Digital Apollo:

Human and Machine in Spaceflight

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1 Human and Machine in the Race to the Moon

A July Day on the Moon

On a July day in 1969, after a silent trip around the far side of the moon, the two Apollo spacecraft reappeared out of the shadows and reestablished contact with earth. The command and service module (CSM) (sometimes simply "command module") was now the mother ship, the capsule and its supplies that would carry the astronauts home. The CSM continued to orbit the moon, with astronaut Michael Collins alone in the capsule. "Listen, babe," Collins reported to ground controllers at NASA in Houston, "everything's going just swimmingly. Beautiful." His two colleagues Neil Armstrong and Edwin "Buzz" Aldrin had just separated the other spacecraft, the fragile, spidery lunar module (LM, pronounced "lem"), nicknamed Eagle, from the command module. This odd, aluminum balloon, packed with instruments and a few engines, would carry the two men down to the lunar surface.

A rocket engine fired to slow the LM, causing it to fall out of orbit. Once on its way down, the spacecraft would either execute a dangerous abort or soon hit the moon. Whether the impact was a landing or a crash depended on the next ten minutes—the longest continuous series of critical events in the entire mission.

In the LM, weight was such a premium that seats had been eliminated altogether. The astronauts stood up, stabilized by tensioned cables connected to the floor. The spacecraft was an enclosing home, complementing the astronauts' bodies. It supplied their food, exchanged their gases, and collected their wastes. The human occupants, in turn, controlled flows of the spacecraft's numerous fluids, drinking some for hydration and carefully igniting others for propulsion. An inertial navigation system—accelerometers wedded to precisely spinning gyroscopes—measured the vehicle's motions. A radar reached an invisible beam down to sense the first approach of the moon's surface, like a blind man's stick tapping for a curb.

Tying the whole thing together was an embedded digital computer, made out of exotic devices called "integrated circuits"—silicon chips, running a set of esoteric programs. In the middle of the instrument panel, amid familiar dials and switches, stood the computer interface, a numeric keypad glowing with segmented digits. Throughout the mission the astronauts punched in numbers, ran programs, and read the displays. Much of the landing was under direct control of these programs. Neil Armstrong, when he did fly, did not command the spacecraft directly, but rather used two control sticks to command the computer, whose programs fired the thrusters to move the LM. Every move was checked and mediated by software, written by a group of young programmers half a world away.

Nor was the LM alone with its computer, for the command module had an identical computer of its own; both were linked to Houston's control center. Down in Houston, numerous experts monitored systems, offered advice, and controlled some parts of the flight (they even had a remote computer keypad for entering commands directly into the computer in either of the two spacecraft). Communication between the three nodes was calm, matter-of-fact conversation, the precise technical banter of professionals, with an audience of millions.

As the LM began to descend the ground controllers focused their attention. Mission Control locked its doors.

Suddenly, the LM lost contact with Houston. The main antenna that carried data and voice communications to NASA's control center in Houston was having problems. It had to point directly at the earth to work, but other parts of the spacecraft blocked the path, so a computer-controlled feedback loop was commanding the antenna to "hunt" around to seek a new orientation. Aldrin intervened, turned off the automatic control, and adjusted the antenna by hand. The imperfect communications now required Aldrin's attention to keep on track. Frustrated flight controllers in Houston strained through the noise to hear the astronauts, struggling to piece together a continuous story from intermittent bursts of data. "This is just like a simulation," one controller observed on the intercom. Indeed, the performance had been rehearsed, countless times in countless variations, in computer-controlled virtual simulations on the ground.

The astronauts stood in a high state of tension. Their attention was a scarce resource, and any increase in the "workload" could cause them to lose control of the situation. Indeed, for Armstrong the faulty communications detracted from the intense focus of his task.

Uncertainty and ambiguity: on one hand, the astronauts were in control, piloting an autonomous machine far from home; on the other hand, they were part of a network of communications channels, human experts, and control centers. Intermittent communications caused Aldrin to oscillate across this borderline: "You didn't know where you were—whether you were on your own, or whether you were still under the close supervision of ground control. And that sort of reality is rarely simulated in training." The engineers who designed the system (including the astronauts themselves) did not anticipate how electrical noise could interfere with this critical control loop, half a million miles long. Still, in the scheme of things, these problems were minor, easily handled by the conservative design of the LM and the calm professionalism of the astronauts.

