MASTERCLASS

CHRIS HADFIELD

TEACHES SPACE EXPLORATION

INTRODUCTION

ABOUT THIS WORKBOOK

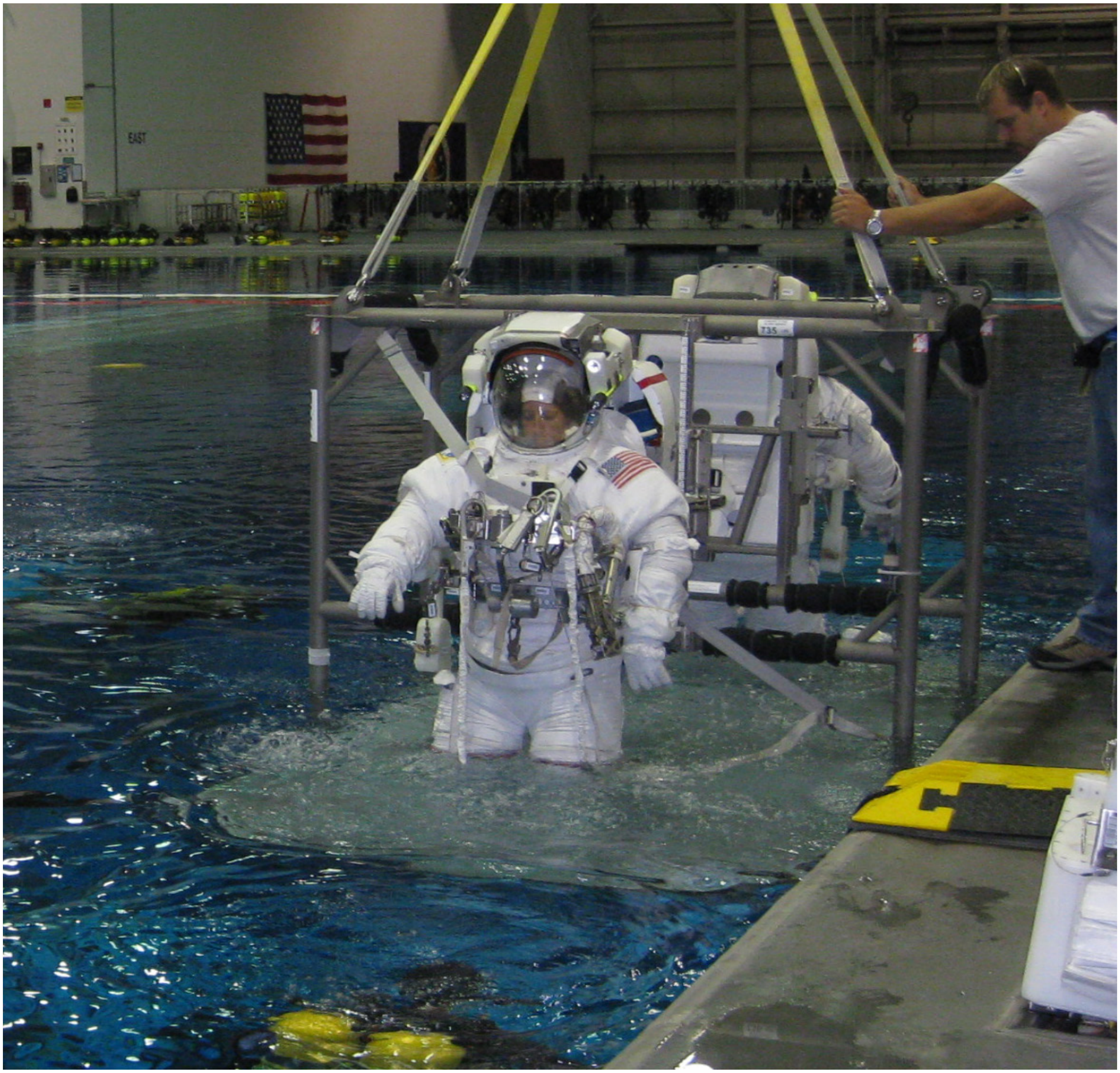
The MasterClass team has created this workbook as a supplement to Chris's class. In each chapter you'll find a review of Chris's video lesson, explanations of key concepts, and opportunities to learn more. Caption information for all photos in included in an index in the complete version of this workbook.

ABOUT
CHRIS HADFIELD

Referred to as "the most famous astronaut since Neil Armstrong," Colonel Chris Hadfield is a worldwide sensation whose video of David Bowie's "Space Oddity"—seen by over 75 million people online—was called "possibly the most poignant version of the song ever created," by Bowie himself. Acclaimed for making outer space accessible to millions, and for infusing a sense of wonder into our collective consciousness not felt since humanity first walked on the Moon, Colonel Hadfield continues to bring the marvels of science and space travel to everyone he encounters.

In 1992, Colonel Hadfield was selected as a NASA Mission Specialist, and three years later he was aboard the Shuttle Atlantis, where he helped build the Mir space station. In 2001, on the Shuttle Endeavour, Colonel Hadfield performed two spacewalks and in 2013, he became Commander of the International Space Station for six months off planet. A heavily decorated astronaut, engineer, and pilot, Colonel Hadfield's many awards include the Order of Canada, the Meritorious Service Cross, and the NASA Exceptional Service Medal. He was named the Top Test Pilot in both the US Air Force and the US Navy, and was inducted into Canada's Aviation Hall of Fame. Colonel Hadfield is the author of three internationally best-selling books, *An Astronaut's Guide to Life on Earth*, *You Are Here*, and his children's book, *The Darkest Dark*. Additionally, he released his musical album, *Space Sessions: Songs From a Tin Can*, in 2015. He is also featured on Ted.com for his talk, "What I Learned from Going Blind in Space."

Currently, Colonel Hadfield can be seen as the cocreator and host of the internationally acclaimed BBC series *Astronauts*, and he is cohosting, with actor Will Smith, the National Geographic series *One Strange Rock*, directed by Darren Aronofsky. Colonel Hadfield is also the producer of the celebrated *Rare Earth* series on YouTube, and the creator of the onstage celebration *Generator*, which combines science, comedy, and music for sold-out audiences. Additionally, Colonel Hadfield is an adjunct professor at the University of Waterloo.



2.

ASTRONAUT TRAINING

"We're going to need some really special people to go to Mars."
—Chris Hadfield

2.

ASTRONAUT TRAINING

SUBCHAPTERS

- Forget the Movies
- You're an ASCAN Now
- Become an Expert in Everything
- Train to Survive Emergency Landings on Earth
- Learn Leadership Techniques for Survival
- See the Body as a System
- Become an Astronaut of the Future

CHAPTER REVIEW

The astronaut personality we often see portrayed in movies is an overly dramatized version of the type of person who is actually trusted to go to space. Astronauts need to have cool heads and be able to calmly execute highly difficult tasks under extremely stressful situations.

Upon being selected as an astronaut candidate, a position with the unfortunate abbreviation "ASCAN," you find yourself at the bottom of the heap. It takes years of work to get in the door to astronaut training, but that hard-won acceptance is actually just the beginning.

Astronauts need to know everything about everything that happens on board a spaceship because, as Chris puts it, "when you're in space, often there's no one else to ask." Thus ASCANs study for two years before they even qualify as rookie astronauts. They cover everything from how rockets work to weather patterns, geology, electronics repair, and medical procedures. The International Space Station (ISS) is exquisitely complicated; as an astronaut on board, the only person who can fix it will be you, so motivation is high.

Survival training turns out to be a necessary part of astronaut preparation. In an emergency, your spaceship may have to undock from the ISS quickly, and thus you could end up landing anywhere on Earth. Since roughly 70 percent of our planet is water, you must learn how to use all the safety equipment in the event of a splashdown. Astronauts similarly need to train to survive in the Arctic and deserts. However, survival training isn't just about preparing for emergency landings—it also helps a crew evolve and bond as a team, with mutual trust and respect under stress.

Astronauts must also develop expertise in the human body and how it works, in order to properly conduct medical experiments and be ready to handle health emergencies on the ISS. It may feel unnatural and daunting at first, but you need to learn to look at the body as just another system. Chris trained at a hospital in Houston to develop skills needed to deal with a range of injuries, from practicing on cadavers to treating eye injuries and burns, and on to intubating, stitching, and administering an IV.

2.

ASTRONAUT TRAINING

Chris concludes this lesson by noting that looking to the future, we'll need astronauts with even more remarkable personalities and skill sets to live on the Moon, and go all the way to Mars.

LEARN MORE

- To find out about the type of astronauts NASA recruits, read up on the latest class of astronaut candidates.
- Want to become an astronaut? Start with NASA's list of requirements, and then read this feature from CNNMoney, which explains what is required and goes into further depth about the training experience.
- Astronaut training has changed over the years. This feature from *Wired* provides a look back through the decades at the methods previously used to prepare astronauts for space.
- To get a sense of the specifics involved in advanced training, read this report from the European Space Agency (ESA), which details the training some previous astronauts have gone through. This feature from ESA looks at water survival training conducted by European and Chinese astronauts.
- Learn how astronauts deal with emergencies in space by reading this report from the BBC.

3.

ROCKETS: HOW ROCKETS WORK

"How do you balance this broomstick as it's pushing its way up to space?"
—Chris Hadfield

3.

ROCKETS: HOW ROCKETS WORK

SUBCHAPTERS

- Fuel, Steering, and Something to Carry
- Saturn V
- Rocket Stages: The Space Shuttle
- Multiple Stages: Saturn V
- Reusable Rockets

CHAPTER REVIEW

In order to get an object to space, you essentially need the following: fuel and oxygen to burn, aerodynamic surfaces and gimbaling engines to steer, and somewhere for the "hot stuff" to come out to provide enough thrust. Simple.

Fuel and oxygen are mixed and ignited inside the rocket motor, and then the exploding, burning mixture expands and pours out the back of the rocket to create the thrust needed to propel it forward. As opposed to an airplane engine, which operates within the atmosphere and thus can take in air to combine with fuel for its combustion reaction, a rocket needs to be able to operate in the emptiness of space, where there's no oxygen. Accordingly, rockets have to carry not just fuel, but also their own oxygen supply. When you look at a rocket on a launch pad, most of what you see is simply the propellant tanks—fuel and oxygen—needed to get to space.

Within the atmosphere, aerodynamic fins can help steer the rocket, like an airplane. Beyond the atmosphere, though, there's nothing for those fins to push against in the vacuum of space. So rockets also use gimbaling engines—engines that can swing on robotic pivots—to steer. Sort of like balancing a broom in your hand. Another name for this is *vectored thrust*.

Rockets are normally built in separate stacked sections, or *stages*, a concept developed by Konstantin Tsiolkovsky, a Russian math teacher, and Robert Goddard, an American engineer/physicist. The operative principle behind rocket stages is that we need a certain amount of thrust to get above the atmosphere, and then further thrust to accelerate to a speed fast enough to stay in orbit around Earth (*orbital speed*, about five miles per second). It's easier for a rocket to get to that orbital speed without having to carry the excess weight of empty propellant tanks and early-stage rockets. So when the fuel/oxygen for each stage of a rocket is used up, we jettison that stage, and it falls back to Earth.

The first stage is primarily used to get the spacecraft above most of the air, to a height of 150,000 feet or more. The second stage then gets the spacecraft to orbital velocity. In the case of the Saturn V, there was a third stage, which enabled astronauts to get to the Moon. This third stage had to be able to stop and start, in order to establish the right orbit around Earth, and then, once everything was checked a few hours later, push us to the Moon.

3.

ROCKETS: HOW ROCKETS WORK

Even the Lunar Module—which Apollo astronauts used to get to the surface of the Moon and back—was a two-stage rocket. When we launched from the Moon to return home, the landing stage was left on the surface.

The first rockets that were built were single use, with no thought of reusing them again. The Space Shuttle was the first spacecraft that was designed to be reused, and it was capable of being flown to space one hundred times. Even its solid rocket boosters were partially reusable—they could be recovered after falling into the ocean, salvaged, cleaned and recertified, and refilled with fuel for later launches. Today, companies are building even more reusable rockets; SpaceX is able to launch and then land the first stage of its Falcon rocket, recovered intact and ready to be filled again with liquid fuel. Similar technology is also being used by Blue Origin for their New Shepard rocket.

LEARN MORE

- This piece from NASA explains in more detail how gimbals work to help steer a rocket.
- Konstantin Tsiolkovsky was a Russian rocket scientist and one of the fathers of modern rocketry. Read this article from Space.com about his life and work.
- Learn more about the development of modern rocketry from this feature by NASA.
- Learn more about the Saturn V. This feature from Space.com runs through some of the more surprising facts about the Saturn V rocket, and this feature from *Air & Space* magazine talks about how the rocket was built and the people behind the design.
- This infographic from Space.com provides more information on the Space Shuttle and how it worked.

4.

ROCKETS: WHAT IT FEELS LIKE TO LAUNCH

"It's pretty amazing to come around that corner at the Kennedy Space Center in Florida, and in the distance you see your spaceship. And that's how you feel about it. It's not a spaceship, but this is your spaceship."
—Chris Hadfield

4.

ROCKETS: WHAT IT FEELS LIKE TO LAUNCH

CHAPTER REVIEW

The morning of launch marks the culmination of years of training and the realization of a lifetime of dreams. It's a day filled with sensory experiences, extreme danger, and elite execution. Focus is paramount. Your extensive, realistic preparation makes everything second nature, from waving at the crowd to flying the rocket itself.

As the clock counts down to zero, you're lying on your back, intensely watching the instruments as all the rocket engines ignite. The whole crew could not be more focused. Your entire world comes down to only what is happening on the flight deck of the spaceship. Once you've cleared the launch tower, communication switches from Launch Control in Florida to Mission Control in Houston. Outside the windows the light blue sky rapidly gets darker and darker, until it turns black. The ride is intensely physical, with g-forces three times normal and rough, high-frequency vibration as the vehicle shoulders its way through the thick air. After two minutes you're high enough that the air has thinned to almost nothing, and the first-stage boosters explode off in a burst of fireworks.

Then the ride is suddenly smooth—but steadily getting heavier as the ship burns off fuel and the acceleration grows. The spaceship rolls through 180 degrees to let the communication antennae point at orbiting relay satellites. The ship becomes light enough that you reach 3G, and the computers ease the throttles back to not overstress the vehicle. Each passing second takes you past emergency abort and failure options, and improves your chances of making it to orbit today. And after eight and a half minutes, suddenly the moment you have been dreaming about but never believed would happen has come. The engines shut down and you are safely there, weightless, in space.

As this class progresses and you learn more about what being an astronaut requires and feels like, remember Chris's description of leaving Earth. That's what you're working toward.

4.

ROCKETS: WHAT IT FEELS LIKE TO LAUNCH

LEARN MORE

- Chris's first two missions to space were on board the Space Shuttle. Learn what happens before the astronauts board and the countdown begins here.
- The launch of the Space Shuttle is meticulously planned in order to allow the launch team to target a precise launch window. This timeline by NASA provides the key steps in the hours leading up to the launch of the Space Shuttle.
- There are many checks before the crew is given the final "go" for launch. The ground team needs to ensure that systems are working properly and everything is ready for liftoff. These are the major milestones of checks during the last few minutes before launch.
- Chris talks about focus during launch. Sometimes in our own lives it can be difficult to stop our minds from wandering. This article from the BBC talks about focus and how, in a world where there are so many distractions, we can tame our wandering minds.

5.

ROCKETS: ATMOSPHERIC DRAG

"You have to understand that equation like you understand the alphabet, or speaking, or breathing, or walking."
—Chris Hadfield

5.

ROCKETS: ATMOSPHERIC DRAG

CHAPTER REVIEW

In order to fly in space, you need to get through Earth's atmosphere, and then accelerate until you're going fast enough so that you can successfully stay in orbit. The main impediment to achieving this is the drag caused by resistance from the atmosphere. Drag is determined by the following equation:

$$D = \frac{1}{2}\rho v^2 C_D S$$

D = drag. Drag is a force that slows you down. It's important to remember that drag is a force. It pushes against your spaceship and—if not thoughtfully allowed for in the spaceship's design—can prevent the spaceship from going any faster, or even tear the ship apart.

ρ = *rho*, the density—or thickness—of the air around your ship. As the spaceship moves away from Earth and higher in the atmosphere, air density decreases and so, per the equation, does drag. Note that the density of the atmosphere at any given altitude is variable since air expands when warmed by the sun—warmer air is less dense. And remember that out in the vacuum of space the density is essentially zero, so (by the equation) there is virtually no drag there.

v = velocity, or the speed of your spaceship. Notice that in the equation, drag is a function of velocity times velocity, or v squared. Thus as velocity increases, the drag increases rapidly—double the speed, four times the drag, etc. This is why Chris says that "flying a rocket through the atmosphere is the hardest part": at this stage the velocity of the rocket is continually increasing down where the air is still thick. Once you're beyond the atmosphere, though, you can increase the speed without increasing the force of drag because there's no atmospheric density.

CD = the drag coefficient, a characteristic of vehicle streamlining and surface roughness. As this value is largely fixed for a rocketship, Chris disregards CD in the discussion.

S = the cross-sectional area of your spaceship. A lower area (think: skinny versus fat rockets) helps lower drag. The implication is that atmospheric drag is a much bigger problem for spaceships that are still in the atmosphere and trying to leave than it is for a ship like

5.

ROCKETS: ATMOSPHERIC DRAG

the International Space Station, which is so high above the planet that there's only a minute amount of air density acting against it. That's why the ISS can be such an ungainly shape, and why rocketships have to be streamlined. (*Note that the drag equation is often written using the letter A to indicate area. In the world of physics, area is indicated by A. Pilots, however, often use S. Chris's use of S for area comes from his experience as a pilot.)

The drag equation creates a clear goal in rocket design and flight strategy. Not only do the most efficient rockets have lower areas, they also do as much of their accelerating (increase in velocity to orbital speed) as possible once they've gotten above the atmosphere into areas of lower air density.

LEARN MORE

- Read this NASA report to find out more about how the drag equation applies to rockets.

6.

ROCKETS: ORBITAL MECHANICS

"Once the rocket has done its job and gotten your spacecraft up to orbital speed, five miles a second, 25 times the speed of sound, eight kilometers a second, ... there's virtually nothing to slow you down. So sorta like the Moon, you'll stay in orbit forever."
—Chris Hadfield

6.

