

Welcome Back: Connecting the Journey

Today we bring it all together — every phase of spaceflight, from the thunderous launch off the pad to the quiet precision of orbital maneuvering, and the fiery drama of reentry. These aren't isolated events. They're chapters in a single physics story, and each one follows directly from the last.

 Orbit

 Launch

 Reentry

 In Between

Essential Question: How do spacecraft maneuver once they are already in space?

Quick Review Discussion

Before we move forward, let's make sure our foundation is solid. Take a few minutes with your table group to discuss the following three questions. Each one connects directly to what we'll explore today.

1

Why does satellite mass cancel in orbital velocity?

Think back to our derivation of $v = \sqrt{\frac{G \cdot M}{r}}$. When we set gravitational force equal to centripetal force, both sides contain the satellite's mass m . It divides out completely — meaning a tiny CubeSat and the massive International Space Station orbit at the **same speed** at the same altitude. This is a profound result: orbital velocity depends only on the central body's mass and the orbital radius.

2

Why must rockets turn sideways?

Going straight up only gets you altitude — it doesn't keep you in orbit. To stay in space, a spacecraft needs enormous **horizontal velocity** (about 7.8 km/s in low Earth orbit). The gravity turn maneuver tilts the rocket's trajectory so that most of the engine's energy goes into building sideways speed, not just fighting gravity vertically.

3

Why is reentry an energy problem?

A spacecraft in orbit carries tremendous **kinetic energy** (from its speed) and **gravitational potential energy** (from its altitude). To land safely, all of that energy must be converted into something else — primarily **heat**, via friction with the atmosphere. If you can't manage that energy dissipation, the vehicle burns up. Reentry is fundamentally a thermodynamics challenge.

Do Satellites Just Stay There?

It's easy to imagine that once a satellite reaches orbit, the hard part is over. But that's far from the truth. Space is a **dynamic environment**, and maintaining a useful orbit requires constant attention and occasional action.

Why Orbits Drift

Even in the vacuum of space, satellites face subtle but persistent forces that gradually push them off course:

- **Earth's uneven gravity field** — Our planet isn't a perfect sphere. Variations in mass distribution (mountains, ocean trenches, dense mineral deposits) create gravitational "bumps" that tug on satellites unevenly.
- **Solar radiation pressure** — Photons from the Sun carry momentum. Over weeks and months, this tiny push adds up.
- **Lunar and solar gravitational perturbations** — The Moon and Sun exert tidal forces that slowly warp orbital paths.
- **Atmospheric drag** — Even at 400 km altitude, trace amounts of atmosphere create drag that lowers orbits over time.

What Satellites Must Do

• Correct Orbital Drift

Fire small thrusters to nudge the satellite back to its assigned position when gravitational perturbations push it off course.

• Maintain Orientation

Keep antennas pointed at Earth, solar panels aimed at the Sun, and sensors facing the right direction using attitude control systems.

• Avoid Debris

Thousands of pieces of space junk orbit Earth. Satellites must occasionally perform collision avoidance maneuvers to dodge dangerous objects.

• Deorbit at End of Mission

Responsible operators use remaining fuel to push dead satellites into "graveyard orbits" or deorbit them to burn up in the atmosphere.

📌 **Key Takeaway:** Space is not a "set it and forget it" environment. Maintaining a useful orbit is an ongoing engineering challenge that requires propulsion, power, and planning.

Station Keeping — Especially in GEO

Geostationary orbit (GEO) is one of the most valuable real estate zones in space. At an altitude of approximately **35,786 km**, a satellite's orbital period matches Earth's rotation — meaning it appears to hover over a single point on the equator. This is ideal for communications satellites, weather monitoring, and broadcast services because ground-based antennas can point at one fixed spot in the sky.

The Challenge of Staying Put

Despite the elegance of GEO, satellites don't just sit still. Gravitational perturbations from the Moon and Sun, solar radiation pressure, and Earth's slightly non-spherical shape all conspire to push GEO satellites off station. Without correction, a GEO satellite would drift east or west along the orbit, eventually wandering into a neighboring satellite's "slot" — a potential collision risk and a regulatory violation.