At 50,000 feet above the moon's surface, the LM rocket engine fired again, the powered descent initiation (or PDI) that would bring the vehicle to the surface. "Throttle up. Looks good!" Aldrin radioed. They were going down. The computer was in control.

Then, as the spacecraft passed 35,000 feet above the moon, an unexpected light flashed on the computer display.

"Program alarm," Armstrong called out, with noticeable concern.

The computer was having a problem, calling the astronauts' attention. Like its users, the machine had a limited amount of workload and the processor was overloaded with data. This problem might not be serious, but at this moment even a benign distraction could cause trouble. The computer restarted itself, Aldrin punched some keys to inquire about the problem, and it indicated alarm code 1202.

"Give us a reading on the 1202 Program Alarm," Armstrong urgently asked Houston. With the push of a button, the astronaut could abort the landing, an action practiced countless times in simulation. Yet he held off. Armstrong later explained himself as a mechanism: "In simulations we have a large number of failures and we are usually spring-loaded to the abort position. And in this case in the real flight, we are spring-loaded to the land position."

Houston checked out the problem. Young engineers recognized it from a recent simulation, and conferred with their support teams in the back room. They quickly found the cause. The computer was overloading and restarting but not shutting down. It was ignoring low-priority tasks, but these were not critical for the mission. "We're go on that alarm," the ground controller replied, meaning the LM could proceed. For his role in clearing the landing, engineer Steven Bales later accepted a presidential award on behalf of the flight control team.

Armstrong surveyed the computer display; it had frozen. He checked the LM's systems. The vehicle seemed to be responding to his commands, meaning the computer was still running. So he continued. But these checks focused his attention inside the cockpit for critical moments when he should have been looking out the window for a landing site.

Now 2,000 feet above the surface, he again looked out the window. There he saw a potential disaster—a large crater stood where the landing area should have been, boulders surrounding its rim. In that moment Armstrong quit being a computer operator and became a pilot. He seized control of the spacecraft from the computer and flew the LM past the crater. The move took precious additional seconds, and ground controllers became concerned the LM would run out of fuel. Armstrong knew the limits, however, and guided the vehicle down. When the computer sensed the LM was a few feet off the moon Armstrong hit a button and shut off the engine. The LM fell the last few feet with a gentle thud. Aldrin called out the descent systems' shutdown sequence: ''Mode control: both auto. Descent engine command override: off. 413 is in.''

Relieved, Armstrong then chimed in with his definitive line of technical poetry: ''Houston, Tranquility Base here. The Eagle has landed.''

Human and Machine

The Eagle's landing is a familiar story, one of the great technological mythologies of the twentieth century.[1] I have retold it here by emphasizing elements that usually hide in the background: the interaction between human and machine, the role of the computer in mediating the astronauts' responses, the network of connections in space and on the ground (figure 1.1). Frequently mentioned but rarely analyzed, these relationships lie at the core of manned spaceflight since its inception, and they continue to frame questions surrounding our proposed future in space.

Figure 1.1
Jim Lovell on Apollo 8 aligning the optics for the Apollo guidance and control system. His left hand controls the spacecraft's attitude, while his right hand points the optics. (NASA JSC photo S69-35097.)

Human and machine: their relationship is not a new story. Indeed, it is one of the great narratives of the industrial world, from the mythical John Henry, who won a race with a steam drill at the cost of his life, to Charles Lindbergh, who used the word "we" to describe his partnership with his aircraft.[2] Even during the 1960s, scholars and philosophers debated the appropriate trade-offs between automatic systems and human skills. Yet the many accounts of space travel have failed to explore this profound part of the venture. This book tells the story of the relationship between human and machine in the Apollo project and how that relationship shaped the experience and the technology of flying to the moon. It is a story of human pilots, of automated systems, and of the two working together to achieve the ultimate in flight. It is also a story of public imagery, professional identities, and social relationships among engineers, pilots, flight controllers, and many others, each with their own visions of spaceflight.

To engage the nation, NASA's publicity machine drew on age-old American icons of control and mythologies of individuality and autonomy, from cowboys to sea captains.[3] Apollo's astronauts shared their title with the men who plied the great riverboats down the Mississippi: they were pilots. From the beginnings of aviation up through Apollo and the spaceflight of today, the identity of the aviator-pilot shaped, and was shaped by, technologies of flight.