ROCKETS: ORBITAL MECHANICS

SUBCHAPTERS

- Launch Site Logic
- How to Change Orbits
- Changing Orbits With the Hohmann Transfer
- Orbital Velocity vs. Escape Velocity
- Perceived Weightlessness
- Newton's Law of Universal Gravitation

CHAPTER REVIEW

Where a rocket is launched from comes down to physics. As a general rule, rockets launch from as near as possible to the equator, in order to take advantage of the velocity of Earth's rotation, which is highest at the equator—about 1,000 miles an hour. The more orbital velocity a rocket gets from Earth, the less fuel it requires to reach orbital speed, which increases its efficiency. Not all rockets can take advantage of Earth's spin—some are designed to send payloads such as satellites into north-to-south orbit, around the poles.

Orbital mechanics is a term for the mathematics by which a spaceship changes orbit. For objects that are in orbit, the closer they are to the object they are orbiting, the faster they will travel around it. This applies to any object orbiting another—Earth orbiting the Sun, the Moon orbiting Earth, or a spaceship orbiting a planet. In orbital mechanics, the concepts of speeding up and slowing down are complex and counterintuitive. In orbit, firing your engines frontwards moves you forward into a higher orbit, which actually means you slow down, because objects in a higher orbit move more slowly. In order to go faster you need to decelerate and fall into a lower orbit.

The farther away you are from Earth, the less magnified this effect is. When you get far enough away from Earth, the relative effects of orbital mechanics are so low that you can navigate as if you are operating your spaceship in deep space.

Because of small bits of air around the ISS, the station gets pulled back toward Earth ever so slightly as it orbits. In order to avoid a continued spiral inward to Earth, the crew on board the ISS or Mission Control has to fire its engines every so often to move it into a higher orbit.

To move their spaceship from a lower orbit to a higher one, the crew normally uses the classic orbital change: the Hohmann transfer. In the 1920s, German engineer Walter Hohmann, inspired by science fiction, calculated the most efficient way to move to a higher orbit. The Hohmann transfer works by firing the rocket engines once at a certain point in the lower orbit. This firing adds energy to the orbit and propels the spaceship farther from Earth, changing its orbit from a circular orbit to an oval-shaped orbit.

At the point in that new oval orbit at which the spaceship is farthest from Earth, the crew fires the rocket's engines again, and the oval orbit turns back into a circle—this one farther from Earth than the last.

The Hohmann transfer is the industry standard for the most energy efficient orbital transfer, and it applies no matter how far into space you are traveling.

If a spaceship in orbit fires its engine long enough, it will eventually go fast enough to fly away into deep space, escaping the planet's gravity. That speed, called *escape velocity*, is simply the square root of 2, or 41 percent faster than orbital speed.

To illustrate the principle behind perceived weightlessness for astronauts in space, Chris uses the metaphor of a person jumping off a diving board into a swimming pool. The faster you run off the end of a diving board, the farther you travel before hitting the water. If you could somehow run fast enough, you would still fall due to gravity, but Earth would curve away beneath you to match. You'd fall forever. A spaceship orbiting Earth "falls" in this way. The astronauts on board are falling at exactly the same rate that Earth curves, so even though gravity is still acting on them, they feel and behave as though they're weightless.

One of the governing equations in spaceflight is Newton's law of universal gravitation. The law states that two bodies in space pull on each other with a force proportional to their masses and the distance between them. For large objects orbiting one another—the Moon and Earth, for example—this means that they actually exert noticeable force on one another. It may seem like the Moon is orbiting a relatively static Earth, but actually the Moon and Earth are rotating around a third point between them. That point is called the *barycenter.*

For a spaceship orbiting or leaving Earth, since the mass of the spaceship relative to Earth is tiny, the ship doesn't exert much force on Earth. The primary implication for spaceflight is that the force of gravity on the spaceship decreases as the distance between the spaceship and Earth increases. In fact, the force decreases rapidly, as it's divided by the distance squared.

LEARN MORE

6.

ROCKETS: ORBITAL MECHANICS

- Deepen your understanding of orbital mechanics and the principles behind it by studying these books: *The Fundamentals of Astrodynamics* by Roger R. Bate, Donald D. Mueller, and Jerry E. White and *Orbital Mechanics* by Bruce A. Conway and John E. Prussing.
- This page gives a clear look at the considerations involved in launching a rocket off a spinning planet.
- Find out more about the Hohmann transfer and the math behind it from this page from the University of Georgia mathematics department.
- Here's another great resource for more learning on orbital mechanics.
- Take a look at this lesson plan from MIT, which covers orbital transfers and interplanetary trajectories.
- Read more about escape velocity in this feature by NASA.

7.

ROCKETS: FUELS AND PROPULSION

"Like all spaceships, rockets are a compromise in design."
—Chris Hadfield

7.

ROCKETS: FUELS AND PROPULSION

SUBCHAPTERS

CHAPTER REVIEW

Rocket design is all about trade-offs: every extra pound of cargo that a rocket needs to lift off the surface of Earth requires more fuel, while every new bit of fuel adds weight to the rocket. Weight becomes an even bigger factor when trying to get a spaceship somewhere as far away as Mars, land there, and come back again. Accordingly, mission designers have to be as judicious and efficient as possible when figuring out what to pack on a ship headed for space and which rockets to use.

There are two main types of fuel used to get rockets off Earth: solid and liquid. Solid rockets are simple and reliable, like a Roman candle, and once ignited there's no stopping them: they burn until they run out, and can't be throttled to control thrust. Liquid rockets provide less raw thrust, but can be controlled, allowing astronauts to regulate the speed of a rocketship, and even close and open the propellant valves to turn the rocket off and on.

The Space Shuttle used a combination of solid and liquid rockets for launch. The solid rocket boosters were used only to take the crew above the air; while the liquid fuel rockets burned the entire time.

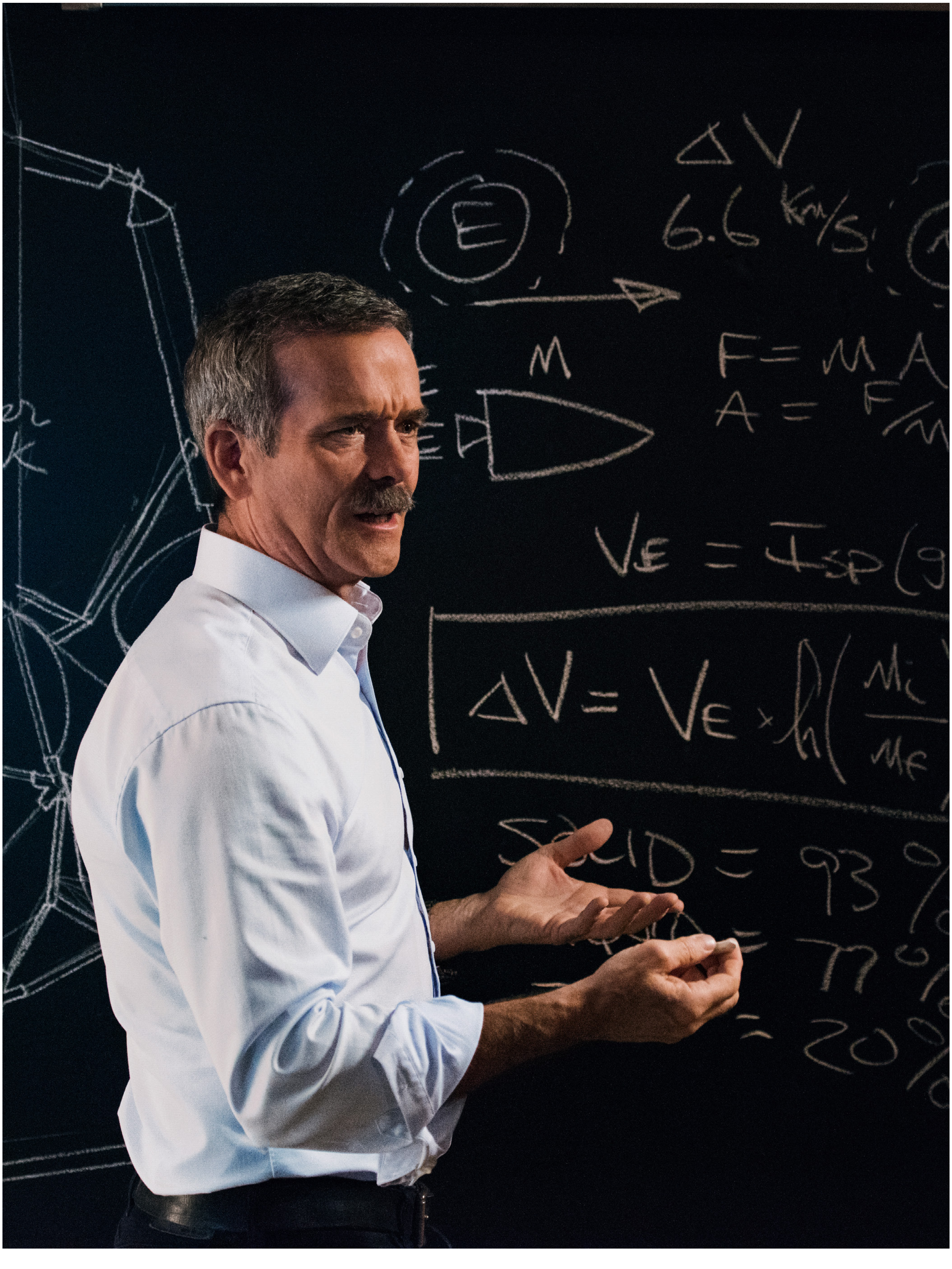
There have been few changes in the fundamental chemistry of rocket fuel since the beginning of spaceflight, but there are designs in the works for more fuel-efficient rockets. In order to improve their efficiency, rockets need to be less fuel-hungry, which means the fuel needs to come out the back as fast as possible to give the desired momentum, and achieve the same thrust. Ionized gas, propelled through a rocket nozzle using a magnetic accelerator, weighs substantially less than traditional rocket fuels. The ionized particles are pushed out the back of the rocket at an incredibly high velocity, which compensates for their small weight, or mass. Ion propulsion works well for long, sustained propulsion, but because it creates a lower specific impulse, it so far only works on small satellites already in orbit and has not been scaled up for large spaceships. To do this will require a powerful energy source—perhaps nuclear, or something not yet invented.

7.

ROCKETS: FUELS AND PROPULSION

LEARN MORE

- This feature from NASA gives further detail about the Space Shuttle's solid rocket boosters (SRBs), and this one discusses the external fuel tank that contained the liquid propellant.
- This article from NASA looks at the future of rocket engines for NASA's SLS rocket, which could one day be used to take humans to Mars.
- This guide from the European Space Agency (ESA) compares liquid and solid rocket fuel.
- This article from NASA provides more details on how ion propulsion works.
- This feature from Space.com looks at testing of an ion rocket and how one could be used to send humans to Mars.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8.

ROCKETS: THE PRICE OF EXPLORATION

"I think you need to decide in your heart what is worth doing in life....And then accept that there are risks. Not everyone is going to succeed....But don't let that stop you."
—Chris Hadfield

8.

ROCKETS: THE PRICE OF EXPLORATION

SUBCHAPTERS

- Come to Peace With Risk and Learn From Tragedy
- Turn Fear Into Motivation
- Move Forward With Optimism

CHAPTER REVIEW

Rockets are inherently dangerous, and no rocket that astronauts fly on is ever going to be completely safe. Compromises that engineers made in the design of the Space Shuttle resulted in the loss of two entire crews, in the Challenger and Columbia accidents. For the design of future rockets, the real question is whether and when the rockets will be proven safe enough that we are willing to risk not only cargo, but human lives on them.

In life, everything that's worth doing involves risk. Chris urges you to judge what in your life is worth taking a risk for. For him, even though space travel is inherently dangerous, it's worth facing the risk to pursue the knowledge we gain from venturing away from Earth.

When taking a risk, it is natural to fear the unknown. The best antidote for fear is competence. If you decide you are going to take a risk—and if you decide it is a worthwhile risk to take—you should then train and prepare until you get to the point that you're not fearful, but competent and empowered to handle anything that could happen. After all, no astronaut launches on a rocket merely with their fingers crossed.

In space exploration, lives are inevitably lost. Chris lost his friend and fellow test pilot Rick Husband when the crew of the Space Shuttle Columbia died as they returned to Earth in 2003. As he grieved this loss, Chris knew that if it had been the other way around and he had been killed during a mission, he would never have expected Rick to quit. In life, tragic things happen, but what really matters is what you do next.

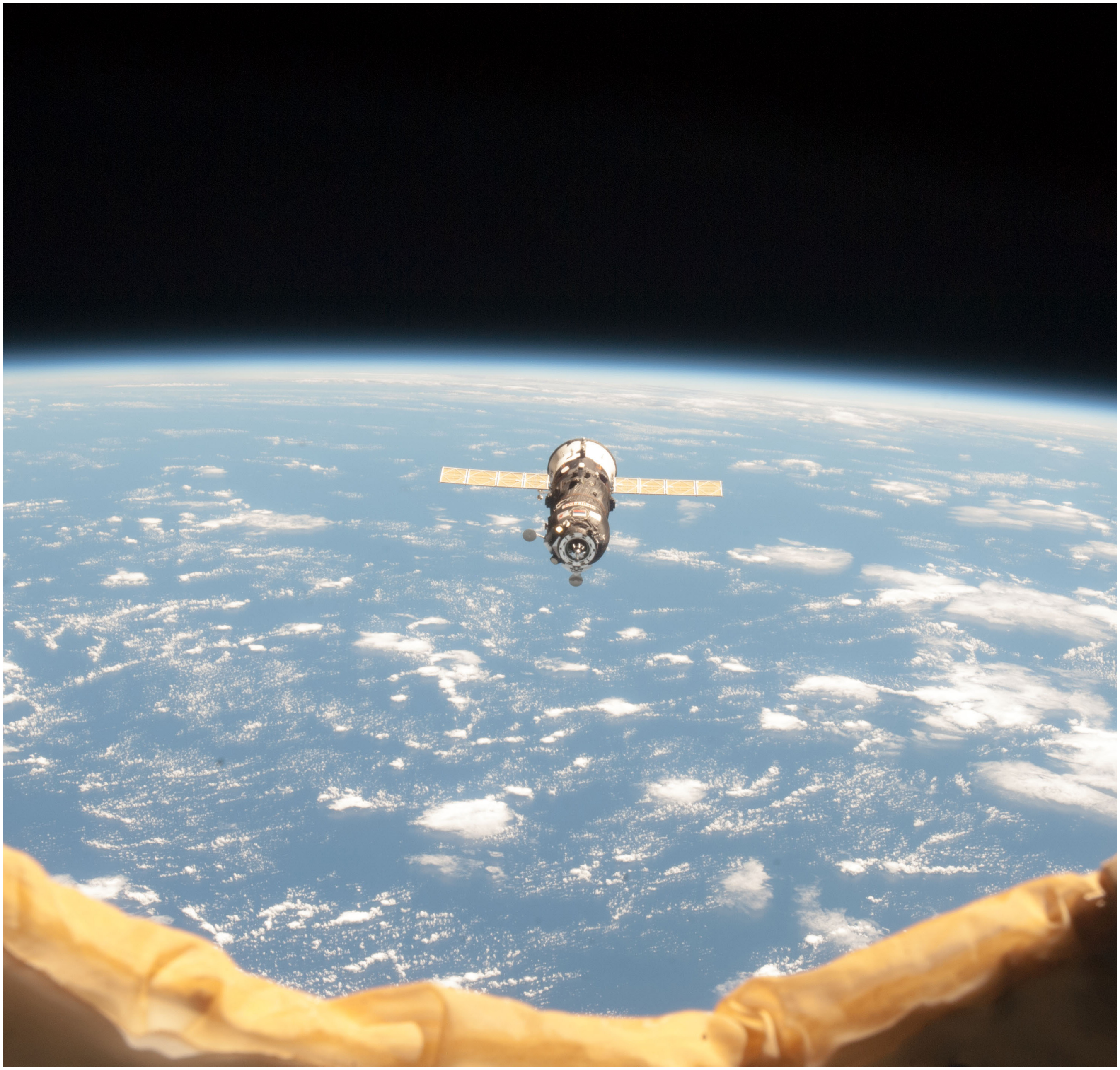
Chris is ultimately optimistic in the face of adversity. He believes that humans and life itself are tough, that our planet is tough, and that you should deliberately pursue the things that you think are worthy, in spite of the risks. Seeing Earth from space gives him optimism for how rugged and ancient our planet is, and gives him hope for the future of life on Earth.

8.

ROCKETS: THE PRICE OF EXPLORATION

LEARN MORE

- Read the report that was delivered to President Ronald Reagan about the Challenger accident, and read the investigation into the Columbia accident.
- Read this essay by NASA looking at how much risk individuals and organizations should take in the pursuit of exploration.
- Read the NASA biography of Rick Husband, Chris's friend who died tragically in the Columbia disaster.
- Read this feature on the Columbia accident on Space.com for insights into what happened, what NASA learned, and the legacy of the crew.
- For a perspective on the resilience of our planet, look through this collection on Space.com of NASA's best photos of Earth taken from space.



9.

SPACESHIPS: CAPSULE DESIGN

"A spaceship is essentially a little sample of Earth taken off the planet—a little bubble of life away from the natural place where we all began."
—Chris Hadfield

9.

