something small? You fold it. And then, once in orbit, you must unfold it — reliably, once, with no one there to help, in the vacuum and cold of space, with no second chances. A spacecraft is, to a surprising degree, a work of origami that must open itself.

THE TYRANNY OF THE FIRST MOVE

This is harder and more terrifying than it sounds, because

deployment is almost always a one-shot, irreversible event, and if it fails, the mission very often simply dies. A solar array that does not unfold cannot power the spacecraft; an antenna that jams half-open cannot talk to Earth. There is no astronaut to give it a shove, no way to fold it back and try again. The mechanism must work the first time, perfectly, after the violence of launch and the deep cold of space, having sat folded and motionless perhaps for years. An astonishing amount of spacecraft engineering goes into these moments of unfolding, and when I ranked the entire class of spacecraft patents by how heavily later inventions cited them, the deployment mechanisms rose conspicuously to the top — a sign of how central, and how hard, this problem is.

The single most-cited in that cluster is a small and beautiful thing: TiNi Alloy Company's "release device for retaining pin" (US 5,771,742, granted 1998). It addresses the delicate business of holding everything folded securely through launch and then releasing it cleanly on command in orbit — the trigger of the origami. Many such devices exploit an almost magical class of materials, shape-memory alloys, which can be deformed and then made to snap back to a remembered shape when heated, providing a controlled, shock-free release without the violence of an explosive bolt that might damage delicate structures nearby. Alongside it in the rankings sat inventions for the unfolding itself — Astro Aerospace's "foldable low concentration solar array" (US 5,520,747, granted 1996), which is exactly what it sounds like: a large solar array engineered to fold

compactly for launch and open reliably in orbit. Both patents are long expired; the art of packing a spacecraft small and opening it large is now common property.

THE UNFOLDING THAT RUNS THE SPACE AGE

Watch a satellite reach orbit and come to life, and what you are watching is this: the careful, sequenced, irreversible unfolding of a machine that travelled folded. The solar wings swing out and lock; the antennas deploy; the booms extend. Every one of those motions is a mechanism that had to work the first time, and the engineering behind them — the hold-downs, the releases, the hinges, the springs, the shape-memory triggers — is some of the most quietly ingenious in all of spaceflight. It is also, now, some of the most freely available, its foundational patents expired, surfaced from the public record by their own influence. The origami of spacecraft, once guarded, is ours to fold and unfold as we please.

CHAPTER 10

POWER IN THE DARK

A spacecraft needs power to do anything at all — to run its computer, warm its instruments, turn its radios, fire its thrusters, unfold its origami. And out beyond the reach of any wire, it must make that power itself, from what little the universe offers. For most spacecraft, near enough to the Sun, the answer is sunlight; and turning sunlight into electricity in space is a problem the space age both depended upon and dramatically advanced.

WINGS OF GLASS

The solar cell — a slice of semiconductor that turns light directly into electricity — was not invented for space, but space became its most important early proving ground and its most demanding customer. Down on Earth, in the mid-twentieth century, solar cells were a costly curiosity. In orbit, where there is no fuel to burn and no

wire to plug into but sunlight is endless and unfiltered, they were transformative, and satellites became one of the first places solar power was not merely viable but essential. The great folding wings of a modern satellite or space station are vast arrays of solar cells, drinking sunlight and turning it into the electricity that keeps the machine alive.

But sunlight in space is not a steady, tame thing, and using it well is harder than simply pointing a panel at the Sun. When I ranked the spacecraft patents by influence, the management of solar power surfaced strongly — not the cells themselves so much as the cleverness of using them. General Electric's "solar array output regulator using variable light transmission" (US 5,289,998, granted 1994) is a characteristic example: a means of regulating the power a solar array delivers, taming the raw, variable output of sunlit panels into the steady, controlled electricity a spacecraft's systems need. It is the kind of unglamorous power-conditioning engineering on which everything else silently depends, and its high citation count reflects how many later designs had to solve the same problem. It, too, is long expired and freely available.