For Apollo, NASA and its contractors built a "man-machine" system that combined the power of a computer and its software with the reliability and judgment of a human pilot. Keeping the astronauts "in the loop," overtly and visibly in command with their hands on a stick, was no simple matter of machismo and professional dignity (though it was that too). It was a well-articulated technical philosophy. It was also necessary to achieve the political goals of the space program and show that the classical American hero—skilled, courageous, self-reliant—had a role to play in a world increasingly dominated by impersonal technological systems (especially in contrast to the supposedly over-automated Soviet enemy).

That technical philosophy reflected policy making at the highest levels. When NASA administrator James Webb argued for the project, he cautioned that the decision "can and should not be made purely on the basis of technical matters," but rather on the "social objectives" of putting people into space. He and Secretary of Defense Robert McNamara argued that, "it is man, not merely machines, in space that captures the imagination of the world."[4] Presidential science advisor Jerome Wiesner famously opposed a manned lunar program because its scientific goals did not justify the cost. The debates leading up to Kennedy's decision distinguished between "exploration," which is manned, and "science," which has higher intellectual prestige value but is best conducted remotely.[5]

Yet the grammar of President Kennedy's 1961 call to action contained an ambiguity. "Achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the earth,'' made the astronaut a passive participant.[6] Indeed, NASA made an early, radical decision to use a digital computer, a ''thinking machine,'' in the Apollo capsule that would control much of the flight. The computer design and its software then reflected a philosophy of automating the fights while not actually replacing the astronauts.

In the end, the astronauts ''flew'' a very small part of the total mission by themselves, but their control included critical moments of the lunar landing (as well as rendezvous and docking)—landing having long been the ultimate expression of a pilot's skill. Even then, the astronauts controlled the lander indirectly: unless in an emergency mode, their sticks actually commanded a software program, which then controlled the vehicle. Software, a concept barely understood at the start of Apollo, became critical during its development. The programs had the ability to bring the LM right down to the lunar surface under automatic control. They could also crash and kill the astronauts if they went wrong.

Despite the automation, on each of the six Apollo landings the astronaut in command took control and landed in a manual mode. This book explores why.

Chapter 2 begins by examining the anxieties surrounding the role of aircraft pilots in the 1950s. Professional test pilots debated human-machine interactions in the years just before human spaceflight as a host of new technologies—from electronic flight controls to computers in the cockpit—both mediated their control of the machine and gave them access to new realms. When the shock of Sputnik launched the space age in 1957, pilots pondered their potential role in this new era. The X-15 rocket-plane, the subject of chapter 3, sought to prove that human skill and judgment would be required for at least one phase of spaceflight: reentry from space back into the atmosphere. Pilots mastered reentry with the help of computers that augmented their skills and stabilized their flight.

In the wake of the Sputnik scare, NASA was created out of the National Advisory Committee on Aeronautics (NACA) and a variety of federal research groups, and chapter 4 follows pilots into the space age. X-15 test pilots like Neil Armstrong proclaimed that human operators could manually fly the huge new rockets directly off the launch pad and on toward the moon. The powerful Wernher von Braun had an alternative vision, of rockets as automata, carrying passive human cargo. His idea would overrule the astronauts' desire to fly off the pad.

Yet pilots had new powers of their own. The Project Mercury astronauts sparked intense public interest in human spaceflight and immediately pressed for their vision of professional identity, heroism, and control. Arguments over ''spam in a can'' and the amount of control appropriate for the human cargo ran throughout the Mercury project. Engineers working on the project, who would go on to form the core of the Apollo team, had long experience studying human-machine interactions in aircraft. They held pilots in high regard, relished a close collaboration, and spent years flying and testing dangerous machines. Project Mercury's successor, Project Gemini, epitomized the pilot-centered approach, enabling hands-on control of orbital maneuvers. The complexity of rendezvous operations, however, also called for computational aids, from paper charts to digital computers.

The Apollo program began with the new Kennedy administration and its recognition of the public, political impact of human spaceflight. Kennedy's speech launching the moon program came just weeks after the suborbital flight of Alan Shepard, who was hailed as a space-age Charles Lindbergh. Yet the first contract of the new moon program was let not for rocket engines or fuel tanks or launch pads, but for a computer, the subject of chapter 5. Engineers at MIT's Instrumentation Laboratory, who would build that computer, in the 1930s had helped change the nature of flight from "seat of the pants" intuition to numerical, instrument-based tasks. Their Apollo proposal derived from a Mars probe, designed but never built, and from the inertial guidance system for the Polaris nuclear missile. The MIT engineers valued accuracy and autonomy and studied how a set of gyroscopes could find its way to the moon and back.