SPACESHIPS: CAPSULE DESIGN

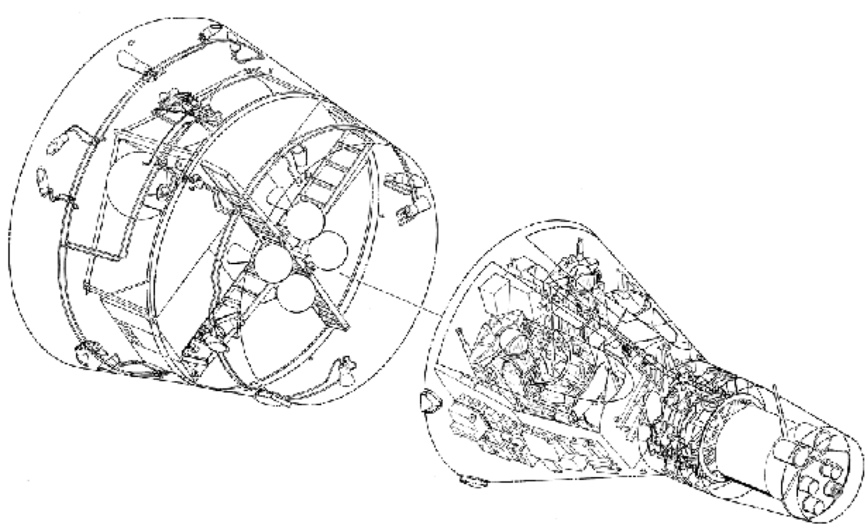
SUBCHAPTERS

- Gemini
- Apollo
- Lunar Lander Design
- Capsules: Disposable Reentry Modules

CHAPTER REVIEW

The fundamental human needs are air, water, food, and shelter. We have evolved on Earth where these are readily available, but to leave our planet, a spaceship needs to be capable of reliably providing them all. The complexity of this task is exacerbated by weightlessness and the surrounding vacuum: from blood pressure to convection, nothing behaves the same in space as it does on Earth.

Spaceships have improved since we began traveling to space in the 1960s, but a lot of our current technology originates from those first designs. Mercury and Gemini were essentially orbiting cockpits with mechanical systems to keep the crew alive: air pressure regulation, oxygen/CO_2 processing, temperature control, and food and water storage. They proved that orbital spaceflight was possible for humans and opened the door to explore further.



Gemini spacecraft interior arrangement
from *Project Gemini Familiarization Manual*, December 31, 1964

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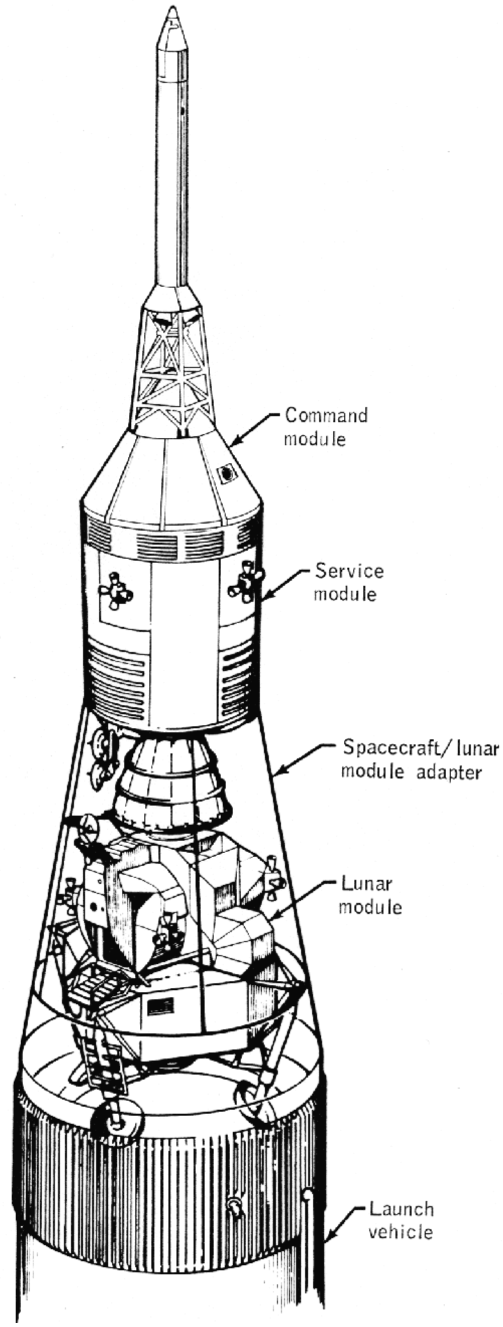
SPACESHIPS: CAPSULE DESIGN



Apollo spacecraft launch configuration
from *Apollo Program Summary Report*, April 1975

The Apollo program took 12 astronauts to the surface of the Moon and back. The ship was rugged and capable enough that even in the face of a major explosion—such as the one that occurred on Apollo 13, destroying much of the ship's oxygen supply—the crew made it safely home. A major design constraint on all spaceships is atmospheric reentry. How does the vehicle safely slow down and land, from the initial speed of five miles per second for Mercury/ Gemini to the nearly seven miles per second for Apollo?

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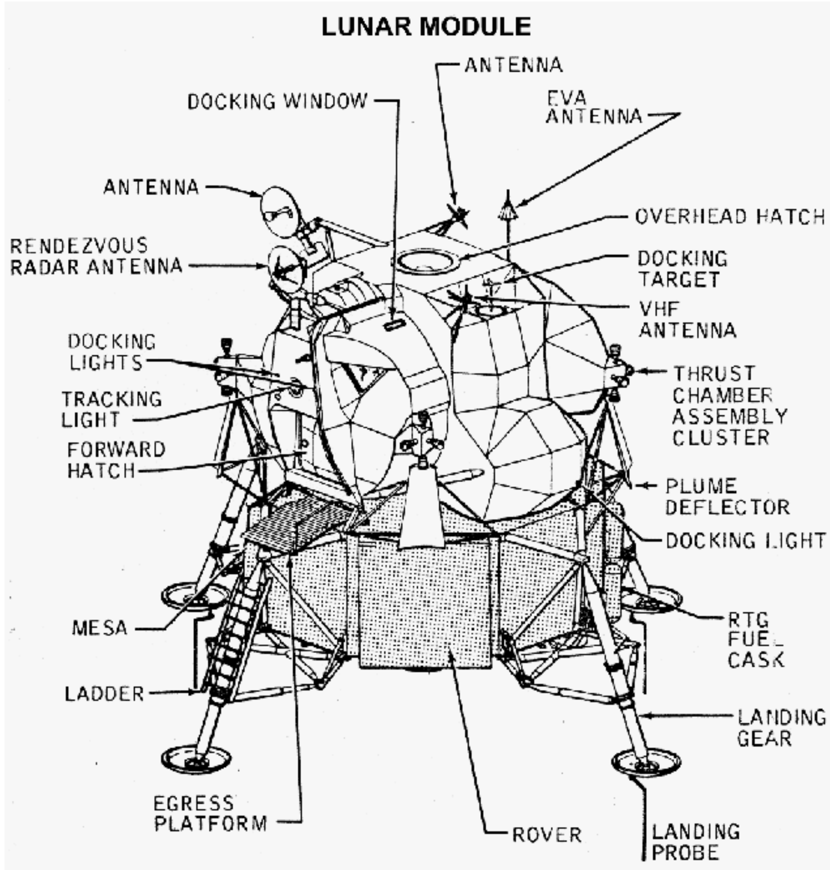
SPACESHIPS: CAPSULE DESIGN



Lunar Module exterior
from *Apollo Program Press Information Notebook*, 1972

Intuitively, it would seem to make sense that a spaceship should be pointy, like a high-speed aircraft. Research done in the 1950s, however, showed that, for orbital speeds, no material could be tough enough to take the tremendous heat on that pointed tip. A brilliant engineer named Max Faget realized that reentry spaceships need to be blunt, to spread the intense heat and pressure over a large area. He was key in designing Mercury, and thus the space capsule was born.

Apollo was more than just a capsule, however. It also carried the spider-like Lunar Lander, and had a large Service Module that supported the crew to the Moon and back. To regulate the temperature difference between the Sun's heat on one side and the cold of deep space on the other, the Apollo spacecraft rotated as though on a rotisserie throughout its transit to the Moon.

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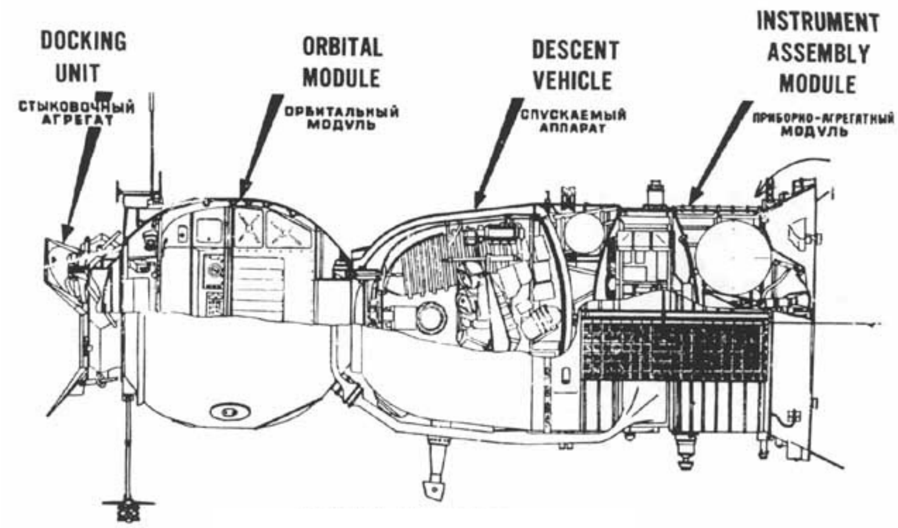
SPACESHIPS: CAPSULE DESIGN



Soyuz spacecraft
from *Prelaunch Mission Operation Report No. M-966-75-01*,
July 7, 1975

The first spacefaring nation, the Soviet Union, also realized that capsules were a natural shape for reentry spaceships. Their Soyuz capsule has been successfully flying since the late 1960s, with the design being improved and updated with every flight.

Chris describes his own experience in the Soyuz and the forces at play during reentry. The capsule is rolled and thus steered using small peroxide thrusters while in the upper atmosphere. This allows surprisingly accurate control of g-loads and touchdown location. Once the majority of the speed is bled off and the ship is around 35,000 feet, a drogue chute is deployed, followed by a main parachute. Just before touchdown small solid thrusters fire to slow the impact speed with the ground.

While capsules are tough and reliable, they undergo tremendous stress from heat and pressure, and until recently have been single-use only. The Dragon cargo capsule, made by SpaceX, is the first of the reusable capsules, with human-rated versions to follow.

LEARN MORE

- Find out more about the design of spacecraft. This resource from NASA provides technical diagrams for the Apollo spacecraft, and this NASA assignment sheet looks at how spacecraft are designed.

9.

SPACESHIPS: CAPSULE DESIGN

LEARN MORE CONT.

- This feature from Space.com discusses America’s first space capsule.
- This short feature from NASA talks through the stages of reentry for the Soyuz capsule.
- This feature from the Lunar and Planetary Institute discusses space capsules and how they reenter Earth’s atmosphere.

10.

SPACESHIPS: SHUTTLES AND BEYOND

"Two-thirds of everybody who's ever flown in space flew on board the [Shuttle]—the first great lifter of humanity into space."
—Chris Hadfield

10.

SPACESHIPS: SHUTTLES AND BEYOND

SUBCHAPTERS

- Shuttles: Reusable Reentry Modules
- Buran
- Winged or Wingless?
- The Future of Spaceship Design

CHAPTER REVIEW

The Space Shuttle had three revolutionary design objectives: to carry large, delicate payloads in its cargo bay; to return the payloads to Earth; and to be reusable. It was built to be big enough to carry the largest of the US Air Force's reconnaissance satellites, and it needed wings to be able to glide back to a runway for gentle landing. A major design constraint was to launch north/south into an orbit around the poles, take spy photos on the other side of the world, and land after just one orbit. During that time Earth rotates 22.5 degrees, and thus the Shuttle had to be able to steer up to 1,000 miles left/right to land, requiring even bigger wings. Even though it never flew that mission, the early requirement set the design.

The Shuttle was launched as a multistage rocket. It flew for up to 18 days like a space station, yet still had to overcome the same problems as a capsule during reentry. In order to withstand the heat, the underside of the Space Shuttle was covered in thermal protection tiles. It reentered Earth's atmosphere with its nose up at an angle of 40 degrees to spread the heat across its belly. Steering a hypersonic aircraft at that angle is immensely challenging and requires advanced computer control and multiple thrusters. As the Shuttle descended further into the atmosphere, the air became thick enough that it could fly more like an airplane, lower its nose, and the rudder and elevons took over from the thrusters. Its final approach speed was 300 knots, with touchdown around 200 knots.

The do-everything design of the Space Shuttle (and the very similar Soviet Buran shuttle, which flew just once, unmanned), gave it tremendous capability, but also immense complexity. The wings were needed for descent and landing, but were just extra weight and drag during ascent. The requirement to land gently on a runway meant that return to Earth could not be simple and rugged. The Shuttle had two major accidents, destroying Challenger and Columbia and killing their 14 astronauts.

The design of crewed spacecraft is evolving back toward the simpler, tougher capsule design, launching the crew separate from the cargo. As with cars and airplanes, we are slowly evolving toward the optimal design.

10.

SPACESHIPS: SHUTTLES AND BEYOND

Chris teaches that the design of future spaceships will ultimately be driven by their purpose. The type of craft needed to take humans back to the Moon will be quite different than the one needed to get people to Mars. Getting to the Moon is a three-day trip, so a utilitarian spacecraft will suffice. Going to Mars is a much longer journey, so the spacecraft would need to have more living space, more room for backup systems, equipment for space walks, and—perhaps most importantly—recreation facilities to keep the crew engaged, productive, and sane. Chris urges you to think about ideas put forth in science fiction novels as a window into what the long-haul spacecraft of the future could look like.

LEARN MORE

- Read more about the pioneering spacecraft designer Max Faget on the NASA website.
- There is lots of information available online about thermal protection for spacecraft. This piece from AZO Materials discusses the materials used for the Space Shuttle. NASA also has several features about thermal protection. This feature looks at thermal protection systems and the materials they use. This feature looks at the thermal protection systems for the Space Shuttle. This feature looks at the future of thermal protection systems for NASA's next spacecraft, Orion.
- Read this feature from *Air & Space* magazine that explores how the Space Shuttle evolved during its 30 years of flight.
- Read this article from *Popular Mechanics*, which looks at the design of Buran and asks if it was an improved version of the Space Shuttle.

11.

SPACESHIPS: NAVIGATION SYSTEMS AND HUMAN VARIABLES

"You're going blisteringly fast—five miles a second. You're crossing continents in minutes. The world is turning underneath you. Where are you, exactly?"
—Chris Hadfield

11.

SPACESHIPS: NAVIGATION SYSTEMS AND HUMAN VARIABLES

SUBCHAPTERS

- Orienting the Ship
- Navigating the Soyuz Visually
- Navigating With Instruments
- Propagating State Vectors
- The Future of Navigation

CHAPTER REVIEW

The first step for navigating in space is understanding which way you are pointed. The Space Shuttle had optical sensors that could orient using the stars, and in case of computer failure astronauts also needed to know how to navigate visually using the stars. By marking the ship's position relative to stars using a tiny telescope, astronauts could build a three-dimensional reference frame that told them which way the ship was pointing in space.

The next key part of navigation is where you are relative to Earth. Astronauts use a combination of visual techniques and instruments to figure this out. Earth's magnetic field can be used to help determine north and south. Altitude can be estimated by measuring the amount of drag of the upper atmosphere around you. Large antenna on the ground precisely track the ship and send it position and speed data. GPS gives not just position and speed, but multiple GPS receivers on the ship can be compared to determine orientation too. Gyroscopes and accelerometers on board keep track of movement.

On board the Russian Soyuz capsule, the crew uses a mirrored periscope to visually line the ship up exactly with the horizon of Earth, firing thrusters to also turn it to parallel motion across the ground. Once aligned like this, the gyroscopes and accelerometers know the ship's orientation relative to Earth. Thus the computers and the crew know which way they are pointing at all times, and can accurately fire engines as needed.

The combination of all of the readings from various instruments helps create what is called a ship's *state vector*, which is a measurement that tells you precisely where you are and exactly where you're going. This is especially critical when you consider the enormous speeds and lack of standard navigation references for a spacecraft.

Future missions to the Moon and Mars will use a similar combination of visual navigation tools and instruments. For a human mission to Mars, this could even include use of Mars's two moons and the faint magnetic field still emanating from the surface rock of Mars.

11.

SPACESHIPS: NAVIGATION SYSTEMS AND HUMAN VARIABLES

LEARN MORE

- Read more about star trackers in this NASA article.
- This article gives you a closer look at the navigational systems and interfaces on the Soyuz capsule.
- Read this brief article from NASA about the use of GPS in ISS attitude control.
- This article from the Technical Institute of Denmark will give you more information on the magnetic fields present on Mars.

12.

SPACESHIPS: NAVIGATING TO THE INTERNATIONAL SPACE STATION

"Trying to fly [and dock] a Space Shuttle, which weighed as much as the [International] Space Station during construction—it was sort of like an elephant ballet. You know, you try and make it graceful."
—Chris Hadfield

12.

SPACESHIPS: NAVIGATING TO THE INTERNATIONAL SPACE STATION

SUBCHAPTERS

- Approaching the Space Station
- Navigate by Committee
- Docking With the Space Station
- Learning to Dock: Practice Systems Failures
- Breaking Into Mir

CHAPTER REVIEW

Docking with the International Space Station as it orbits Earth is a complex, exacting, multidimensional process. Your ship and the Space Station are both going 17,000 mph, you start thousands of miles apart, you have limited time and fuel, and there are no guideposts. Each time Chris docked with a Space Station, he felt like success was somewhat miraculous.

The way you approach and dock depends on your ship's ever-changing position in relation to the ISS and to Earth. Initially, when you are far away from the ISS, information for maneuvers comes from Mission Control; satellite farms have tracked both vehicles, done the math, and figured out the exact geometry for you. Instructions are sent to the onboard computers for vehicle pointing and engine firings.

If the ISS is in front of your ship, you have to decelerate and descend to a lower orbit—which, because of the strangeness of orbital mechanics, will actually make you go faster—so you can catch up. If your ship is out in front, you have to fire thrusters forward to get to a higher orbit, and then drift back to get closer to the ISS.

As you move closer to the ISS, you can lock on with radar and then with lasers. This precise speed and position data is fed to onboard predictor programs so you can maneuver accurately without help from Houston. You want to end up a few hundred feet from the ISS, with no relative motion, in the most fuel-efficient way possible. You then switch from rendezvous mode to proximity operations, where fuel efficiency isn't as much a concern—you just want to dock successfully. When Chris and his crew docked the Space Shuttle with the ISS, docking was primarily done visually, with manual control. The crew would carefully fire thrusters inch by inch until finally locking with the docking mechanism on the ISS.