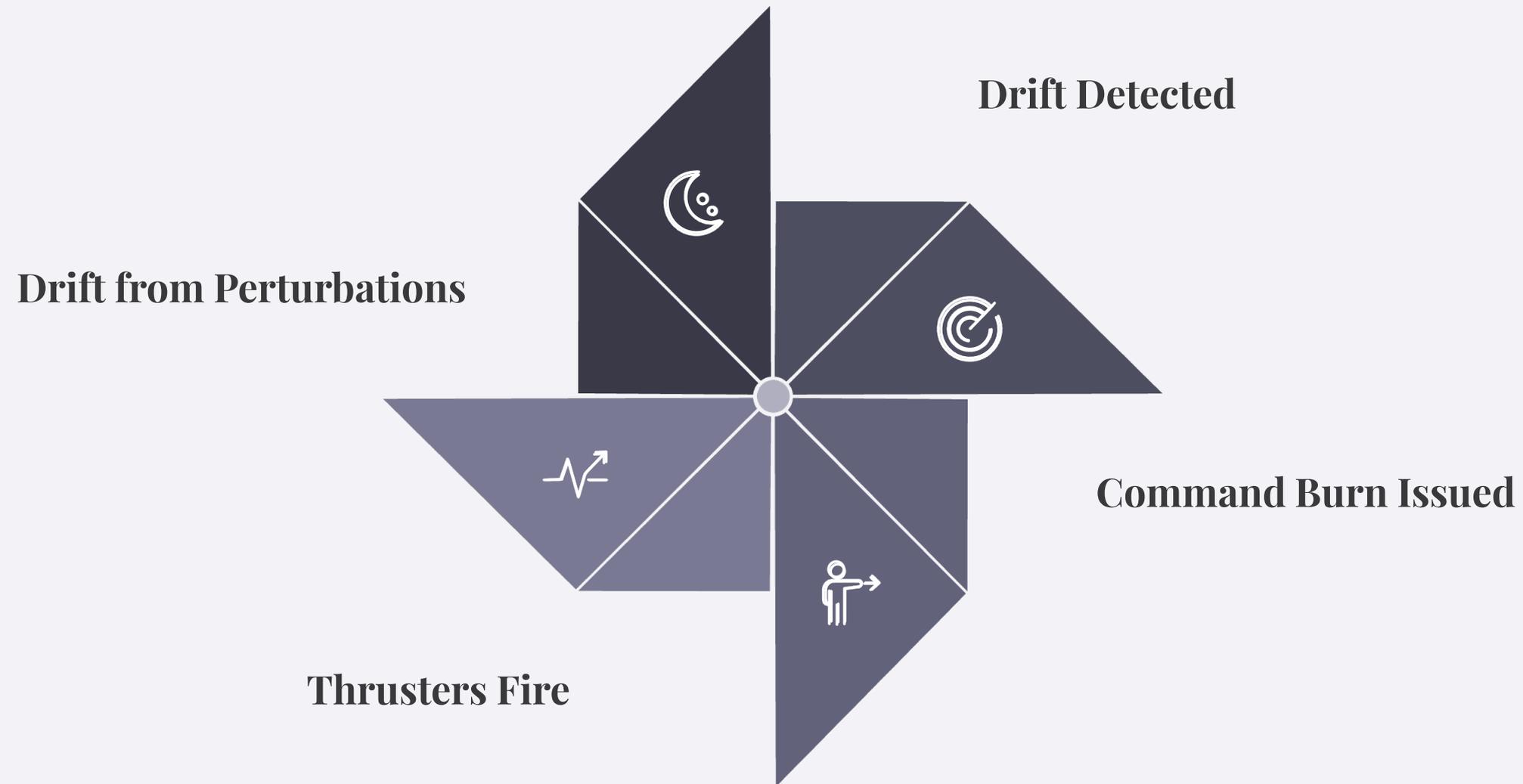
To counteract these forces, mission controllers command small thruster firings — typically every few weeks — to nudge the satellite back within its assigned **$\pm 0.1^\circ$ longitude box**. This process is called **station keeping**, and it's the single largest consumer of onboard propellant over a satellite's 15–20 year lifespan.

When the fuel runs out, the satellite can no longer maintain its position. That's usually what determines end of life — not a hardware failure, but simply running out of propellant for station keeping.



GEO Station Keeping in Action

The diagram below illustrates how a geostationary satellite maintains its fixed position relative to the rotating Earth. Notice the small correction thrust arrows — these represent the periodic "nudges" that keep the satellite locked above its assigned longitude.



Each correction burn uses only a tiny amount of propellant, but over a satellite's 15–20 year operational life, these burns add up. Engineers must carefully budget fuel at the start of the mission to ensure enough remains for the entire planned service life. Modern satellites are also experimenting with electric propulsion for station keeping, which uses far less propellant mass for the same total correction — a topic we'll explore shortly.

Traditional Hydrazine Thrusters

For decades, the workhorse of satellite propulsion has been **hydrazine** (N_2H_4) — a simple but effective chemical monopropellant. Understanding how it works gives us a baseline for comparing the newer technologies that are beginning to replace it.