But the Apollo system had a human user, someone who would require an "interface" to issue commands and requests to the computer and read out information. This requirement raised a series of difficult, interesting problems. The machine would have to be much more reliable for the two-week lunar missions than for a missile's short flight. It would interact with two planetary bodies instead of one, and two spacecraft instead of one. It would need to be calibrated against the stars by a human user. And if it failed, people might die. Chapter 6 follows the Apollo computer as it became operational hardware and recounts its designers' decisions about human interface, reliability, and manufacturing.

Exotic as it seemed, the hardware adapted for Apollo was relatively familiar in the world of military avionics. Radically new, however, was the software that would interact with the astronauts to control the mission, the subject of chapter 7. At first, programming was treated as a secondary, almost trivial task, but by 1966, it seemed the early Apollo flights might be delayed for lack of available computer programs. Only the 1967 Apollo 1 fire that killed three astronauts and NASA's management intervention into the programming team brought the software project under control and on schedule. Early, unmanned Apollo flights revealed the delicate mix of reliability, flexibility, and accountability that would surround these new, software-controlled systems.

The entire Apollo program culminated in the landing. The final ten or so minutes before touchdown formed the most critical period of the mission. The remainder of the book examines the design and execution of the lunar landings. Chapter 8 describes the plans for this phase of the flight, incorporating fundamental physics, lunar models, computers, human performance, and a host of uncertainties, including questions about the human role. From 50,000 feet down, the LM made the transition from purely inertial guidance to include radar and the human eye. To allow the astronauts time to visually assess their landing site, the maneuver's design had to incorporate detailed consideration of human capabilities. Automatic systems would fly the LM down to an altitude of a few hundred feet, where the commander could take over semi-automatic control and bring the LM down with his hands on a stick.

The final chapters go through each of the landings and the interactions between the astronauts and their machinery, and with their colleagues on the ground. The minute details afforded by transcripts and data telemetry allow a kind of real-time ethnography, a thick description of human-machine interactions and their cultural context during critical operations.

Each of the landings stood out in some dimension. Chapter 9 dissects Apollo 11 and the famous ''Program Alarm'' that began this chapter to examine risk, responsibility, and error in the distributed software-based system. Chapter 10 looks at the remaining landings. As they progressed, the technical task lost some of its challenge and uncertainty, while the scientific goals of the program took greater prominence—hence the later missions landed in geologically more interesting, but tactically more difficult, areas.

The final chapter of the book extends the analysis to the broader history of human spaceflight in America and follows some threads from the Apollo story into today's world. Human-machine relationships in Apollo had significant implications for the space shuttle, and hence for decades of American space policy. Reframing the ''humans versus robots'' debate into one that is richer and more forthright about both human and remote presence and their social implications is crucial for U.S. space policy as it faces the space shuttle's retirement and a possible return to the moon or human venture to Mars.

Rethinking Apollo

Flying to the moon was among the most notable technological achievements of the entire twentieth century, or at least the most noted. Even today, scan the culture for references to the Apollo program and you'll it everywhere: from clips in music videos (music television network MTV's first moments of broadcast in 1981 were a picture of Buzz Aldrin on Apollo 11 superimposed with the MTV logo; the icon remains the basis for the network's Video Music Award statuette) to repeated calls for a new Apollo project to solve one or another of society's ills. I recently looked up from my seat on a subway to see the Apollo motto, ''For All Mankind,'' emblazoned on the derriere of a pair of designer jeans.

Even a casual bibliography has hundreds of entries. Ever conscious of its public image, NASA documented and wrote Apollo's own history in parallel with the project itself, producing numerous informative, if ponderous, volumes on everything from the spacecraft to the launch pads and the lunar science experiments.[7] NASA has also conducted hundreds of oral history interviews, from the beginnings of Apollo up to the present day. Those collected during the 1960s provide immediate, primary insights into the project, while those collected more recently document the participants' memories.

Of the twelve men who walked on the moon, at least eight have written, or have had ghostwritten, some kind of memoir, and numerous other Apollo crew members have chimed in as well.[8] Lately the ground controllers have gotten into the act, with similar, though delayed, levels of public interest and attention.[9] One account used interviews with engineers to tell the story of the technical people behind the scenes.[10] A few of Apollo's engineers have added their own stories as well.[11] Numerous other popular accounts cover the project from a variety of angles; one was even made into a TV miniseries, following on the successful feature film *Apollo 13*.[12]

With shelves straining from all this Apollo material, what could possibly be left to say? To begin with, histories of the Apollo program are nearly all project oriented—they begin at Apollo's beginning and end at its end. Other than personal background in memoirs, little is said about Apollo's connection to larger currents in the history of twentieth-century technology. The technical histories focus on hardware and description, with little broader analysis.