WHEN THE SUN GOES OUT

There remains the hardest case: what to do when there is no sunlight at all. A spacecraft passing into a planet's shadow, or voyaging out to the dim cold of the outer solar system where the Sun is a bright star

and little more, cannot rely on solar power. For orbiting craft, the answer is batteries, charged in the sunlight and drained in the dark, cycling endlessly. For the great deep-space probes that journey beyond the reach of useful sunlight, the answer is stranger and more wonderful: a nuclear battery, a radioisotope thermoelectric generator, which makes electricity from the heat of slowly decaying radioactive material and needs no light at all. It is such generators, warm with their own decay, that still power the Voyager probes as they drift beyond the edge of the solar system, whispering back to Earth decades after launch, their nuclear hearts the reason they can speak at all. From folding wings of glass to a warm lump of decaying atoms, the problem of power in the dark has many answers, and the space age advanced nearly all of them — and, patent by expired patent, gave them back.

CHAPTER 11

THE STEADY GAZE

A satellite that cannot control which way it is pointing is very nearly useless. A communications satellite must keep its antennas aimed precisely at the Earth; an observation satellite must hold its cameras steady on their target; a solar array must be turned to face the Sun; a telescope in orbit must fix its gaze on a distant galaxy and hold it, unwavering, for hours. And all of this must be done in the frictionless freedom of space, where there is nothing to push against, where the smallest disturbance sets a spacecraft slowly tumbling and nothing will ever stop it turning unless the spacecraft itself acts. The problem of holding, and changing, a spacecraft's orientation is called attitude control, and it is a subtle and beautiful corner of engineering.

PUSHING AGAINST NOTHING

The difficulty is that in space there is nothing to brace against. On

Earth you turn by pushing against the ground; a boat turns by pushing against water, a plane against air. A spacecraft floating in vacuum has none of these. It must turn itself by internal means, borrowing from the deep physics of spinning things. One elegant approach uses the gyroscopic principle we met in the guidance chapter, but in reverse — instead of using a spinning wheel to sense orientation, use spinning wheels to change it, speeding them up or slowing them down so that, by the conservation of angular momentum, the spacecraft turns in response. Another approach, for a satellite near the Earth, is subtler still: use the planet's own magnetic field. Run current through coils aboard the satellite to create a magnetic field, and it will push gently against the Earth's field, exactly as a compass needle feels a turning force — a way to nudge a spacecraft's orientation using nothing but electricity and the invisible magnetism of the planet below.

Both ideas surfaced when I ranked the spacecraft patents by influence. Recon/Optical's "gyroless platform stabilization techniques" (US 5,124,938, granted 1992) addresses holding a platform steady without relying on conventional spinning-gyroscope hardware — keeping the gaze fixed by other means. And reaching further back, RCA Corporation's "magnetic torquing system for changing the spin rate" (US 4,114,841, granted 1978) is a foundational expression of exactly that trick of pushing against the Earth's magnetic field to control a satellite's spin. That this last patent dates from 1978 — and has therefore been in the public domain

since the 1990s — is a reminder of how deep the roots of this quiet art run. Both are long expired.

THE UNWAVERING EYE

Every crisp satellite photograph, every uninterrupted phone call routed through space, every long exposure of a distant galaxy by an orbiting telescope, depends on a spacecraft holding its attitude with exquisite precision — pushing against nothing, steadying itself by spinning wheels and magnetic nudges and the careful exploitation of physical law. It is invisible work, noticed only when it fails, and the foundational techniques for doing it are, now, freely available to all — surfaced from the record by the field's own citations, their patents long expired. The steady gaze of every spacecraft is built on knowledge that belongs to everyone.