12.

SPACESHIPS: NAVIGATING TO THE INTERNATIONAL SPACE STATION

Chris describes the process of flying and docking a spaceship as being an unnatural act. The key to being able to learn to dock in space is practice, both in theory and in using different types of simulators. Chris also explains that docking techniques were invented and developed to help astronauts assemble their complex ships in orbit to get safely to the Moon and back.

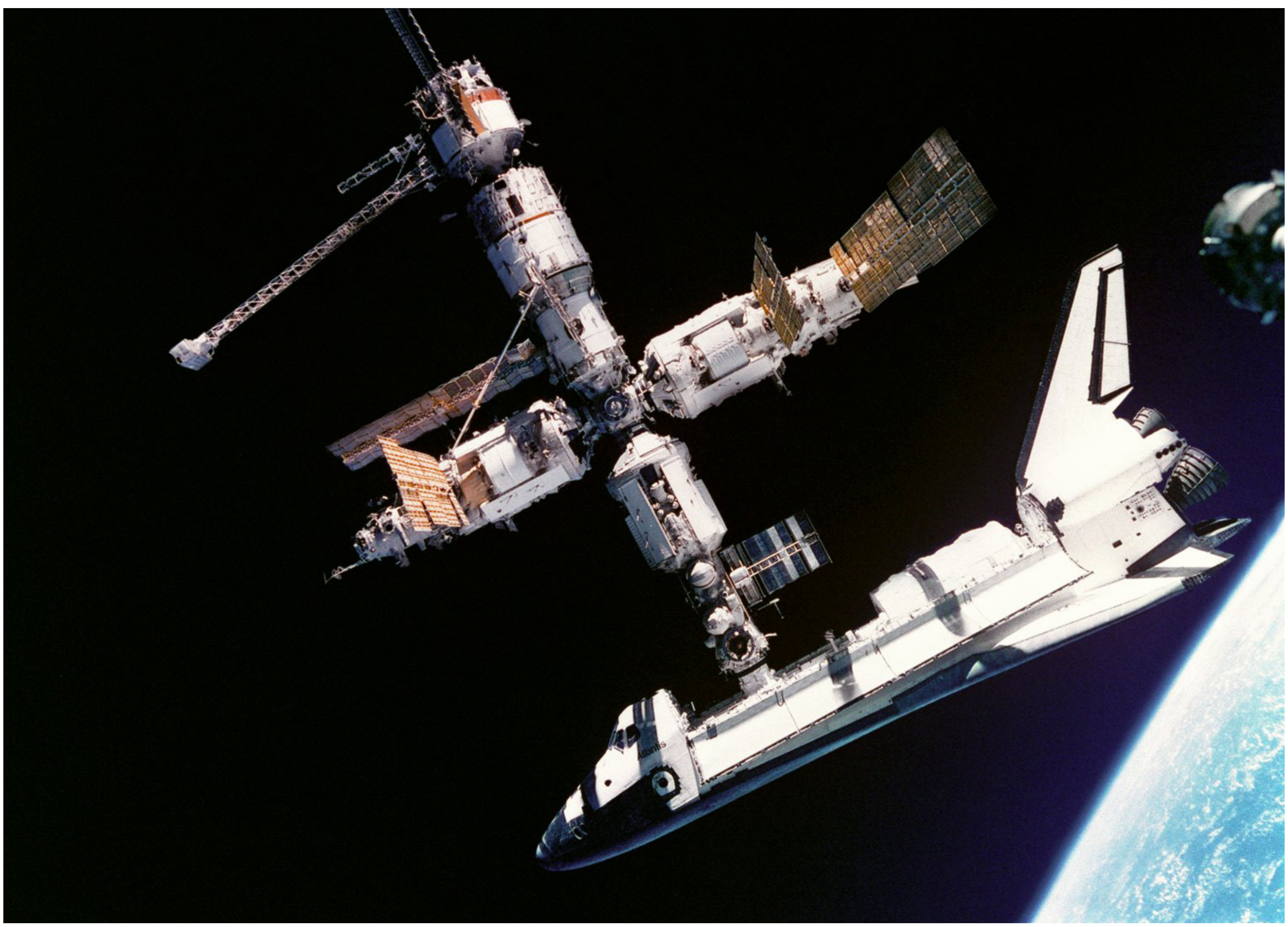
In a reminder of just how manual and occasionally comic spaceflight can be, Chris recounts the time, after he and his crew had docked Atlantis with the Russian space station Mir, that he needed his jackknife to break into the space station.

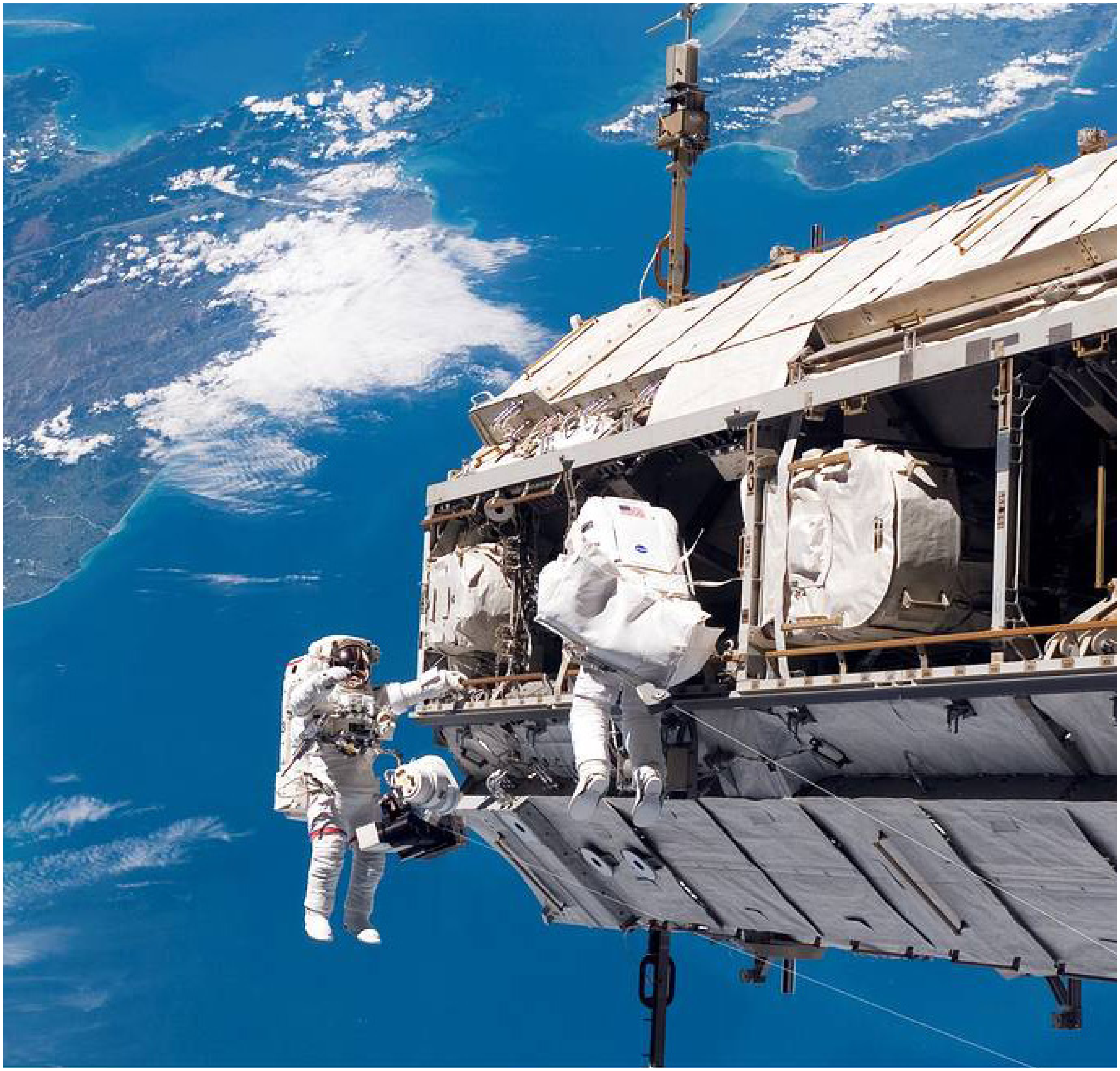
12.

SPACESHIPS: NAVIGATING TO THE INTERNATIONAL SPACE STATION

LEARN MORE

- For a more in-depth look at docking in space, read this paper from NASA, which includes details of the history of docking and the mechanisms used.
- In this NASA feature, find out about the first docking in space, which occurred between two unmanned Soviet spacecraft in 1967.
- This feature from *Time* magazine looks at docking and undocking the Soyuz at the ISS.





13.

THE ISS: CONCEPTION, DESIGN, AND CONSTRUCTION

“We’re trying to use this Station as completely as we can. Take advantage of all this power, take advantage of the cooling, the stability of it, the weightlessness of it, and try and learn about things that we can’t test anywhere else.”
—Chris Hadfield

13.

THE ISS: CONCEPTION, DESIGN, AND CONSTRUCTION

SUBCHAPTERS

- Our First Settlement in Space
- A Laboratory Built on International Collaboration
- Big Picture Modular Design
- Power, Heating, and Cooling
- Orientation
- Placement of Docking Ports
- Laboratories
- Canadarm and Canadarm2: Building the ISS
- Commercial Space Stations

CHAPTER REVIEW

Space stations enable us to experience and take advantage of spaceflight over long periods of time. Chris describes them as "purpose-built laboratories orbiting the world." Their unique environment allows us to conduct experiments that aren't possible on Earth—directly observing the universe and our planet with multiple sensor types, and using the unending, near-perfect vacuum and microgravity environment for research and manufacture. They are also a test bed for spaceship hardware, to gain proven experience and confidence close to home before we head further into the solar system.

The Soviets built the first space station, Salyut 1, in the early 1970s, and launched steadily improved versions of it through Salyut 7 in 1982. NASA's first space station, Skylab, was in orbit from 1973–79. It was built using the heavy lift capabilities of the Saturn V rocket. The first segment of the Russian space station Mir was launched in 1986, and additional segments were sent using Proton rockets and the NASA Space Shuttle until Mir's deorbit in 2001. (Chris and crew built the Shuttle Docking Module onto Mir in 1995.) The International Space Station, the world's largest structure ever in space, began assembly in orbit in 1998, and has had crews aboard continuously since 2000. With 15 countries cooperating on a daily basis to operate it, the lessons learned have been political as well as operational, technical, and scientific. ISS was designed for 30 years of life, through 2028, when the cost of maintenance is expected to start becoming prohibitive. At that time, to avoid an unplanned orbital decay and random impact with Earth somewhere, it will be deliberately driven into the empty expanse of the South Pacific.

The ISS was constructed and assembled module by module. The size of each module was limited by the place and way in which they were launched to space—for example, by the dimensions of the payload bay of the Space Shuttle, or the height of the railway overpasses between Moscow and the Russian launch site in Baikonur, Kazakhstan. The ISS central modules are pressurized habitats where the crew lives and works, while the main transverse truss supports power, cooling, communications, external stowage, and scientific test equipment.

13.
THE ISS: CONCEPTION, DESIGN, AND CONSTRUCTION

The ISS is electrically powered using solar arrays that rotate to track the Sun throughout each orbit. Waste heat is gathered by cooling loops inside the ship and expelled out into space through large, flat radiators. The Station is primarily flown in an orientation known as LVLH, which stands for "local vertical, local horizontal," such that the "bottom" of the ISS faces Earth and the "nose" is pointed into the velocity vector (the direction it's moving).

There are multiple docking ports on the ISS to allow for different types of spacecraft to dock, including the Space Shuttle, the Russian Soyuz spacecraft, planned human-rated capsules, and various resupply craft. The specific docking mechanisms vary from port to port.

The Canadian-built robotic manipulators Canadarm (Shuttle-based) and Canadarm2 (ISS-based) helped assemble, grow, and repair the ISS. The ISS also has a two-armed dexterous robot called Dextre for delicate work outside, and a Japanese-built robotic arm for deploying experiments externally.

There are hundreds of experiments running on the ISS simultaneously, including those sponsored by governments, space agencies, universities, and private companies. The eventual intent is that the cost of launching and operating a space station will become low enough that they can be purely commercial platforms.

LEARN MORE

- This article by *Popular Science* looks at the history of space stations and their design.
- Chris talks about the Mir space station and how it was the second-most successful space station. This feature by *Popular Mechanics* looks at its significance.

13.

THE ISS: CONCEPTION, DESIGN, AND CONSTRUCTION

LEARN MORE CONT.

- This photo series from Space.com shows the construction of the International Space Station.
- Learn more about the basic components of the ISS through this NASA resource.
- Get an in-depth look at the ISS through NASA's reference guide.
- This infographic from Space.com provides more details on the structure of the International Space Station.
- Read about LVLH and other attitudes the ISS sometimes uses on the NASA website.
- International cooperation has been vital in spaceflight. This document provides details of the memorandum of understanding between NASA and the Russian Space Agency.

14.

THE ISS: LIFE SUPPORT SYSTEMS

"In order to go further from the world, we want to be able to count on our spaceship, on the water recycling system, on the power generation system, on the reliability of every little component."
—Chris Hadfield

14.

THE ISS: LIFE SUPPORT SYSTEMS

SUBCHAPTERS

CHAPTER REVIEW

Astronauts live aboard the ISS using a combination of supplies brought up from Earth, including oxygen and water, and onboard technology that regenerates them. To explore further into space, we'll need to develop reliable equipment that will allow us to eventually wean ourselves from Earth resupply entirely.

Much of what the life support equipment does on the ISS mimics what happens naturally on Earth. Processors purify the astronauts' air, filtering trace gases and removing their exhaled carbon dioxide. Where possible, the oxygen is extracted and released back into the cabin, but the small losses are supplemented with stored oxygen. Water is similarly recycled from urine and dehumidifiers, typically with about 90 percent efficiency. That's better than ever, but every cargo ship still carries air and water to the ISS—we need to get to virtually 100 percent recycling before we can venture with confidence to Mars.

Food is even more difficult to recycle, as farming is a multi-stage process, growing seasons take time, and a balanced diet is essential. For simplicity and reliability, the ISS receives virtually all of the astronauts' food via regular deliveries from Earth. To ensure long shelf life and to minimize the chance of food poisoning, meals are dehydrated, irradiated, thermo-stabilized and/or canned. Preparation is kept simple, with a water dispenser and warming ovens. Only rarely, as a kindness from the support team, can a few items of fresh fruit or vegetables be sent to the crew, added as late stowage on a resupply ship.

For missions further into space, bringing prepared food will become less practical. There are currently experiments on the Space Station to explore how to grow crops, testing things such as what direction a plant grows without gravity, how to pollinate, and what types of hydroponic soil are best. The ability to grow food while in space is just one of the many needed technologies for missions to Mars and beyond.

The ISS is thus a test bed for new ideas and technologies, and that includes habitats. On the ISS is a minibus-sized habitable protrusion called BEAM (Bigelow Expandable Activity Module). It was launched like a collapsed accordion, installed using Canadarm2, and then extended full size. This could provide an alternative design for

14.

THE ISS: LIFE SUPPORT SYSTEMS

future space habitats, as it uses less space during launch—meaning smaller rockets can carry it, which reduces cost.

LEARN MORE

- This fact sheet developed by NASA provides details about how water and air are recycled on the ISS.
- Watch this piece from the BBC about lettuce grown on the Space Station.
- These webpages from NASA's Ames Research Center provide details on research into biosciences being developed to help humans live off planet.
- Find out more about expandable habitats on the Bigelow Aerospace website.

15.

THE ISS: EXPERIMENTS

"The [International] Space Station is this great amalgam of experiments all jammed together."
—Chris Hadfield

15.

THE ISS: EXPERIMENTS

SUBCHAPTERS

- Testing the Composition of the Universe
- Detecting Radiation
- Prepare for the Pressure

CHAPTER REVIEW

There are hundreds of experiments running on the ISS, both inside and out. In order for an experiment to be manifested on the ISS it is assessed on many things, including scientific merit, peer review, safety, power/cooling needs, launch constraints, and how the results are returned to Earth. Also taken into consideration is the financial contribution to the ISS made by that international partner and the associated share of onboard resources needed.

Among the experiments mounted outside is a collaboration with the CERN laboratory called the Alpha Magnetic Spectrometer. This giant, instrumented magnet is designed to observe and quantify the subatomic particles moving past the Station, in order to help scientists better understand what the universe is made of (we can only account for 6 percent of what we see). Currently we simply call this great unknown *dark matter* and *dark energy*, but the aim is to help physicists develop a unified theory of how the universe works.

A series of experiments inside the ISS detect and quantify radiation types, both to further understand Earth's magnetic field and to better protect astronaut health. Testing how different structures within the ship act as radiation insulation will be key for travel to Mars, when we are out in interplanetary space, unprotected by Earth. Typical radiation experiments on board are a "bubble detector"—a polymer gel that visually traces passing neutrons—and a phantom human torso equipped with sub-skin detectors.

The role of an astronaut in these experiments is to install them, maintain them, and act as the real-time hands and eyes of the researchers. These experiments not only represent advancements in science, but also in many cases the life's work of the people on Earth who developed them. Astronauts take that responsibility just as seriously as they do looking after the health and safety of the ISS itself.