Those histories that provide ''context'' tend to be political or cultural, and don't delve into the machines themselves, the people who built them, or what they meant.[13] Hence they solidify the canonical narrative of the project around key themes and events: Kennedy's visionary decision, the frenetic engineering efforts, the triumphs of the astronauts, the tragic fire, the triumph of Apollo 11, the drama of Apollo 13, and so on.

Most Apollo histories adopt a heroic tone, retelling how the skill and cunning of the astronauts, ground controllers, and engineers brought the mission to a safe, successful conclusion, sometimes in the face of bureaucratic incompetence or technical failures. Heroic stories have been with us for a long time, at least since Homer, and play important cultural roles. Heroic narratives follow a prescribed ''cycle,'' with a variety of stages in which the hero matures and proves himself—think of the labors of Hercules, or the island challenges of Odysseus.[14] The astronauts' stories, which vary widely in quality and interest, tend to follow a similar pattern—the boyish fascination with flight, early military service, transition to test piloting, miraculous selection by NASA, rigorous training, climactic moments of judgment and skill at critical points in the flight. Historian Asif Siddiqi calls them ''nosecone histories'' for their limited views of the projects they describe, yet they still carry cultural weight because of the "there I was..." character and the astronauts' lingering heroic public image.[15]

The human-machine relationships of Apollo both reflected and shaped the political and cultural goals of the program and the machines themselves. Sometimes technical decisions threatened the centrality of the human pilot. At other times they left key tasks to human skill and judgment. At no time, however, did some abstract set of technical requirements uniquely define the human role. Engineers and astronauts, as well as journalists and policymakers, constantly debated the appropriate tasks for the spacecrafts' human operators, continuing conversations rooted in the earliest days of aviation.

Aviation Heroism

Michael Collins, who orbited the moon on Apollo 11, remembered being inspired as a young man in the 1930s by the dashing figure of the barnstormer pilot Roscoe Turner. "Roscoe had flown with a waxed mustache and a pet lion named Gilmore," Collins remembered wistfully. "We flew with a rule book, a slide rule, and a computer." His comment captures in one sentence Apollo's relationship to aviation. Collins felt caught between "the colorful past I knew I had missed and the complex future I did not know was coming"[16] (figure 1.2).[17]

Roscoe Turner's career peaked just a few decades before Collins's, but the two seemed worlds apart. Dubbed "Aviation's Master Showman," in the 1920s and 1930s Turner barnstormed his way from rural America to Hollywood. He had little training and even less formal education. Yet he fashioned himself as a colorful character, sporting a waxed mustache and a made-up uniform from a nonexistent military in which he had never served. He was married in the cockpit of his Curtiss Jenny and flew his giant Sikorsky S-29 airplane, dressed up as a German bomber, in Howard Hughes's film *Hell's Angels*. As Collins noted, Turner flew with his pet lion Gilmore, named after the oil company that sponsored them. Turner embodied the showy, excited world of aviation in its "golden age" of transition from dangerous curiosity to commercial service.[18]

Collins was not alone in noting the passage from a hands-on past to a computer-controlled and rule-based future. In the mid-twentieth century, a host of professionals and craftspeople—from industrial managers to shop-floor machinists, from farmers to soldiers—reacted to the advent of computers and automated systems. Yet along with computers came new skills, work practices, and professional identities. Astronauts and their spacecraft were but the most visible manifestation of broad changes that raised fundamental questions: in a world of intelligent machines, who is in control? Can it be "manly" to control a machine by simply pushing buttons? How does software change the equation?