PART FIVE — THE SKY FULL OF SATELLITES

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CHAPTER 12

THE SATELLITE THAT STANDS STILL

There is a particular ring in space, a little over thirty-five thousand kilometres above the equator, that is one of the most valuable pieces of real estate in the solar system — and its value rests on a single, elegant coincidence of physics. At that exact altitude, a satellite orbits the Earth in precisely the time the Earth takes to turn once: twenty-four hours. And so, from the ground, such a satellite appears to hang motionless in the sky, fixed above one spot on the equator, neither rising nor setting. It stands still. This is the geostationary orbit, and it made possible the entire age of satellite communication.

THE IDEA BEFORE THE MACHINE

The idea came, remarkably, from a science-fiction writer. In 1945, Arthur C. Clarke — years before any satellite of any kind had flown — described in a technical article how satellites placed in that

special orbit could relay radio signals around the world, and pointed out the beautiful economy of it: because each such satellite could see nearly half the globe and stayed fixed in the sky, just three of them, spaced evenly around the equator, could blanket almost the entire planet with communications, always in view, never setting. It was a complete vision of global satellite communication, sketched before the technology existed to build any part of it.

Turning that vision into a working machine fell, most decisively, to an engineer named Harold Rosen and his team, who in the early 1960s built the satellites that proved it could be done. The first attempt, launched in early 1963, was lost to a failure; but the second, later that same year, succeeded and became operational — the first satellite to demonstrate the practicality of the geostationary orbit. Its successors quickly showed the world what it meant: a live two-way telephone call between heads of government relayed through space, and, in 1964, live television carried across the Pacific from the Tokyo Olympics, images of the Games arriving in distant living rooms by way of a machine hanging motionless above the equator. The world had, quite suddenly, been wired together through the sky.

THE RING THAT CONNECTED THE WORLD

For decades, the geostationary ring was the backbone of global communication — the path of international phone calls, of television distribution, of data across oceans. To sit still above the Earth,

always in view, was to be the perfect relay station in the sky, and the satellites that did it grew into vast and sophisticated machines.

Clarke's foundational vision was published, not patented — he gave it freely, and later wryly noted the fortune he might have made had he tried to own it. The engineering that realised it, Rosen's and his successors', has aged into history and expired patents. The satellite that stands still, once a science-fiction dream and then a Cold War marvel, is now simply part of the furniture of the world, its founding ideas long since common property.

CHAPTER 13

A CONSTELLATION FOR THE REST OF US

The satellite that stands still has one inescapable drawback, and it is a consequence of the very altitude that lets it hang motionless. To appear fixed in the sky, a geostationary satellite must orbit more than thirty-five thousand kilometres up — a vast distance, and radio signals, fast as they are, take a noticeable time to cross it and come back. For television or one-way broadcast this hardly matters. But for a live telephone conversation, that round trip adds a delay long enough to be heard, an awkward pause that makes natural back-and-forth talk strangely difficult. And a signal that has travelled so far is faint, demanding large antennas to catch it. The satellite that stands still is a magnificent broadcaster and an awkward telephone.

BRINGING THE SATELLITES DOWN

The alternative is to bring the satellites much lower — into orbits

only hundreds or a couple of thousand kilometres up, where the signal delay shrinks to something imperceptible and a small handset can reach them. But a lower satellite pays a price for its closeness: it no longer hangs still. It races across the sky and is gone over the horizon in minutes. To provide continuous service from low orbit, then, you cannot use three satellites standing still; you need many satellites moving in a carefully arranged fleet — a constellation — handing each user off from one satellite to the next as they pass overhead, so that there is always one in view. It is a far more complex idea than the geostationary ring, and it became one of the defining architectures of modern space.

This is a domain where the spacecraft-patent data speaks clearly, because the companies that chased it patented heavily, and later work cited them heavily in turn. Space Systems/Loral's "wireless telephone/satellite roaming system" (US 5,303,286, granted 1994) was among the most-cited spacecraft patents of all in my ranking — foundational work on letting a wireless phone connect through satellites and roam seamlessly between them and the ground. TRW's "medium-earth-altitude satellite-based cellular telecommunications" (US 5,433,726, granted 1995) staked out the middle-orbit approach to global mobile telephony. And Orbital Sciences' "method and apparatus for deploying a satellite network" (US 5,199,672, granted 1993) addressed the sheer logistics of getting a whole constellation into orbit and arranged. All are long expired.