LEARN MORE

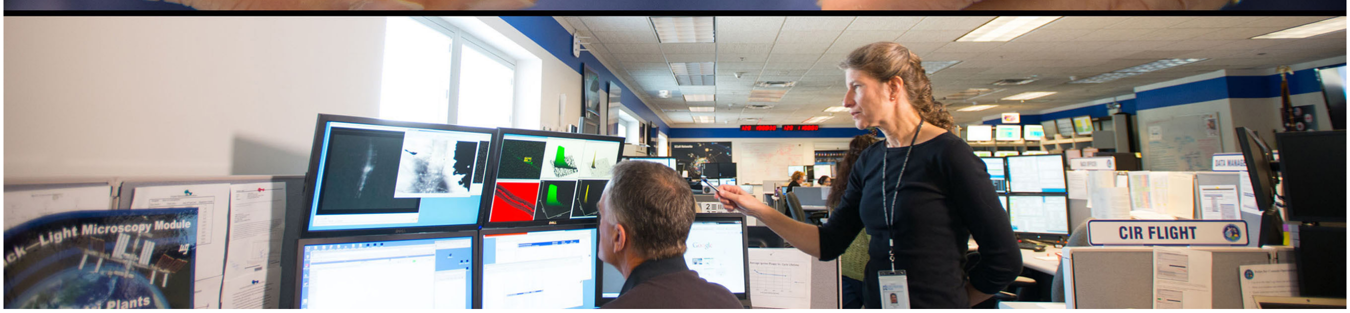
- Find out more about CASIS, the US national lab on the Space Station.
- Find out more about CERN and the work they are doing on the International Space Station to better understand our universe.

15.

THE ISS: EXPERIMENTS

LEARN MORE CONT.

- There are hundreds of experiments running on the International Space Station. This alphabetical rundown from NASA lists all experiments that have taken place on the ISS over the years.
- Read this NASA blog post about some of the more surprising things we have learned from research on board the Space Station and this feature from NASA about how the research carried out in space is benefiting life on Earth.



16.

LEADERSHIP: COMMANDING THE ISS

"Leadership is the art of influencing human behavior to accomplish a mission in the manner desired by the leader."
—Chris Hadfield

16.

LEADERSHIP: COMMANDING THE ISS

SUBCHAPTERS

- Protect the Crew, the Ship, and the Science
- Create Strong Relationships Through Leadership
- Keep Preparing, Learning, and Improving

CHAPTER REVIEW

Commanding the planet's only space station is a huge privilege, but also an unparalleled responsibility. In this role you are not only responsible for the ship and its singular place in the world's space program, but also the lives of the crew on board.

In order to lead properly, you need to know what victory will look like. This is essential to then prioritizing the most important actions to take. For Chris and his crew on the ISS, they defined victory firstly as guaranteeing the survival of the crew, secondly as ensuring the survival of the ISS, and thirdly as conducting as much science as possible for the space agencies. A fourth measure of success was that when the mission was done, they all would be eager to start over, and do it again.

As the Commander, you must work to understand the people you lead—learning their language and culture as much as possible in the time available—and tirelessly build mutual understanding and respect. You have to be able to work constructively with not just the astronauts on board, but also with the Flight Directors and their teams in the Mission Control centers around the world.

Given the level of competence of astronauts on the ISS, the normal command structure on a day-to-day basis is flat and evenly distributed. Thus the role of the Commander is generally subtle, developing the crew ahead of launch and making sure they are protected and feel fulfilled pursing their own personal objectives. But in the case of a serious problem on board, the time for subtlety is over; the command structure moves from flat to vertical. Decisions need to be swift, clearly communicated and rapidly executed by the whole crew. Responding in an emergency is the ultimate test of the Commander.

You can never prepare too early to lead. Take time to think about the things that are important and liable to happen to you, and get ready for them, always. Even bad leaders can be great examples: pay attention to them to learn how not to lead ineffectively.

LEARN MORE

- The Commander and crew of the ISS are constantly changing. Find out more about the current crew at this NASA site.

17.

TRAINING AND LEARNING: ONE-PAGERS

“A large part of successfully being an astronaut is learning how to manage information.”
—Chris Hadfield

17.

TRAINING AND LEARNING: ONE-PAGERS

SUBCHAPTERS

- One-Pagers: Pistol Grip Tool

CHAPTER REVIEW

To be successful as an astronaut, you must learn how to manage a sometimes overwhelming amount of information. Chris processes information pertaining to complex systems by learning the totality of the information and then methodically breaking it down into one-page summaries. Chris used this technique as a test pilot and each time he went to space: he distilled the most complex information he needed to know for a flight into a personal flight manual, made up of one-pagers that focused on his personal interface with the task, tool, or system at hand. Condensing and sorting information in your mind to make a one-pager helps it become less overwhelming. A quick scan of the page just before doing the task reminds you of what you learned, now that you actually need it.

18.

COMMS: MISSION CONTROL EVOLUTION AND OPERATIONS

"Every astronaut should work in Mission Control as much as possible before a flight, because you really get a sense of the pace and the critical nature and the intertwined requirements of operations. It gives you a great awareness of the amount of support that it takes to successfully fly in space."

—Chris Hadfield

18.

COMMS: MISSION CONTROL EVOLUTION AND OPERATIONS

SUBCHAPTERS

- Evolving From Launch Control to Mission Control
- Mission Control Around the World
- Russian Mission Control
- A Constant Web of Information
- Listen for the Quindar Tone
- CAPCOM: Be the Crew's Trusted Liaison

CHAPTER REVIEW

Astronauts in space are supported by a team of experts on the ground known as Mission Control. There are ISS Mission Control centers across the globe in the US, Canada, Russia, Germany, and Japan. While on the ISS, you communicate daily with the teams in all these centers. Astronauts call them on the radio by their host city, like "Houston," or "Munich."

The structure of Mission Control is akin to a pyramid. At the top is the Flight Director, who carries overall responsibility for the team and decision-making. Flight is supported by the rest of the flight controllers in the Mission Control room: specialists by subject such as electrical systems, environmental/life support equipment, robotics, and the flight surgeon. Each console in the room is then further supported by back rooms full of even more specialized subsystem experts.

The role of Mission Control in the United States has evolved since the first manned launches in the early 1960s. Those initial spaceflights were very short, so they only required a support team to provide launch control. However, as spaceflight capabilities and duration expanded, so did the need for a team to oversee the entire mission. The support has thus grown to include both Launch Control to get the crew safely off of Earth, and Mission Control for the duration of the flight. When the Shuttle crew called "Roll Program Houston" just after liftoff, that signified transfer of control from Launch to Mission.

In the US, Mission Control remains in near-constant communication with the crew, using geostationary satellites to relay information between the ISS and Houston, no matter where the spaceship is around the planet. In Russia, Mission Control (abbreviated as ЦУП or TsUP, pronounced like "soup" with a hard "s"), early missions were only able to communicate occasionally, when they passed over large dish antennas within the Soviet Union. Today, that tradition of not being in constant communication with the crew is still in use: TsUP plans specified windows of communication, whereas in Houston the communication line is constantly open.

18.

COMMS: MISSION CONTROL EVOLUTION AND OPERATIONS

The experts sitting in Mission Control are listening to many different communication loops through their headsets, often five at a time, trying to piece out what is important to the system they are responsible for, how it might affect the mission operations, and communicate that information clearly to the Flight Director. The Flight Director then makes decisions about whether that information changes the mission.

Some artifacts from early Mission Control remain to this day. The Quindar tone was the audio chime that was used to turn remote transmitters on/off to communicate with the crew anywhere in orbit. It was needed for technical purposes, but a side effect was that whenever anyone in Mission Control heard that sound, they knew the crew was talking—so they'd stop talking. When Mission Control was digitally updated in the 1990s, the sound was no longer technically needed, but the flight controllers relied on it so much that NASA brought back an artificial version.

In Mission Control, if everyone was talking to the crew on orbit simultaneously, it would be a noisy, confusing babble. Right from the beginning astronauts realized they needed one voice—someone they could trust—to be their relay on Earth. That person is called the Capsule Communicator, or CAPCOM, harking back to when the original spaceships were all capsule-shaped.

The CAPCOM's job is to listen to all of the information about the mission from every console in the room, hear what the Flight Director wants the crew to know, and then turn it into words the crew will understand, and decide when best to tell them. The CAPCOM is also the crew's trusted agent on the ground, to fight battles and argue in their stead. This role is normally filled by an experienced astronaut or someone who works closely with the astronauts. Chris supported 25 Shuttle missions in a row as CAPCOM, and was NASA's Chief CAPCOM for several years.

LEARN MORE

- Read more about the role of Mission Control in the book *Go Flight!: The Unsung Heroes of Mission Control, 1965–1992* by Rick Houston and Milt Heflin, which tells the story of the people who worked in Mission Control at NASA during the Apollo era.

18.

COMMS: MISSION CONTROL EVOLUTION AND OPERATIONS

LEARN MORE CONT.

- Find out more about Mission Controls in Germany, Japan, Russia, Canada, India, and the United States.
- Read more about the Johnson Space Center in Houston, where NASA's Mission Control is located, in this article by Space.com.
- Read this feature from the *Washington Post* about how Mission Control has evolved since the Apollo era.
- Listen to this podcast from NASA, which discusses the history of Mission Control and how it will evolve in the future.
- Hear the Quindar tone for yourself.
- Watch *Mission Control: The Unsung Heroes of Apollo*, which tells the story of Mission Control during the Moon landing and the modern Flight Directors who work in Mission Control.

19.

SPACEWALKING: SPACESUITS

"It's not really a suit. It's more like a one-person spaceship—completely self-contained and different from the ship you crawl out of."
—Chris Hadfield

19.

SPACEWALKING: SPACESUITS

CHAPTER REVIEW

The vast majority of astronauts' work is done inside the relatively safe environment of the spaceship, and they use robots like Canadarm2 to remotely do work outside in the harsh thermal vacuum. Occasionally, though, external work needs to be done that requires direct human judgment or dexterity. When the need outweighs the risk, a spacewalk is planned.

Spacewalks, or EVAs (Extra Vehicular Activities), are dangerous, physically demanding, and rare. Since Alexei Leonov did the first in 1965, just over 200 people, including the 12 moonwalkers, have ever performed an EVA—Chris was the 127th.

EVA spacesuits are designed to protect astronauts from the hostile, deadly environment of space. They are pressurized with pure oxygen to one-third of sea-level pressure, can withstand the extreme cold and heat of the vacuum, and protect astronauts from the constant bombardment of tiny, high-speed micrometeoroids that fly through the solar system at 10 kilometers per second.

The suit has a portable life-support system in its backpack. It contains your oxygen-purification system, cooling system, radio, and battery power. On your helmet, there are cameras so that Mission Control can get a visual record of work you carry out, as well as lights for working in the dark. It also has a gold visor and sunshields to protect your face and eyes from the incredibly harsh, unfiltered Sun. On the chest there is a computer display and control module to run the suit and a purge valve to dump pressure if needed. The controls and labels on the front of the suit are oriented backward so that you can read them using the mirror on your suit's wrist. Two hard clips on the front of the suit allow you to attach a metal frame that holds all your tools. During a spacewalk you keep yourself connected to the Space Station with at least one tether, clipped to the suit using locking metal hooks.

Spacesuits are white to reflect the heat from the Sun. The suit itself consists of 14 layers of material, with each layer playing a different role in keeping you alive. The most fragile part of the whole suit is the palm and fingers of the gloves: they're just a few layers thick to enhance dexterity. Since the gloves are so delicate, astronauts pause to check them for damage regularly during spacewalks. In order to have as much tactility in the hands as possible, there is a curved metal bar in the palm of the gloves that can be cinched tight with

19.

SPACEWALKING: SPACESUITS

a strap across the back of the hand, to stop the pressurized glove from bunching up in the palm.

Unlike for the Apollo moonwalkers, the boots on your ISS spacesuit are designed to lock into a portable foot restraint, known as a PFR. PFRs can be located at various places around the outside of the ISS; once you're locked in, both your hands are free to do work. Without it, you'd always have one hand busy just hanging on.

Before you do a spacewalk there are years of training on suit systems, in virtual reality simulators, in vacuum chambers, and simulating weightlessness under water. Chris spent over 400 hours suited in the pool prior to his first spacewalk. In addition, you need to qualify on SAFER, the Simplified Aid for EVA Rescue. It is a jetpack, used as an emergency self-rescue system in the event that you were to detach from the ISS and go tumbling into space. SAFER is operated by a deployable joystick that fires puffs of nitrogen gas through 24 small nozzles to stop you from tumbling, and help steer yourself back to grab onto the Station.

Suits have to be checked for contaminants when they get back to the Space Station to make sure that nothing foreign comes on board that will be a hazard to the health of the crew. The Apollo astronauts had to check for little pieces of unweathered, glass-like Moon dust, and current astronauts check for ammonia from the cooling system of the ISS. Future suits will need to think about contaminant considerations: maybe the suits don't need to come all the way back into planetary bases and can instead just attach to the outer wall of the astronaut habitat.

LEARN MORE

- Find out more about early spacesuits, the evolution of spacesuits, and how they are constructed today. This infographic from Space.com provides details of the evolution of spacesuits, and this one provides further details of the workings of spacesuits.
- What is a spacesuit? NASA provides further details of what they are and links to other great articles here.

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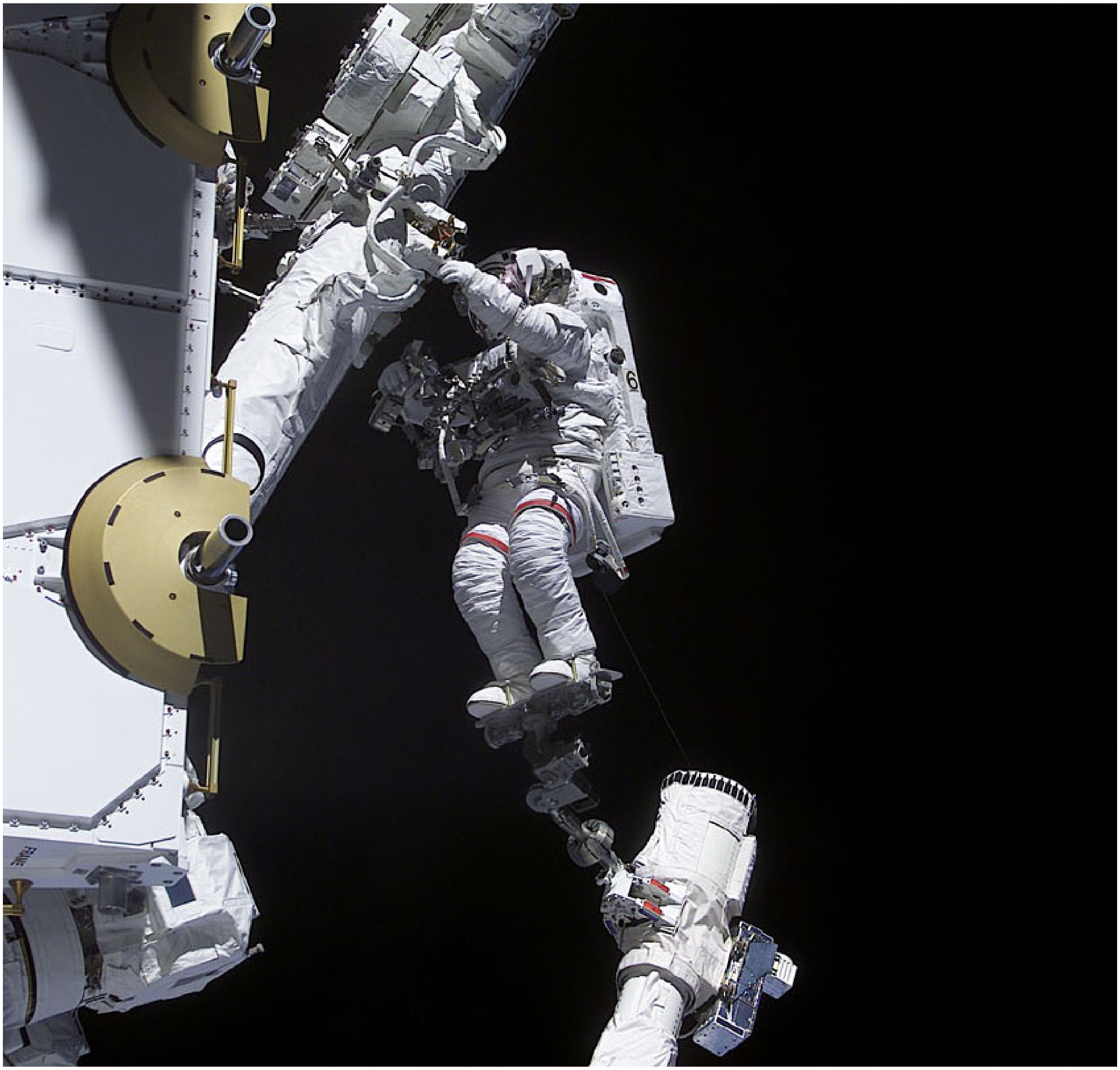
SPACEWALKING: SPACESUITS

LEARN MORE CONT.

- This video from NASA talks further about the development of spacesuits.
- The way we explore space is changing, which means our spacesuits will change also. Read this report from MIT on the future of spacesuits and how they may eventually become like a second skin for humans traveling to Mars.



20.

SPACEWALKING: SPACEWALKS

"[There's] nothing between you and the universe, but the plastic of your visor."
—Chris Hadfield

20.