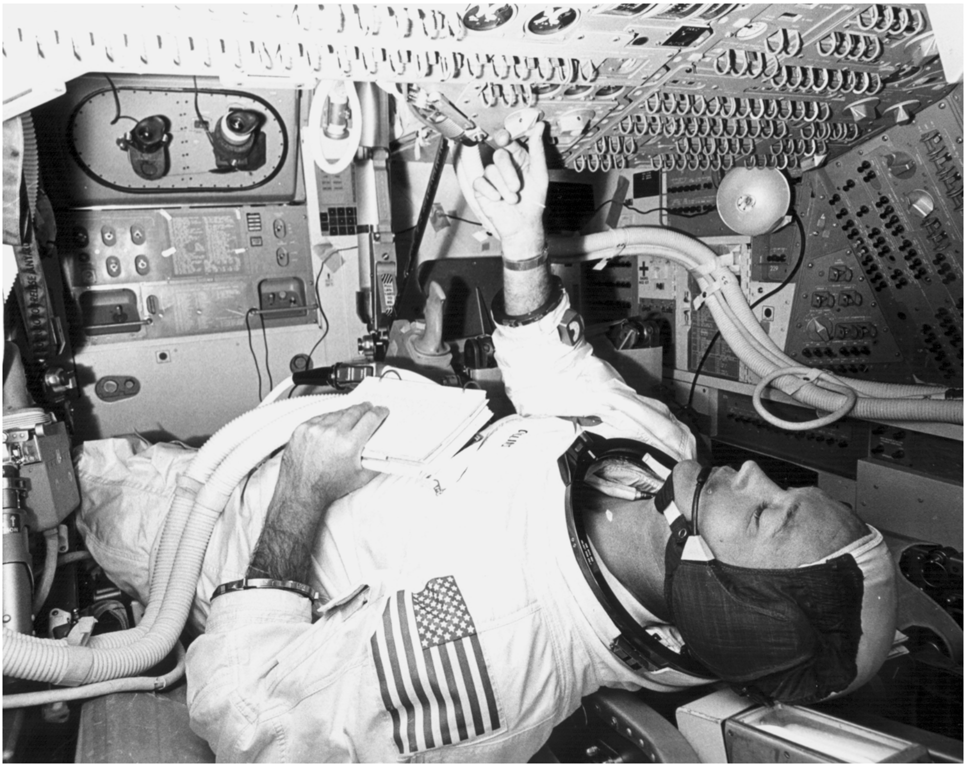

Figure 1.2
Michael Collins training in a command module simulator. Note the checklists in his left hand, the hand controller at his right, and the optical sighting equipment for the Apollo guidance and navigation system at his feet. June 1969. (NASA photo 69-H-978. Scan by Ed Hengeveld in *Apollo Lunar Surface Journal*, http://www.hq.nasa.gov/alsj/frame.html [accessed February 2007].)

Spacecraft and Symbolism

As different as they were, Michael Collins shared one characteristic with Roscoe Turner: both were on display. Turner flew in an age when aviation's commercial potential had yet to be realized, when the airplane remained a dazzling curiosity and most professional pilots earned a livelihood through entertainment. By Collins's day a pilot could make a living with more prosaic tasks like flying airliners; however, the astronauts, like Turner, worked with a technology of unclear civilian utility but whose imagery captivated the attention of the press, the public, and the state.

Put a human being inside a rocket, add the resonance of a journey into the blackness of space with all its allusions to the heavens and the long history of human fascination with the stars, and one has a technology that linked humankind's most earthly, practical endeavors (fuels, oxidizers, pipes, breathing, eating, shitting) to its most lofty ambitions.

None of the symbolic power of spaceflight was lost on the visionaries who promoted the space program, the politicians who supported it, the press who reported it, or the public who consumed the news about it. They very consciously built symbols as well as spacecraft.

In creating that symbolism, the Kennedy administration drew on American imagery of exploration, individualism, and geographical conquest to sell Apollo to the press and to Congress. Kennedy seized on the most powerful mythology in American history, the frontier narrative, and reopened it by aiming for the moon. Within this framing, the endeavor had all the elements of a classic frontier adventure: an unknown, but conquerable geography full of lurking dangers, even villainous antagonists—the competing Soviets.

Most important, the frontier narrative called upon heroic pioneers. The press may have been biased against large government projects (delighting in exposing waste and fraud), but they were heavily biased in favor of individual, human tales. Human presence made spaceflight into a story. For the American public, that story involved people who embodied American virtues, from humility and self-control to self-reliance and creativity, "part Davy Crockett and part Buck Rogers."[19] And for that story to be credible, the astronauts had to be in control. Frontiersmen could not be passengers.