THE SKY BELONGS TO EVERYONE NOW

These early constellations were, in their first commercial forms, famously ahead of their time — grand, expensive visions of global satellite telephony that arrived before the market and the economics were ready, and several of their pioneers foundered. But the architecture they invented — many small satellites in low orbit, working as a coordinated fleet to blanket the Earth — is precisely the architecture now being built out, on an enormous scale, to bring internet access to every corner of the planet from constellations of thousands of satellites. The pioneers proved the idea and mostly did not profit from it; the foundational patents, surfaced by the data and confirmed by their influence, have expired into the public domain. The idea of a constellation for the rest of us — a fleet of satellites low enough to reach with something in your hand — belongs, now, to everyone who would build one.

CHAPTER 14

KNOWING WHERE YOU ARE

Of all the gifts that spaceflight has given to ordinary life, none is used more constantly, by more people, with less thought, than the ability of a small device in your pocket to tell you exactly where you are standing on the surface of the Earth. It is so woven into daily life — the map that knows your position, the route that guides your car, the timestamp on a transaction — that its sheer strangeness is easily missed. You are being located, continuously, to within a few metres, by a fleet of atomic clocks flying thousands of kilometres overhead. This is satellite navigation, and it is one of the most quietly astonishing systems humanity has ever built.

TELLING TIME TO TELL PLACE

The principle beneath it is subtle and beautiful, and it comes down, surprisingly, to telling time with fantastic precision. High above the

Earth orbits a constellation of satellites, each carrying an atomic clock of extraordinary accuracy, each constantly broadcasting a signal that says, in effect, this is exactly who I am and exactly what time it is. A receiver on the ground — in your phone, your car — listens for these signals from several satellites at once. Because radio waves travel at a known, finite speed, the tiny differences in how long each satellite's signal takes to arrive tell the receiver exactly how far away each satellite is. And knowing your precise distance from several objects whose positions you know allows you, by geometry, to pin down your own position — the one point on Earth consistent with all those distances at once. Navigation, in the end, is a triumph of measuring time: locate yourself by listening to a chorus of flying clocks and noticing, to the billionth of a second, which reached you first.

The system was born, like so much in this book, of military need — built to guide forces and weapons with precision — and then, in one of the great acts of technological generosity, opened to civilian use, its signals made freely available to anyone on Earth with a receiver. That decision transformed the world. An entire universe of everyday technology grew up in the space it opened: the navigation in every phone and car, the tracking of ships and aircraft and parcels, the precise timing that quietly synchronises power grids and financial systems and communication networks, which depend on the system's atomic clocks far more than most people ever realise.

THE CLOCKS THAT GUIDE US ALL

There is a fittingly cosmic irony in satellite navigation, one that speaks to the whole spirit of this book. To know where you are on the ground, you look up — to a fleet of clocks in orbit, descendants of the whole long effort to leave the Earth, now bent back toward serving the people who never will. The system is a public utility of the sky, its signals a global commons freely given to all humanity, its foundational technologies aged into the ordinary infrastructure of the world. The ability to know exactly where you are — once the jealously guarded advantage of a superpower's military — is now the birthright of anyone holding a phone. It is, perhaps, the purest example in this entire book of a technology that left the Earth and then came home to everyone.

PART SIX — THE GIFTS HOME

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CHAPTER 15

THE EYE THAT CAME HOME

Every photograph you have ever taken on a phone, and very nearly every digital image made anywhere on Earth, depends on a way of turning light into electricity that was perfected, in large part, to let machines see across the void of space. The digital eye is one of the great gifts spaceflight gave back to ordinary life, and its story runs straight from the cameras that photographed distant planets to the one in your pocket.