SPACEWALKING: SPACEWALKS

SUBCHAPTERS

- Stay Focused and Aware
- The Spacewalk Experience
- The First Canadian Spacewalk

CHAPTER REVIEW

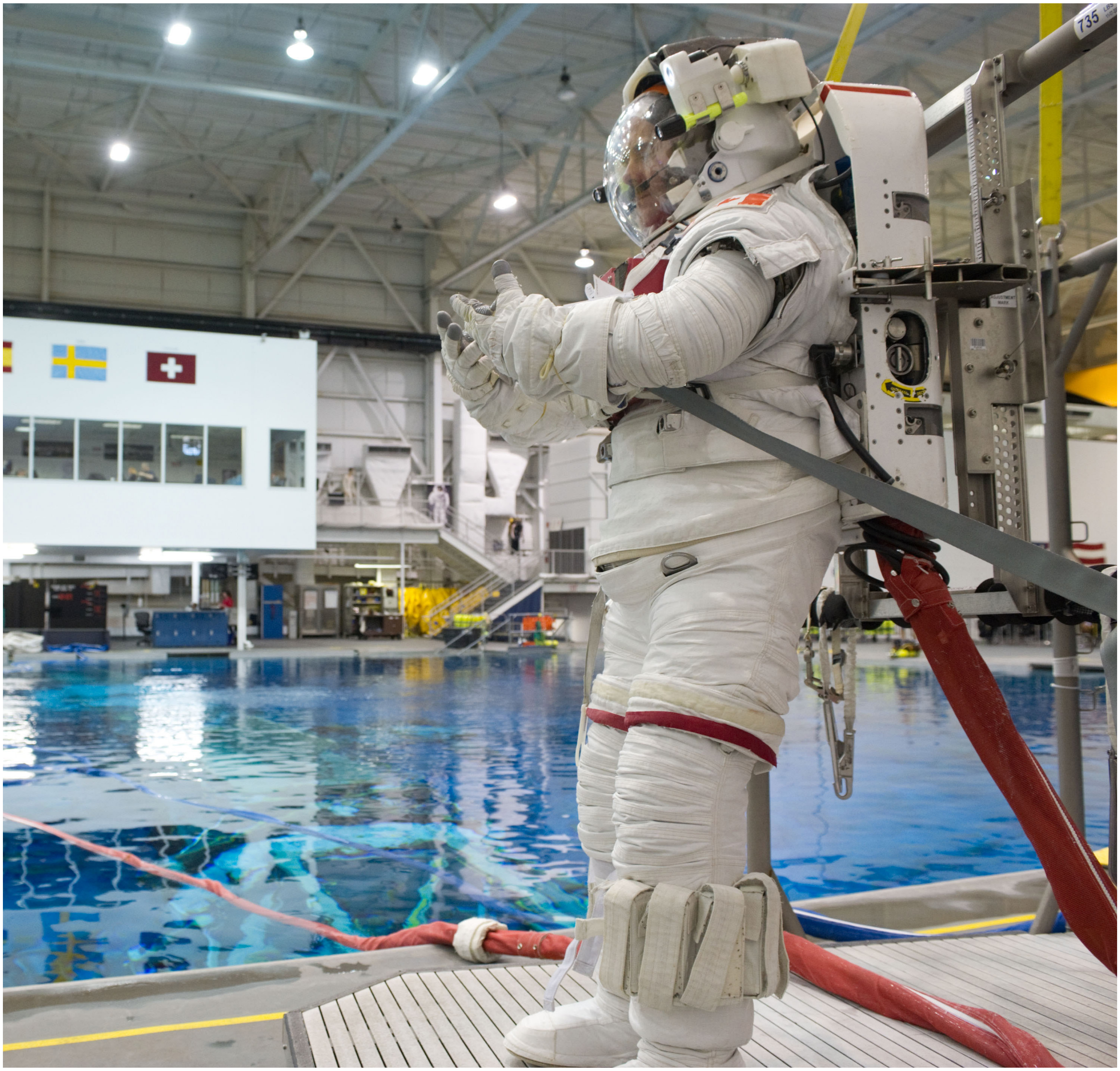
Spacewalking is dangerous and only performed when a job requires the skill and dexterity of a human—something that can't be done by a robot. The process of doing a spacewalk is not just physically challenging due to the pressurized resistance of the suit, it is also mentally demanding—you have to focus on the work you are doing as well as your safety, a vast number of potential tools, interacting with the crew and with the team down in Mission Control, all while the clock is ticking and the universe is ready to kill you.

During a spacewalk you are supported by the crew inside the Station, who help to remind you where you are in the procedures or settings for the tools you are using. You have to work through your tasks with only an emergency checklist, as there is no practical way to carry a printed set of instructions. You are reliant on your crew and a spacewalk-experienced astronaut down on the ground to support you through the procedures. If you are the lead spacewalker, you are also responsible for keeping track of what the other astronaut is doing outside, as well as the cadence, safety, and completion of the entire EVA.

The experience of spacewalking is wildly different from being inside the spaceship. It's akin to standing next to the window of a high-rise building versus being just a few feet over, but now outside that same window. For Chris, one of the most incredible spacewalk experiences was to walk through the Southern Lights while on the Canadarm2, something he likens to "surfing on the aurora." Spacewalking is also a huge honor for you, your family, your agency, and your country—for Chris, his initial EVA was extra special as he was the first Canadian to ever walk in space, an event celebrated on the back of Canada's five-dollar bill.

LEARN MORE

- Find out more about Chris's historic spacewalk on the Canadian Space Agency website.
- Learn more about spacewalking in this feature by NASA.
- This video shows what the aurora australis looks like from space.



21.

SPACEWALKING: TRAINING

"Make it as realistic in your mind at that moment as you possibly can. I'm not 40 feet below the water in a pool in Houston, Texas. I am in the airlock on a space station."
—Chris Hadfield

21.

SPACEWALKING: TRAINING

SUBCHAPTERS

- Spacewalk Simulations
- Mentally Get Yourself in the Game

CHAPTER REVIEW

The environment on Earth that best simulates the weightlessness of spacewalking is under water. NASA astronauts train at the Neutral Buoyancy Laboratory at the Johnson Space Center. In this facility there is a 45-foot-deep pool, which contains a replica section of the ISS and the Canadarm2, used to help practice the choreography of a spacewalk. The main aim of training is to invent, develop, and perfect entire EVAs, and hone the individual skills needed.

Astronauts spend hundreds of hours training under water, learning how to operate and maneuver in their spacesuit, learning how to think in three dimensions, and developing new techniques for spacewalking. During training you practice the skills to monitor the health of your suit, get used to the cadence of hot sunrises and frigid, dark sunsets every 46 minutes, and prepare for the physically demanding experience of spacewalking, as the pressurized, stiff suit resists every motion. You train and prepare to the point that when you are carrying out an actual spacewalk, the experience is not overwhelming, but hopefully familiar and efficient.

There are many different reasons for spacewalking—everything from installing a new piece of equipment or removing a broken piece of apparatus, to deploying experiments, to surveying for damage—but the operational components of a spacewalk are all the same regardless of task. The training facility is where you learn those operational components, from how to tether yourself to the ISS, to how to move your body, to how to understand the communications protocol.

The underwater training is very similar to a real spacewalk. The spacesuit is assembled around the EVA astronaut poolside by a crewmate, in order to accurately simulate the sequence and skills needed in orbit. The suit is so heavy that once you're fully suited up, a crane has to lift and lower you into the water. Safety divers adjust weights on your suit to make it perfectly neutrally buoyant, and then training begins with the two spacewalkers inside the cramped, replica airlock.

21.

SPACEWALKING: TRAINING

In order to get the most out of this simulation, you need to make it as realistic as possible in your own mind. The full-size accuracy of the underwater ISS mock-up and the neutral buoyancy environment help, but you also need to have the right mindset. As fighter pilots say, "you fight like you train."

LEARN MORE

- NASA has professional trainers who train astronauts for spacewalks. Find out what they do in this interview.
- This NASA fact sheet provides more details on the Sonny Carter Training Facility: The Neutral Buoyancy Laboratory.
- This feature talks more about the role of the divers in training astronauts to spacewalk.

22.

SPACEWALKING: SPACE AND PERSPECTIVE

"It's a new human experience. It's a perspective on the world that we've only imagined."
—Chris Hadfield

22.

SPACEWALKING: SPACE AND PERSPECTIVE

SUBCHAPTERS

- Make Decisions With a Global Perspective
- Use Data to Heal and Protect the Earth
- What Does It All Mean?

CHAPTER REVIEW

Aside from the technical tasks that you'll need to accomplish when you get to space, the first thing you will inevitably do is laugh at the startling, new sensation of weightlessness. As soon as possible you'll want to unstrap from your seat, float to the window, and truly see Earth for the first time. From the altitude of a spaceship you can see halfway across continents, to the thin skin of the atmosphere clinging to the horizon, and on to the eternal blackness of space.

Being in space is a new human experience. For Chris, it was something he wanted to capture and soak up as fully as possible so that he could do it justice when describing the experience to the people who helped him get there.

Going into space gives us a new global perspective on the world—not just in terms of exploration, but also what lies beyond our own experience on Earth. All of the information we are able to gather through space exploration from both satellites and astronauts contributes to our ability to make better decisions for our planet. It also increases our understanding of other planets, deepening our awareness of what is typical, normal, and natural versus the impact we have as a species on our Earth.

Astronauts on the Space Station are not passengers, they are crew members on a spaceship with a finite amount of resources. For Chris, Earth is the same—we are all crew members on a planet with a finite amount of resources. Going into space helps us look at how to address problems globally, with a newly factual, worldwide comprehension, and helps instill a sense of responsibility and hope for the future of our human existence.

LEARN MORE

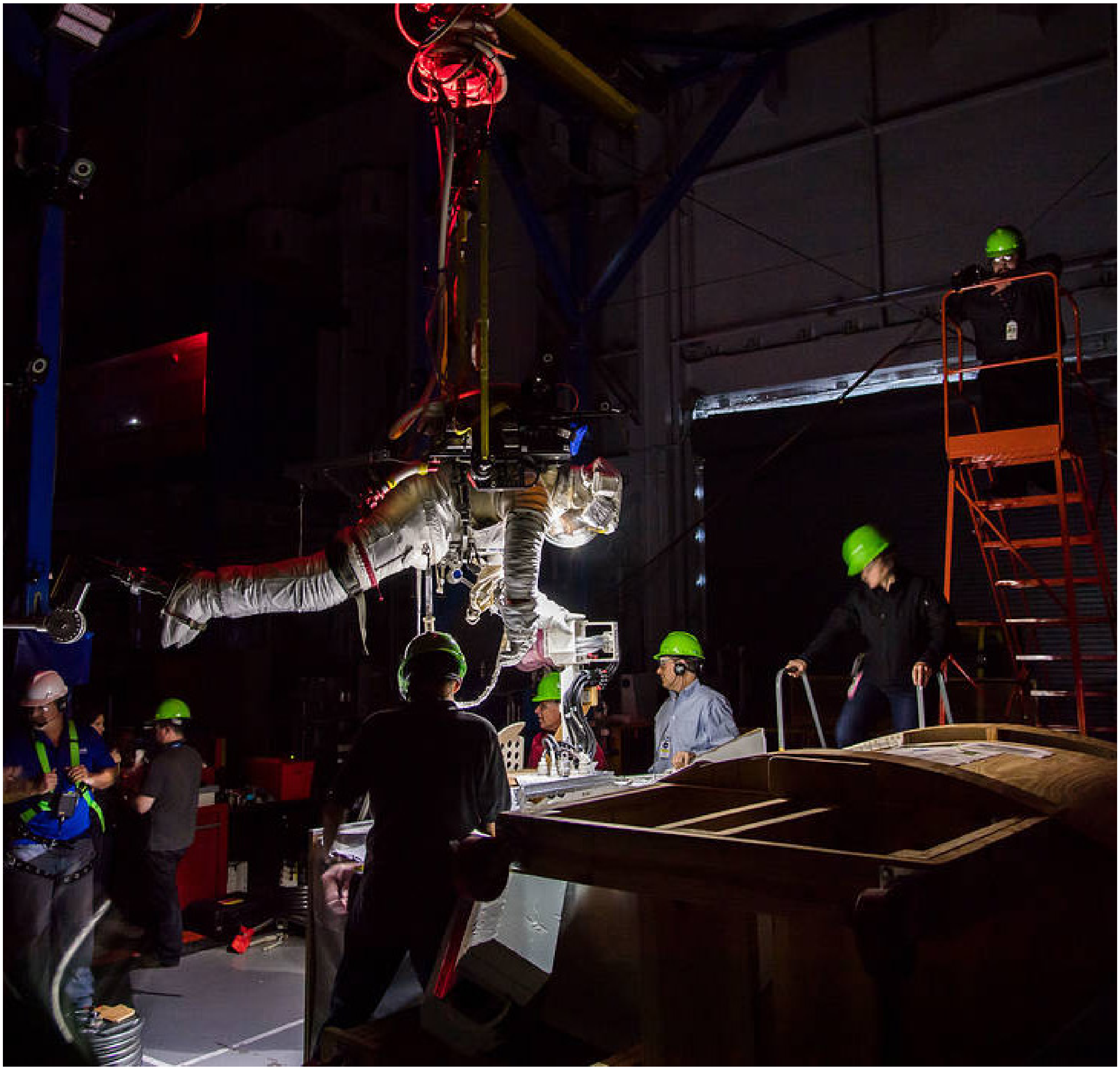
- Going into space has a profound effect on many astronauts and the way they view the world. Read this piece from *National Geographic* about how the experience has changed some astronauts.

22.

SPACEWALKING: SPACE AND PERSPECTIVE

LEARN MORE CONT.

- Hear Chris talk more about the overview effect, and the impact of seeing the world from above on his perspective in this video.
- Space technology is helping to improve the lives of people living on Earth. Find out more about how space is benefiting us all in this feature by the World Economic Forum.
- Learn more about the work NASA is doing to understand more about our environment from space.



23.

TRAINING AND LEARNING: SIMULATIONS

"Simulation is not just important. It's critical to success."
—Chris Hadfield

23.

TRAINING AND LEARNING: SIMULATIONS

SUBCHAPTERS

- Simulators Are Wrong
- Simulate the Worst-Case Scenario
- Visualize and Prepare for Failure
- Emergency Training Across Agencies
- Future Simulations

CHAPTER REVIEW

Spaceships are so complex that you train to operate them in stages. First, you just learn the theory behind everything. Then you study in single-system trainers, seeing how something complex works independently. After that you're ready to get into a more integrated cockpit by yourself, and then with other crew members. Eventually the training team starts injecting system failures into the simulation. Finally you're ready for full mission profiles with multiple, interrelated malfunctions that test the very limits of crew and vehicle. The training team's aim is to show you every possible thing that can go wrong and let you practice how to properly react.

Although simulations are vital, Chris advises some skepticism, because they will inevitably behave slightly differently than the real systems do, especially in the nonintuitive environment of space. He advises you to act as the integrator, looking at which parts are correct and which parts are misleading. Simulators are never going to perfectly replicate reality, especially for rocket forces, weightlessness, and thermal vacuum, so you need to be vigilant for which parts are similar and which are not.

The extent of simulation in astronaut training goes as far as practicing what to do when an astronaut is killed in the line of duty. This type of simulation, known as a *contingency sim*, has to be taken seriously because the reality of exploring space is that some astronauts will die.

Contingency sims bring the entire team together to look at how to react and work through possible scenarios—crewmates, Mission Control, public relations, and management. Although seemingly morbid, these sims can also help the families of the crew better prepare for a dreaded situation. During one contingency sim, Chris brought his wife Helene along, so that she could accurately see how everyone would react and what her role would need to be. As a result she modified her own plans for the duration of Chris's spaceflight.

23.

TRAINING AND LEARNING: SIMULATIONS

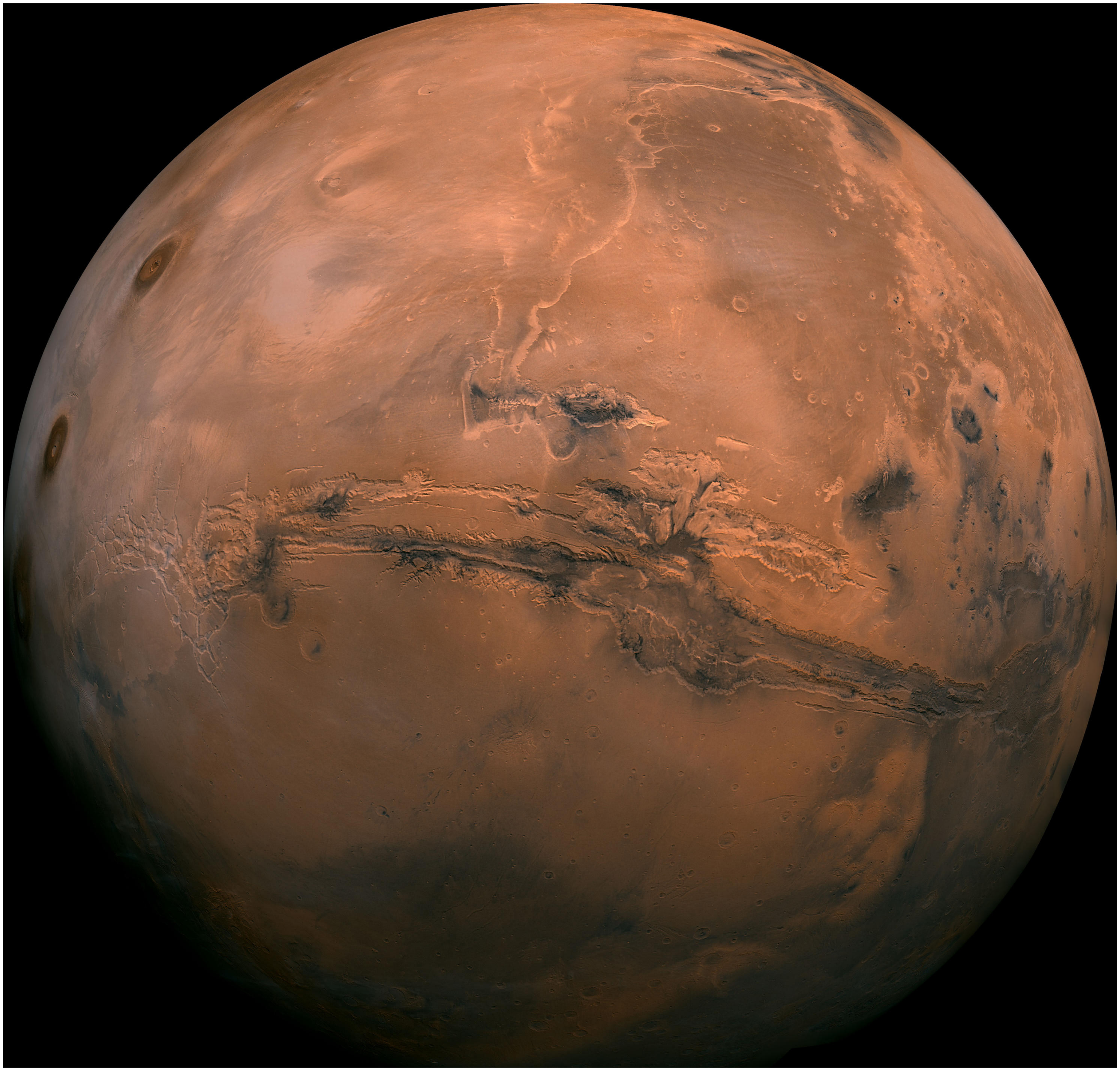
The only way to successfully execute spaceflight is to visualize, simulate, and practice failures—not only death, but also other serious scenarios, such as failures of critical equipment during docking. The worst time to start thinking about failure is during the situation where things are actually going wrong.