Imagery of active pilots pervaded Apollo, but coexisted with another, subtler trend. The moon project resonated within a culture deeply concerned with the social implications of technology. It was conceived in the wake of Russia's Sputnik success and in the early Kennedy years when large-scale science and technical and managerial projects seemed to promise solutions to political problems. But Apollo unfolded in the era of Vietnam, 1960s counterculture, and increasing questioning of the social benefits of large technological systems. Commentators worried about the phenomenon of "deskilling" as computerized machine tools transformed work on the factory floor.[20] In his speeches and writings, for example, Martin Luther King frequently mentioned automation as a cause of the social displacements he was seeking to redress. Even NASA director James Webb suggested that the jobs generated by the Apollo program would help mollify unemployment created by automation.

The Apollo years spanned the release of Stanley Kubrick's *Dr. Strangelove* (1964), about an automated Soviet machine that triggers the end of the world, and his *2001: A Space Odyssey* (1968), in which an intelligent computer murders American astronauts. Also during Apollo, Jacques Ellul's book *The Technological Society* (published in 1965 in English) challenged the increasing dominance of "technique" in human culture. In 1967 Lewis Mumford named the "megamachine" as the aggregate of technology, social organization, and management that suppressed individual human values.

Philip K. Dick published *Do Androids Dream of Electric Sheep* in 1968 (later made into the film *Blade Runner*), recasting traditional demarcations between humans and machines. Thomas Pynchon's *Gravity's Rainbow* (1973) took "the rocket" as its central literary figure, exploring the technical, psychological, and religious dimensions of a state that worshiped at the altar of technology, and the paranoia engendered by its invisible, clockwork plans.[21]

NASA and its astronauts faced such tensions in the daily engineering of their systems, questions with the potential to undermine the symbolic agenda of the program. Would the exigencies of rockets, supersonic flight, and split-second decisions, not to mention onboard computers, threaten the classical heroic qualities? What tasks were susceptible to human skill, and what was too fast, complex, or uncertain for a human to intervene? How were Apollo designers to engineer a system that had a place for a heroic operator? As Apollo's machines were designed, built, and operated they called the very nature of "heroism" into question. What did it mean to be in control?

Embedded Computers, Embedded Assumptions

A note on terminology raises the stakes. Essentially all of the sources from the 1950s and 1960s use the term "manned" for projects sending humans into space, so I use the term "manned," as the participants did. Similarly, I refer to "men" or "men versus machines" when referring to a particular historical group of men, namely, the Apollo astronauts, who were all men. I use the gender-neutral term "human," however, in reference to abstract notions of human-machine interaction. This approach avoids awkwardness and confusion in the text while highlighting the artificial nature of the "manned" terminology (NASA today uses the awkward and easily misheard term "crewed").

We now know how some scientists studied women's potential as astronauts, but NASA chose all of its early astronauts to be men. This decision may have countered engineering logic: when weight and space are premium, skilled women might make more sense than men, as they are smaller, lighter, and consume less. Yet U.S. experts cited the 1963 Soviet feat of putting a woman in space (two decades before an American woman flew) as evidence that the heavily automated *Vostok* spacecraft did not require a skilled operator. At Lyndon Johnson's suggestion, NASA insisted that astronauts be test pilots qualified in jets, which excluded women by definition. "The very qualifications required for NASA astronauts," argues historian Margaret Weitekamp, "proved the complexity of U.S. space achievements. Demonstrating that a woman could perform those tasks would diminish their prestige."[22]

The role and nature of "men" were very much at stake in the design of Apollo's control systems. Scholars have recently begun to outline the changing faces of masculinity during the last century and the public image of the astronaut certainly played a role in that evolution.[23] Astronauts' accounts continually reaffirm that what it means to be a man is related to control and interpret threats to pilots' control as threats to their manhood. Less recognized in the historical literature is how engineers responded to those changes. Did they design systems, knowingly or unknowingly, to leave the operators a sense of mastery? Was that mastery perceived differently when astronauts were pushing buttons and entering computer commands rather than having their hands on a control stick?

Sources and Implications

How did the Apollo engineers accommodate human beings in their machines? How did they build a computer that kept humans "in the loop" for the critical functions of the lunar landing? When were the human operators operating as skilled, intelligent beings, and when were they machine-like, following prescribed scripts? This borderline, *between human and machine*, reveals the human aspects of Apollo amid so many seemingly cold, technical calculations.