CLEANING UP THE VIEW FROM FAR AWAY

The problem began with distance. When the first probes sent back pictures from across the solar system, those images arrived faint, noisy, and degraded — smeared by the vast journey and the limits of the equipment. To recover the worlds hidden in that noise, engineers at places like the Jet Propulsion Laboratory had to invent ways of

cleaning up images mathematically: taking a blurred, speckled, imperfect picture and, through computation, sharpening it, removing the noise, correcting the distortions, pulling a clear world out of a murky signal. This was the birth of much of modern digital image processing — the mathematics of improving a picture after it is taken — and it was driven, in its early days, by the sheer necessity of seeing clearly across interplanetary distances.

Then came the sensor itself. To capture an image electronically rather than on film, you need a device that turns a pattern of light into a pattern of electrical signals, and one of the great inventions that did this was the charge-coupled device, or CCD, developed at Bell Labs at the end of the 1960s — an achievement that would later earn its inventors a share of a Nobel Prize. A CCD is a grid of tiny light-sensitive elements, each of which accumulates an electrical charge in proportion to the light falling on it; read out that grid of charges and you have a digital picture. It was a way of giving a machine an electronic eye. And space was one of its most transformative applications: film cannot be radioed home from Mars, but an electronic image can. The CCD let spacecraft see and send what they saw, and it became the eye of space telescopes and planetary probes, returning images that reshaped our understanding of the cosmos.

THE EYE IN YOUR POCKET

The line of descent from that space-borne eye to the one you carry is direct. The digital image sensor developed and proven in the demanding environment of spaceflight and astronomy is the ancestor of the sensor in every phone camera, every digital camera, every webcam on Earth. The mathematics of cleaning up a faint image from a distant probe is kin to the processing that sharpens and brightens your snapshots automatically. An entire visual culture — billions of images made and shared every day — grew from technologies substantially advanced to let machines see across space. The foundational patents of the digital image sensor have expired; the founding inventions are public knowledge. The eye built to look outward, into the dark between the worlds, came home and multiplied into billions, and now looks at everything. It is, like the flying clocks of the last chapter, a gift from the effort to leave the Earth, handed quietly back to everyone who stayed.

CHAPTER 16

THE THINGS THAT CAME HOME

We have followed the machines that left the Earth — the staged rockets, the guidance that knew its own motion, the computer woven by hand, the shield that burned to bring crews home, the gold blanket and the wearable spaceship, the folding wings and steady gaze of satellites, the ring that stands still and the constellation that races, the flying clocks and the digital eye. It is fitting to end not by looking further out, but by looking down — at everything the effort to leave sent back.

THE ARGUMENT IN THE OBJECTS

There is an old and slightly weary argument about whether the money spent on spaceflight might have been better spent on Earth, and it is not the purpose of this book to settle it. But any honest accounting has to reckon with the sheer quantity of technology that

flowed back down from the effort to go up — not as a justification, exactly, but as a fact. The relentless miniaturisation of computing, pushed in its infancy by the Moon programme's hunger for something small enough to fly. The digital image sensors that became every camera. The satellite navigation that guides every journey and times every transaction. The satellite communication that carried the connected world before the undersea cables caught up. And a long, almost folkloric list of smaller spin-offs — advances in materials, in water purification, in medical monitoring, in insulation, in the preservation of food, in countless quiet corners of industry — many of them refined, if not born, in the impossible demands of keeping fragile machines and fragile humans alive in space.

The point is not that every domestic gadget came from a rocket; that story is often overstated and sometimes plainly wrong. The point is subtler and more interesting. Spaceflight was a forcing function — a problem so extreme, so unforgiving of weight and failure and waste, that solving it dragged whole fields of engineering forward faster than they would otherwise have gone, and much of that acceleration flowed straight back into ordinary life. To make a machine survive the void, you had to make it lighter, smaller, more reliable, more efficient, more self-sufficient than anything before — and those virtues, once achieved, are useful everywhere.