Training for emergency situations is different from country to country, as the procedures and simulators were often developed independently. Because of international cooperation, this gives crews different ways to practice for a similar problem. In Russia, there is a full-scale mock-up of the Space Station built inside a vacuum chamber. Rather than just being told the ISS suddenly has a leak, or watching a pressure gauge drop, this sim adds the realism of actual pressure decrease and ears popping, with the associated natural sense of urgency. Training there is one more useful step in getting truly ready for all that can happen when away from Earth.

Simulating space tasks has always been difficult to properly do on Earth, especially with purely mechanical mock-ups, but virtual reality is helping to provide new ways for astronauts to experience as close as possible to what they will be doing. As space missions become more multifaceted and astronauts venture to the Moon and Mars, training will also become more complex. Astronauts will no longer have an option to land back on Earth if something goes wrong, so they'll need to be more thoroughly prepared to deal with the unknown. Simulations for missions of this kind will need to help astronauts be as prepared as possible, including updated onboard virtual reality to continue to train during the mission itself.

LEARN MORE

- Learn more about simulations by reading this PDF produced by NASA, which provides an overview of simulations used in astronaut training, and this feature from NASA, which explores future simulations with commercial craft on which NASA astronauts are now training.
- Virtual reality is becoming an increasingly integral part of astronaut training. Read about the virtual reality technology being used by NASA for astronaut training in this article from *The Verge*, and check out this article from *Scientific American*, which looks at other uses for virtual reality in spaceflight.



24.

MARS: HOW TO GET TO MARS

"It is still staggeringly complex to send people to Mars. And with complexity comes risk."
—Chris Hadfield

24.

MARS: HOW TO GET TO MARS

SUBCHAPTERS

CHAPTER REVIEW

If you look at the 300,000 year history of human exploration, it is evident that the need to explore is fundamental to our nature. Thus sending humans to Mars isn't really a question of if. It's merely a question of when. Like every exploratory voyage we've made in the past, from crossing the Red Sea for the first time to reaching the South Pole, we've had to decide: When will our technology be good enough to make it? And when will we agree as a people that the risk is worth taking?

Mars is alluring because it has an atmosphere, water, and geothermal heat—meaning there may be fossils there, or even life itself. Yet so far we've agreed that it has been too dangerous for humans to go look. Even our robotic missions have failed 50 percent of the time just trying to get there. It's similar to our attempts to sail the oceans of the world in the 1400s, pushing our technology and understanding to the limit, with many missions failing in the attempt. But, as technology developed, humans were able to cross the oceans more safely, to great commercial and scientific impact. There are both business and scientific benefits to come from the risks of exploration.

The technical and engineering challenge to get to Mars is daunting. Mars and Earth both orbit the Sun, which means the distance between the two planets is constantly changing. If we wait for the optimal alignment and use the best engines we've devised, it's still about five months to get there. That's a long voyage into the unknown with an unproven ship, hauling everything you need, with no way to resupply critical items. And that's just the beginning. On arrival you have to somehow slow to orbital speed, descend through Mars's very different atmosphere, and safely land. Not to mention doing it all in reverse to come home to Earth.

The path we take between planets needs to be decided. While the Hohmann transfer is the most energy-efficient way of moving between orbits, it is not optimized for speed. Every day we spend in transit is one more day spent eating food, drinking water, breathing the ship's air, and producing waste, as well as being exposed to interplanetary radiation and the risk of critical systems failures. If we have enough fuel, we could steer a more direct route, brute-forcing the orbital mechanics. If we invent more efficient engines, we could fire them longer and coast less, also decreasing total time.

24.

MARS: HOW TO GET TO MARS

We may continue to decide that it is infeasible to go to Mars with the engines we've invented so far.

On arrival at Mars, we need to slow down to orbital speed. We could fire the engines, but that means we needed to haul that braking fuel as cargo all the way from Earth. We could use Mars's thin atmosphere to provide braking friction, steering to dip exactly into it to gradually slow to the right speed. But the whole transit ship would need to be tough enough to take the associated heat and pressure. A compromise option might be to jettison the habitat that carried us to Mars, get into a capsule, and ride it directly to the surface.

But the Martian atmosphere is much thinner than Earth's, meaning parachutes don't work nearly as well. Yet it is thick enough that friction causes heating so the ship needs appropriate thermal shielding. The heaviest object we've landed on Mars (as of 2018) was NASA's Curiosity Rover, which weighs around one ton (on Earth). A crewed ship would weigh much more. For putting people on Mars, we'll likely need to use the Martian atmosphere to partially slow down the craft, then fire engines to slow the rate to the surface.

It all sounds very daunting, with a high probability of failure leading to death. But most exploration looked that way at the outset. It is through incremental improvement of technology and choosing the right moment to take a new risk that explorers have succeeded in the past.

LEARN MORE

- Keep up to date with the latest developments on NASA's journey to Mars through this online resource.
- This worksheet from NASA provides details about how to calculate launch windows for Mars.
- The landing of the Curiosity Rover involved different stages in order to slow down in the thin Martian atmosphere. Watch this video from NASA to find out more about how the landing worked. Discover more about the landing of the Curiosity Rover in this feature by Space.com.

24.

MARS: HOW TO GET TO MARS

LEARN MORE CONT.

- This feature from the Planetary Society looks at plans to land humans on the surface of Mars.
- This feature from *Scientific American* looks at different ways of reaching Mars safely.
- Over recent years there has been a lot of news coverage about planned missions to Mars. This report by MIT assesses the feasibility of one such mission, Mars One.
- Read another take on Mars One, the obstacles the company faces, and Chris's perspective on their mission in this article.
- This NASA site provides extensive details of current missions, current research, and plans for the future. The Canadian Space Agency (CSA) also provides further details of our journey to Mars and why humans should go there.

25.

MARS:
LIVING ON ANOTHER PLANET

"Mars is further away than most people think."
—Chris Hadfield

25.

MARS: LIVING ON ANOTHER PLANET

SUBCHAPTERS

- Learn to Grow Food
- Prepare for the Repercussions of Weightlessness
- Make the Adjustment Easier
- Protect Yourself From the Elements
- Abide by the Martian Communication Protocol

CHAPTER REVIEW

Growing food in space is a complex proposition; however, solving this problem would provide a sustainable food source and help support the living environment on a spaceship, as plants convert carbon dioxide to oxygen. Experiments are being run on the ISS to explore what types of food can be grown in weightlessness, and eventually on the Moon or Mars. It is likely that a human mission to Mars will have a garden on board and an astronaut trained in horticulture.

Extended weightlessness takes a toll on the human body. We've learned from the ISS that there are significant impacts on balance, blood pressure regulation, bone density, and sometimes vision. For astronauts that travel to Mars, there won't be a ground support team to assist after landing. Depending how long crews need to adapt under Martian gravity (38 percent of Earth's), the landing ship may need to function as a rehab facility. The weight and configuration of the Martian spacesuits will also have to allow for this adaptation period. In addition, the natural environment on the surface of Mars is deadly for human life; very low air pressure, no oxygen, 96 percent carbon dioxide, and high radiation. The habitat and spacesuits will need to protect the crews from this.

Life on Mars will also be psychologically challenging. Even when Earth and Mars are at their closest, 35 million miles apart, it takes radio waves about four minutes to get from here to there. So if the Martian crew transmits "Houston, Hawking Base here," the quickest they will hear a response is eight minutes later—worst case is 48 minutes later. Real-time communication will thus be impossible, and the Martian crew will need to be self-reliant, technically and mentally.

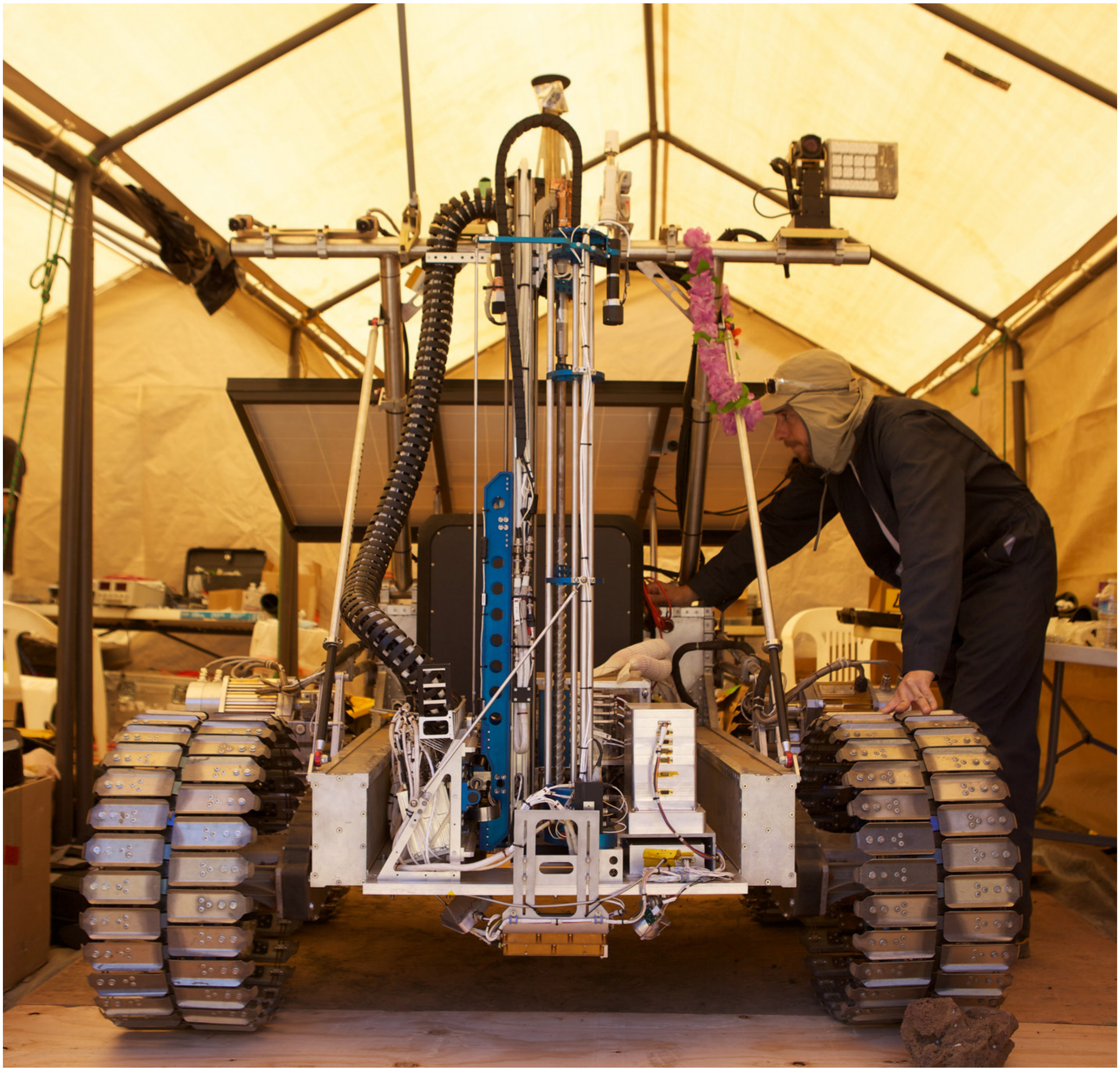
Currently there are simulations looking at possible ways to deal with the communication delay. These include a habitat under the ocean that Chris commanded for two weeks, conducting operations with a Martian-representative time delay. One solution that worked well there used recorded video messages sent back and forth, like has often been portrayed in the movies.

25.

MARS: LIVING ON ANOTHER PLANET

LEARN MORE

- Read this piece from NASA about why it's important to study plants in space.
- Learn about what food can and can't be grown in deep space in this feature from NASA.
- Learn about how astronauts simulate deep-space missions by living under the sea on Space.com and on NASA's website.
- Keep abreast of the latest research from NASA into the human body in space.
- This feature from NASA explores gravity fields and some of the other issues that will affect astronauts traveling to Mars.
- This piece from *Wired* discusses some of the effects being on Mars would have on the human body.
- This piece from Space.com looks at designing spacesuits for Mars.



26.

MARS: IN-SITU RESOURCE UTILIZATION

"I think the first astronauts that walk on Mars will be arriving at a little place that's already built."
—Chris Hadfield

26.

MARS: IN-SITU RESOURCE UTILIZATION

SUBCHAPTERS

- The Chemistry Behind ISRU

CHAPTER REVIEW

One of the best solutions for human travel to Mars is to not have to bring everything in your spaceship. Instead, we could send a cargo ship in advance and start building a small robotic base, remotely taking advantage of resources already on Mars, in a process referred to as in-situ resource utilization (ISRU).

On Mars, there is a thin carbon dioxide atmosphere, as well as a large amount of water ice below the surface and at high latitudes. Thus if the ISRU robot lands in the right place, it can process the local Martian air and ice to produce water to drink, oxygen to breathe, and even fuel. All it needs is the right equipment and an electric power source, like solar. A crew traveling to Mars could arrive to a richness of ready-to-use vital resources.

Chris describes the Sabatier process for creating hydrogen, oxygen, and methane on Mars. The first step is to decompose the water (Martian ice) through electrolysis: essentially, run an electric current through water to separate the H20 into hydrogen and oxygen gases, collecting them separately. Then, by mixing that hydrogen gas with the carbon dioxide in the atmosphere (or from human exhalation) across a nickel catalyst brought from Earth, the Sabatier process generates water to drink and methane to be used for heating and rocket fuel. The chemical reaction looks like this:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The beauty of this reaction is that it’s nearly a closed cycle: the water generated can be split again and pumped back into the reaction to continue generating more oxygen and fuel. And everything you can create there, you don’t have to bring from here.

LEARN MORE

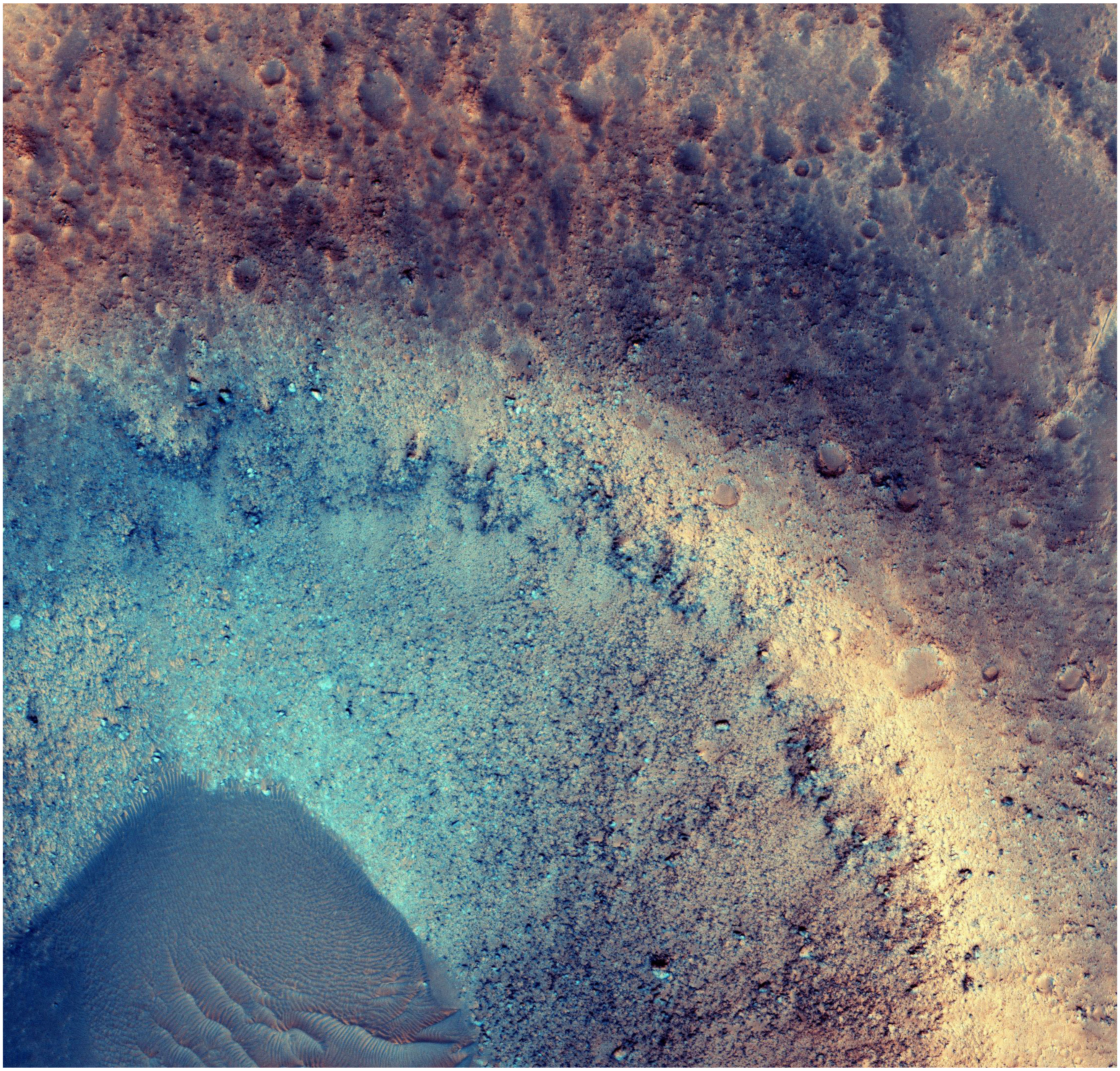
- Find out more about ISRU development here.
- Read about NASA’s use of the Sabatier process on the ISS to generate drinking water here.

26.

MARS: IN-SITU RESOURCE UTILIZATION

LEARN MORE CONT.

- Find out more about how NASA plans to create rocket fuel on Mars in this feature by *Wired*.
- Companies are also planning on mining asteroids for resources, including rocket fuel. Find out about two of the main companies: Planetary Resources and Deep Space Industries.



27.