Much, if not all, of the engineering work was incredibly *mundane*: writing reports, holding meetings, testing machines, developing procedures, practicing pushing buttons, weaving hair-like wires through tiny magnetic cores thousands of times in mind-numbing succession. Human players interacted in ordinary ways: competition, collaboration, professional pride and anxiety, struggles to influence and define the project. Sources prove even more prosaic: project updates, status reports, interoffice memos, engineering drawings, test reports, logs of an astronaut's seemingly endless hours in a simulator, dry mission transcripts, technical debriefs, and mission reports. As participants often pointed out, the high abstractions of systems engineering frequently meant added layers of paperwork bureaucracy. Yet lurking within these ordinary documents are critical tensions and embedded assumptions whose explication makes the detail come alive.

One of my goals is to explain, really explain, how Apollo worked, and to make one of the most difficult engineering accomplishments of the twentieth century accessible and understandable. The story combines the intrigue and suspense of a group of engineers working at the cutting edge of technology with the drama and interest of spaceflight and the social importance of computers. Tracy Kidder's 1981 book about a group of engineers building a computer, *The Soul of a New Machine*, had the ironic result that the computer he focused on, a minor commercial machine, was forgotten, while his book is long remembered. This story has a similar cast of characters but in this case the computer and its task made history.

I hope that the interested, nontechnical reader will gain from this story insight and intuition into the thorny and fascinating engineering problem of how to fly to the moon, particularly how to land on its surface, and some understanding of the fundamental questions of machine control and human-machine interaction. These reappear in high-risk, high-reward technologies of today, from airline operations to nuclear power plants to proposals for a new era of space exploration.

A few words on what this book is not. It is not a reminiscence of NASA's glory days of Apollo, and it does not seek to explain what went wrong at NASA in the three decades since.[24] It does not repeat the numerous clichés of "we went to the moon with a computer that was less capable than a pocket calculator." That may be true if you measure a computer's capability in memory capacity or machine cycles alone. But if you consider interconnections, reliability, ruggedness, and documentation, the Apollo guidance computer is at least as impressive as the PC on your desktop, and the Apollo software an equally intricate ballet of many people's work and ideas.

Members of a video-game generation may find that Apollo makes sense when explained through stories of joysticks, cockpit displays, and hand-eye coordination. Indeed, the word *cyborg* was coined by NASA researchers studying bioastronautics in the 1950s.[25] The earliest video games appeared during the Apollo years, one of which was called "Lunar Lander" (with instructions that read: "You are landing on the moon and have taken over manual control 500 feet above a good landing spot..."). In the climactic moment of George Lucas's 1977 film *Star Wars*, the hero Luke Skywalker turns off his computerized sighting device and relies on the intuitive "Force" to help him destroy the enemy Death Star.

Still, I also do not contend that Apollo *caused* changes in human-machine relationships or that it created new technologies that altered those relationships. My argument is that Apollo exemplified broad changes in human-machine relationships, not that it caused them.

Human and Machine in the Future of Spaceflight

Yet Apollo's human-machine history does speak to the lasting debate over whether humans or robots should be flying into space and exploring the solar system.[26] Current polemics usually polarize around creative, flexible humans versus mindless automata, the former being capable of "exploration" and the latter collecting data for "science." Such rhetoric has arguably produced more heat than light in recent decades, although the stakes are high as NASA determines new policy directions. Yet the advocates for either side usually neglect or misunderstand the mixings and combinations of manual and automated, especially experiences made possible by communications links and remote controls. The Mars rovers named Spirit and Opportunity that captured public imagination in recent years, for example, are less "robots" acting as autonomous agents than "telerobots" responding to commands from the earth and providing data for ground controllers, scientists, and the public to experience a foreign world from afar. Similarly, the Apollo spacecraft and astronauts had tight connections to the ground and transmitted images, words, data, and experience through remote channels. No computers made decisions on their own; all were programmed by people, distanced in space and time from the landings, who embedded their own ideas, models, and assumptions into the machines.

In this vein, I do not take a position on the humans versus robots debate, but rather seek to clarify some of its terms. What, exactly, do people do in space? Which of their tasks require strict adherence to procedures? Which require subtle perceptions and skills? When do they use their judgment? When do they err? Less frequently debated than the humans versus robots question is the equally contentious: which people? What kinds of professionals? If a major goal of human spaceflight is inspiration, or expanding the realm of human experience, should we not consider selecting and training people to communicate those experiences? What follows comprises but a first look, and raises more questions than it answers. Still, the concluding chapter suggests that similar analyses applied to space shuttles, deep-space probes, or robotic missions could help redefine and advance a debate that has been stuck in circular argument for a generation. Informed public discourse on human spaceflight is essential for a successful, sustained human future in space, whether directly or remotely present.