THE FENCE ABOVE THE SKY COMES DOWN

And here, at the last, is the thread that ties this volume to its companions and to the whole idea behind them. Every technology in this book — the rocket stage and the heat shield, the folding array and the standing satellite, the guidance computer and the flying clock — was, in its time, guarded. Fenced off by patents, held as the property of a government or a corporation or a Cold War programme, available only to the powerful and the well-funded. Goddard's rockets, the integrated circuit, the geostationary satellite, the deployment mechanism, the thermal system, the spacesuit cooling — each was, for its twenty years, someone's exclusive right, the reward for the risk of inventing it.

And each, on its own quiet and unannounced morning, has had its fence taken down. The patents have run out their term, one after another, and the machinery of leaving the Earth has passed, filing by filing, into the public domain. The specific knowledge of how to reach orbit, how to survive the void, how to unfold a spacecraft and steady its gaze and hang it motionless above the equator — knowledge that was once the jealously kept advantage of superpowers — now belongs to everyone alive. It is one of the reasons that reaching space, once the sole preserve of two vast Cold War states, is now within the grasp of small companies, of universities, of nations that never dreamed of it, of anyone with the will and the means to build on the freely published foundations.

That is the deepest meaning of the phrase this series keeps returning

to. The patent is not a wall but a gate with a timer. Everything behind it is on its way, by design, to becoming ours. The effort to leave the Earth was among the greatest and most guarded undertakings in human history — and its knowledge, in the end, has come home to all of us, published and free, the fence above the sky quietly coming down. We spent a century learning to leave our world. The learning, now, belongs to everyone who looks up.

A NOTE ON SOURCES AND METHOD

This book is a hybrid, and it is worth being honest about how it was made. Some of its chapters were drawn from data: I harvested the entire class of spacecraft patents — the classification the patent system uses for cosmonautics and space vehicles — from the complete public patent record, and ranked them by how many later inventions cited each one, a rough but honest measure of influence. The deployment mechanisms, thermal systems, solar-power regulators, attitude-control methods, and satellite architectures highlighted in these pages surfaced from that ranking, and the specific patents named — among them TiNi Alloy's release device (US 5,771,742), Astro Aerospace's foldable solar array (US 5,520,747), Midwest Research Institute's compact vacuum insulation (US 5,175,975), Isothermal Systems Research's spray cooling (US 5,220,804), United Technologies' spacesuit cooling (US 5,092,129), General Electric's solar array regulator (US 5,289,998),

Recon/Optical's gyroless stabilization (US 5,124,938), RCA's magnetic torquing (US 4,114,841), Space Systems/Loral's satellite roaming (US 5,303,286), TRW's medium-earth satellite telephony (US 5,433,726), and Orbital Sciences' network deployment (US 5,199,672) — are all real, all drawn from the public record, and all long expired.

Other chapters — the rocket pioneers, the Moon computer, the heat shield, the geostationary satellite, satellite navigation, the digital eye — are told from history rather than from any single patent, because the largest stories of spaceflight are carried by many hands and no one filing captures them. Goddard's foundational rocket patents (US 1,102,653 and US 1,103,503, both 1914) are real and long in the public domain. The historical accounts — of Tsiolkovsky and Goddard, of the integrated circuit and the Apollo Guidance Computer and Margaret Hamilton's software team, of Arthur C. Clarke and Harold Rosen and the Syncom satellites — are drawn from widely available published sources and reflect the author's best understanding. Where I have simplified the science or rounded a date, I have tried not to distort; the specialist will find more detail, and the occasional correction, in the primary sources, and is encouraged to seek them out. Nothing here is engineering advice.

The deeper argument is the one that runs through the whole series. A patent is not a wall but a gate with a timer set upon it. Everything held behind it is on its way, by design, to becoming ours. The

machinery of leaving the Earth is one long, vivid demonstration of that passage — a body of knowledge, once guarded by superpowers, now published and free — and this book has been an attempt to stand on the far side of it and watch the fence above the sky come quietly down.