MARS: EXPLORING MARS, GEOLOGY, AND ASTROBIOLOGY

"If we can just find one fossil on Mars, we know that there is life somewhere else, and therefore there's life everywhere."
—Chris Hadfield

27.

MARS: EXPLORING MARS, GEOLOGY, AND ASTROBIOLOGY

SUBCHAPTERS

CHAPTER REVIEW

One of the greatest impacts of a mission to Mars would be finding life or evidence of extinct life, no matter how simple that life may be. It would not only answer the question of whether we are alone in the cosmos, but would also indicate that there is potential for life everywhere in the universe. Then, the question would be what to do next. Explore further? Transmit our knowledge? Send tiny robotic emissaries? Build better telescopes?

To prepare for Martian exploration, astronauts will need to not only train for spaceship operation and surface life support, but also in geology and even astrobiology. The Apollo astronauts trained like this to be effective explorers on the Moon, learning the difference between sedimentary, metamorphic, and igneous rock, studying on location in lunar-representative places on Earth. Future Martian astronauts will have to do the same, but including places like the Burgess Shale, rich in not just formative geology, but also fossilized life.

Studying the Moon, Mars, and beyond with robots has brought huge new understanding to science. It has also helped teach us about the formation and existence of our own planet. The continued use of telescopes and robots will help us look even further and choose where, as a species, we will go next.

LEARN MORE

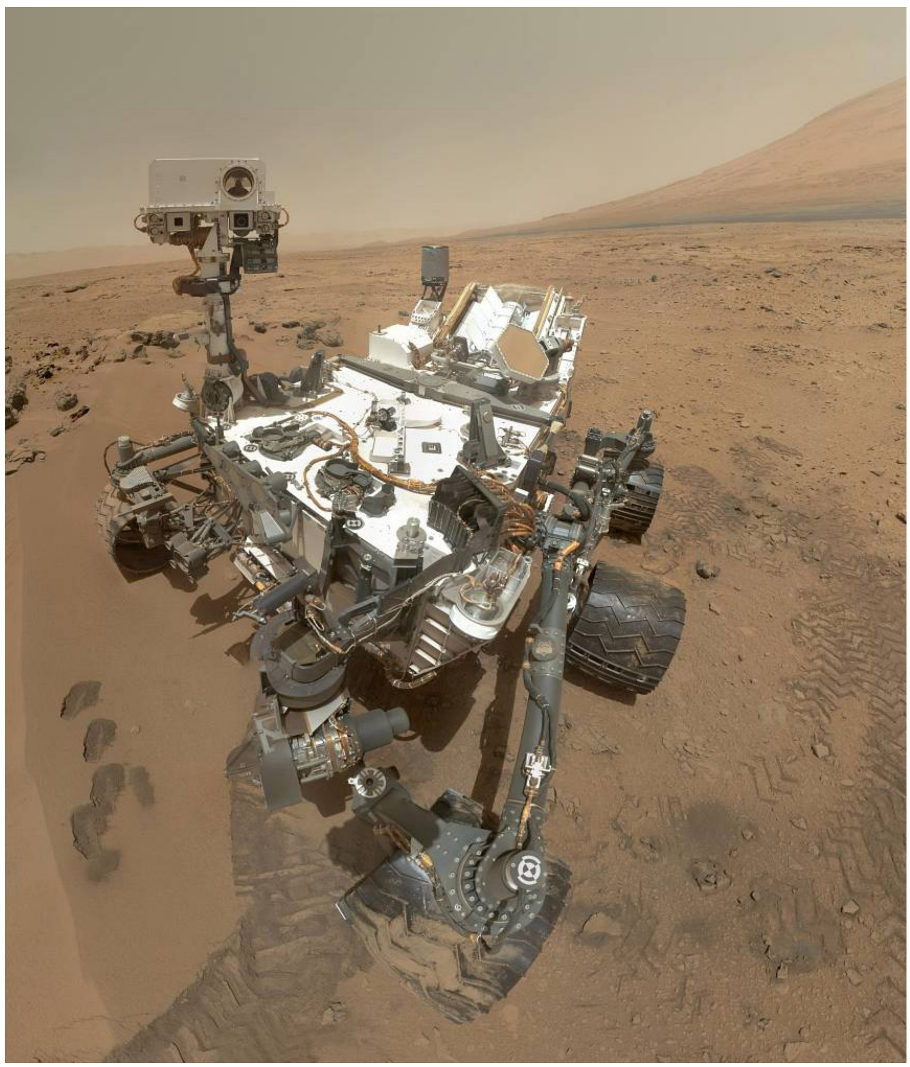
- Learn more about the geology of the Moon from this NASA educator's guide.
- Read this feature from Space.com about Harrison "Jack" Schmitt, the only geologist to have walked on the Moon.
- Learn more about the Burgess Shale and its significance here, and read in this article from the *Smithsonian* magazine about how it changed our view of evolution.

27.

MARS: EXPLORING MARS, GEOLOGY, AND ASTROBIOLOGY

LEARN MORE CONT.

- Understand more about Martian geology from the Center for Planetary Science, which provides an online overview of the planet and its characteristics.
- SETI (Search for Extraterrestrial Intelligence) Institute is an organization charged with looking for life elsewhere. Find out more about the work they do and the implications for finding life in our solar system.



28.

CONCLUSION: THE FUTURE OF EXPLORATION

"It's good that we're impatient. It helps drive us to do things we've never done before."
—Chris Hadfield

28.

CONCLUSION: THE FUTURE OF EXPLORATION

SUBCHAPTERS

- Explore, Understand, Choose, Settle
- Push Yourself to Live a Full Life
- Find Your Place in Space

CHAPTER REVIEW

We have only been exploring space for a little over 50 years, less than one lifetime, and the pattern of exploration in space is no different than what we have been doing as a species on Earth: explore, understand, choose, and settle. We decided some 30 years ago to settle in orbit around the world, which is what humanity has done with the International Space Station. And we're just getting started.

Chris believes settling on the Moon will be our next undertaking, but like all exploration we are currently limited by our technology. While some may feel impatient that we have not returned sooner, Chris sees this as a good thing, as it helps to drive us to do things we have never done before. He also says that some may not realize how far we have come in space, possibly taking for granted the fact that there are six humans permanently living off planet right now.

Chris's philosophy for life is to not squander what you have, to make the most of opportunities, and to take advantage of the windows of chance that open and close around you. Chris's greatest source of pride is having a worthwhile impact on other people and seeing them succeed because of something he has done. Permanently opening a door for others to pass through may be the greatest thing you ever do.

LEARN MORE

- We have come a long way in space exploration since Yuri Gagarin became the first human to travel to space on April 12, 1961. Read this feature from Space.com, which charts our achievements in space.

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Note: Photos are listed in order of appearance.

CAPTIONS & CREDITS BY CHAPTER

Chapter 1: Introduction
Front Cover: Photo courtesy of MasterClass.
Page 02: Photo courtesy of MasterClass.

Chapter 2: Astronaut Training
Page 03: An astronaut is lowered into the Johnson Space Center's Neutral Buoyancy Lab by crane, beginning a day's training under water, working on the full-scale Space Station mock-up, simulating weightlessness. Photo courtesy of Chris Hadfield.

Chapter 3: Rockets: How Rockets Work
Page 06: Photo courtesy of MasterClass.

Chapter 4: Rockets: What It Feels Like to Launch
Page 09: Wearing his Russian pressure suit (called the Sokhol or "Falcon" suit), Chris goes over the final checks in his Soyuz spaceship, prelaunch at the Baikonur Cosmodrome, Kazakhstan, December 2012. Photo courtesy of Chris Hadfield.

Chapter 5: Rockets: Atmospheric Drag
Page 12: Space Shuttle Discovery soars away from Launch Pad 39A at the Kennedy Space Center, beginning its maiden voyage and a storied spaceflight career that spanned more than 26 years. The on-time liftoff occurred on August 30, 1984 at 8:42 a.m. EDT. Photo courtesy of NASA.

Chapter 6: Rockets: Orbital Mechanics
Page 15: As the Soyuz TMA-07M spacecraft was making its final approach to the International Space Station on December 21, 2012, Kevin Ford of the Expedition 34 crew on board the orbital outpost captured this photo of the Soyuz (lower left). Inside the approaching spacecraft were astronaut Chris Hadfield of the Canadian Space Agency, cosmonaut Roman Romanenko of Russia's Federal Space Agency, and astronaut Tom Marshburn of NASA. Photo courtesy of NASA.

Chapter 7: Rockets: Fuels and Propulsion
Page 20: The second and final qualification motor (QM-2) test for the Space Launch System's booster is seen, June 28, 2016, at Orbital ATK Propulsion Systems test facilities in Promontory, Utah. During the Space Launch System flight the boosters will provide more than 75 percent of the thrust needed to escape the gravitational pull of Earth, the first step on NASA's journey to Mars. Photo courtesy of NASA/Bill Ingalls.

Page 22: Photo courtesy of MasterClass.

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Chapter 8: Rockets: The Price of Exploration
Page 23: On November 9, 1967, the uncrewed Apollo 4 test flight made a great ellipse around Earth as a test of the translunar motors and of the high speed entry required of a crewed flight returning from the Moon. A 70mm camera was programmed to look out a window toward Earth and take a series of photographs from "high apogee." Seen looking west are coastal Brazil, the Atlantic Ocean, West Africa, and Antarctica. This photograph was made as the Apollo 4 spacecraft, still attached to the S-IVB (third) stage, orbited Earth at an altitude of 9,544 miles. Photo courtesy of NASA.

Lesson Video Credit: Footage of the Columbia disaster courtesy of CNN.

Chapter 9: Spaceships: Capsule Design
Page 26: An unpiloted ISS Progress resupply vehicle approaches the International Space Station carrying 1,764 pounds of propellant: 110 pounds of oxygen and air; 926 pounds of water; and 3,000 pounds of spare parts, experiment hardware, and logistics equipment—2.9 tons of supplies in all—for the Expedition 34 crew members. Progress 50 docked to the station's Pirs docking compartment at 3:35 p.m. EST on February 11, 2013. The space freighter launched from the Baikonur Cosmodrome in Kazakhstan at 9:41 a.m. (8:41 p.m. Kazakhstan time) on an accelerated, four-orbit journey to rendezvous with the station. Photo courtesy of NASA.

Page 27: Diagram courtesy of NASA.

Page 28: Diagram courtesy of NASA.

Page 29: Diagram courtesy of NASA.

Page 30: Diagram courtesy of NASA.

Page 32: Astronaut Edwin Aldrin Jr. photographed inside the Gemini XII spacecraft cabin during spaceflight, November 13, 1966. Photo courtesy of NASA.

Chapter 10: Spaceships: Shuttles and Beyond
Page 33: Space Shuttle Endeavour approaches the International Space Station from below, April 2001, with Chris aboard. Visible in the payload bay, from front to back, are the docking mechanism, Canadarm2 ready in its launch cradle for installation onto ISS, and a large aluminum Italian-built cargo carrier. Photo courtesy of Chris Hadfield.

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Page 36: The Soyuz TMA-15M spacecraft undocked from the Rassvet module on the International Space Station on June 11, 2015. NASA astronaut Terry Virts, European Space Agency (ESA) astronaut Samantha Cristoforetti, and Russian cosmonaut Anton Shkaplerov are on their way back to Earth. They will land in Kazakhstan a few hours later after more than six months in space. Photo courtesy of NASA.

Chapter 12: Spaceships: Navigating to the International Space Station
Page 39: A rare photo of the Space Shuttle docked to the International Space Station, taken from a Russian Soyuz spaceship that had just undocked and was returning to Earth on May 23, 2011. Photo courtesy of Chris Hadfield, taken by Paolo Nespoli of ESA.

Page 41: Apollo 9 Command and Service Module docked with the Lunar Module, March 6, 1969. Photo courtesy of NASA.

Page 42: Space Shuttle Atlantis docked with the Russian Mir space station, July 4, 1995. Photo courtesy of NASA.

Chapter 13: The ISS: Conception, Design, and Construction
Page 43: Backdropped by New Zealand and Cook Strait in the Pacific Ocean, astronaut Robert L. Curbeam Jr. (left) and European Space Agency (ESA) astronaut Christer Fuglesang, both STS-116 mission specialists, participate in the mission's first of three planned sessions of extravehicular activity (EVA) as construction continues on the International Space Station. Cook Strait divides New Zealand's North and South Islands. Photo courtesy of NASA.

Chapter 14: The ISS: Life Support Systems
Page 47: Forward view of the International Space Station (ISS) taken by Chris during the final flyaround of Shuttle Endeavour during the STS-100 mission. Visible are: US Laboratory / Destiny, Pressurized Mating Adapter 2, Space Station Remote Manipulator System Canadarm2, Z1 Truss, and the P6 Truss. Photo courtesy of NASA.

Chapter 15: The ISS: Experiments
Page 50: Canadian Space Agency astronaut Chris Hadfield, Expedition 34 Flight Engineer, holds bubble detectors for the RaDI-N experiment in the International Space Station's Kibo laboratory. RaDI-N measures neutron radiation levels on board the Space Station. RaDI-N uses bubble detectors as neutron monitors which have been designed to only detect neutrons and ignore all other radiation. Photo courtesy of NASA.

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Page 52: University of Florida investigators monitor plant growth to understand how biology reacts to spaceflight. Photo courtesy of NASA.

Chapter 16: Leadership: Commanding the ISS
Page 53: Expedition 34 Flight Engineer Chris Hadfield of the Canadian Space Agency (CSA), NASA Flight Engineer Tom Marshburn, and Soyuz Commander Roman Romanenko wave farewell from the bottom of the Soyuz rocket at the Baikonur Cosmodrome in Baikonur, Kazakhstan, December 19, 2012. Their Soyuz TMA-07M rocket launched at 7:12 a.m. EST. Photo courtesy of NASA/Carla Cioffi.

Chapter 17: Training and Learning: One-Pagers
Page 55: Photo courtesy of MasterClass.

Chapter 18: Comms: Mission Control Evolution and Operations
Page 57: For the Gemini program, a few changes were made to the Mission Control / Flight Control area layout. One change was to upgrade the old trend charts on both sides of the world map to rear projection screens. The facility continued to be used as Mission Control during the first three flights of the Gemini program. Once the Mission Control function was moved to a new facility in Houston for Gemini IV, the center's function switched to Launch Control and tracking. Photo courtesy of NASA.

Chapter 19: Spacewalking: Spacesuits
Page 61: Photo courtesy of MasterClass.

Chapter 20: Spacewalking: Spacewalks
Page 65: Chris during his first spacewalk, feet locked in a foot restraint on the end of the Shuttle robot arm Canadarm, tightening bolts to assemble the ISS robot arm Canadarm2, Shuttle mission STS-100, April 22, 2001. Photo courtesy of Chris Hadfield.

Chapter 21: Spacewalking: Training
Page 67: Poolside at the Neutral Buoyancy Lab, EVA suit fully assembled around his body, Chris checks his gloves prior to being hoisted by crane into the water to begin spacewalk training. Note his red umbilical which provides air, cooling, communications, and data. Near the Johnson Space Center, Houston, Texas.
Photo courtesy of Chris Hadfield.

Lesson Video Credit: Footage provided by Chris Hadfield © Canadian Space Agency 2014.

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Chapter 22: Spacewalking: Space and Perspective
Page 70: This sprinkle of cosmic glitter is a blue compact dwarf galaxy known as Markarian 209. Galaxies of this type are blue-hued, compact in size, gas-rich, and low in heavy elements. They are often used by astronomers to study star formation, as their conditions are similar to those thought to exist in the early universe. Photo courtesy of ESA/Hubble and NASA; acknowledgement: Nick Rose.

Chapter 23: Training and Learning: Simulations
Page 73: Using a system similar to an overhead bridge crane, Canadian Space Agency astronaut Jeremy Hansen is suspended over a mock-up of the International Space Station during a microgravity simulation in the Active Response Gravity Offload System (ARGOS) at NASA's Johnson Space Center on October 24, 2017. Engineers and astronauts conducted testing in both light and darkness to mimic the 90-minute day–night cycle the astronauts experience in orbit. The crew's feedback will be used for future spacewalks. Photo courtesy of NASA/Josh Valcarcel.

Chapter 24: Mars: How to Get to Mars
Page 76: Mosaic of the Valles Marineris hemisphere of Mars projected into point perspective, a view similar to that which one would see from a spacecraft. The distance is 2,500 kilometers from the surface of the planet, with the scale being .6km/pixel. The mosaic is composed of 102 Viking Orbiter images of Mars. The center of the scene (lat -8, long 78) shows the entire Valles Marineris canyon system, over 2,000 kilometers long and up to 8 kilometers deep, extending from Noctis Labyrinthus, the arcuate system of graben to the west, to the chaotic terrain to the east. Many huge ancient river channels begin from the chaotic terrain from north-central canyons and run north. The three Tharsis volcanoes (dark red spots), each about 25 kilometers high, are visible to the west. South of Valles Marineris is very ancient terrain covered by many impact craters. Photo courtesy of NASA/JPL-Caltech.

Chapter 25: Mars: Living on Another Planet
Page 80: Slope monitoring in Hale Crater's central peaks. Photo courtesy of NASA/JPL/University of Arizona.

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Page 83: The Canadian Space Agency (CSA)'s Artemis Jr. rover holds the Regolith and Environment Science and Oxygen and Lunar Volatiles Extraction (RESOLVE) instruments. This system will be used to drill for water, ice, and other resources during a simulated mission. Photo courtesy of NASA/Joe Bibby.

Chapter 27: Mars: Exploring Mars, Geology, and Astrobiology
Page 86: A crater in Terra Tyrrhena on Mars. Photo courtesy of NASA/JPL/University of Arizona.

Page 88: The Curiosity rover landed on Mars on August 6, 2012, delivering groundbreaking instruments to the planet's surface. Photo courtesy of NASA.

Chapter 28: Conclusion: The Future of Exploration
Page 89: Photo courtesy of MasterClass.

Back Cover: Chris's (and Canada's) first spacewalk, April 22, 2001. In his visor reflection you can see the photographer, NASA astronaut Scott Parazynski. The red stripes signify that Chris was the lead spacewalker. On his left sleeve is the emergency checklist.
Shuttle Endeavour STS-100, ISS assembly mission 6A.
Photo courtesy of Chris Hadfield.


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