Fuel Storage

Hydrazine is stored as a liquid in pressurized tanks aboard the satellite. It remains stable until needed, sometimes for years at a time.



Catalyst Bed

When a burn is commanded, the liquid hydrazine flows over an iridium catalyst (Shell 405). This triggers a rapid exothermic decomposition — no spark or igniter needed.



Decomposition

The hydrazine breaks down into ammonia, nitrogen gas, and hydrogen at extremely high temperatures (~600–1,000°C), creating a rapidly expanding hot gas.



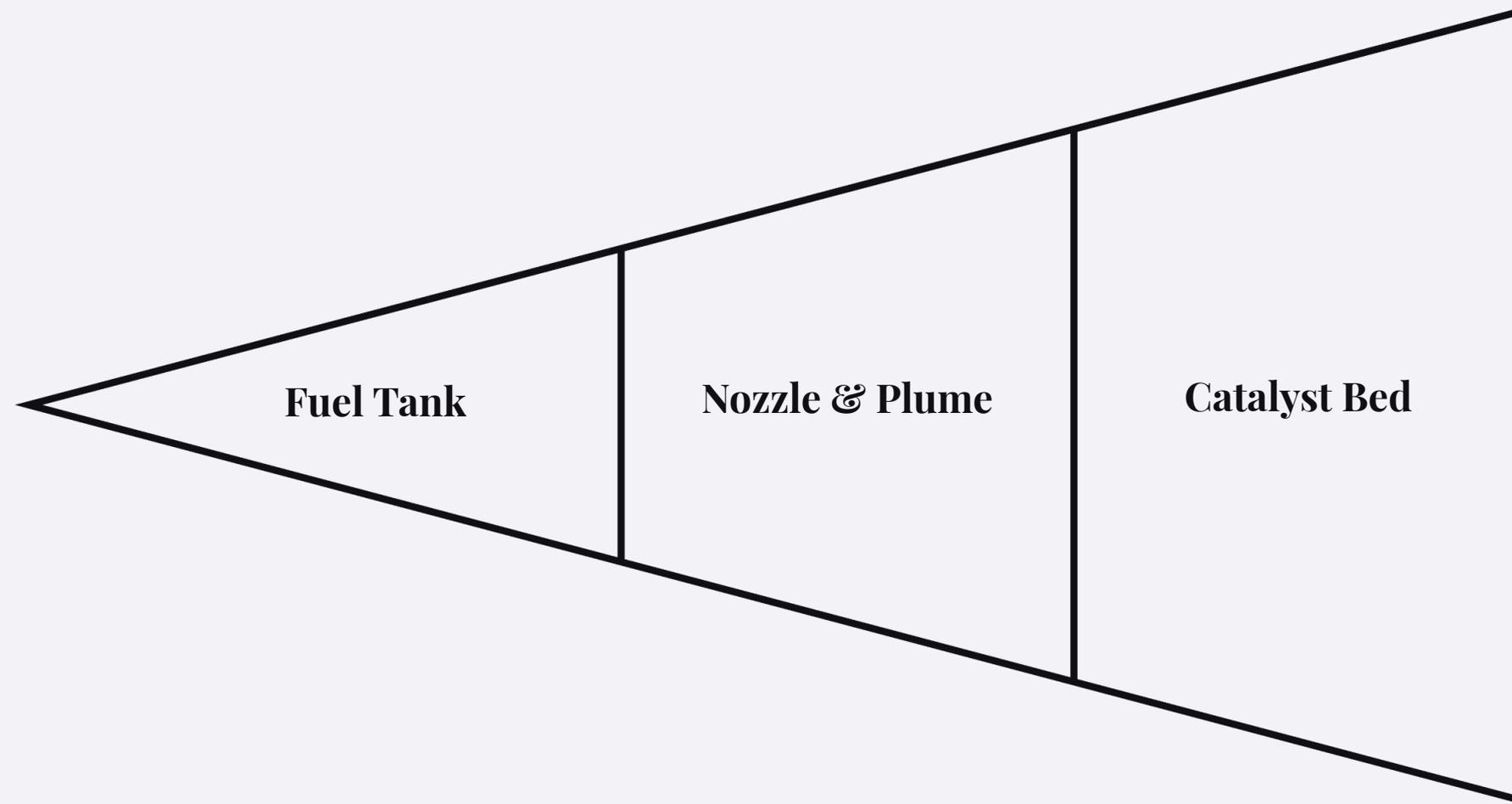
Thrust Output

The hot gas is expelled through a nozzle, producing thrust via Newton's Third Law. The reaction is nearly instantaneous, making hydrazine ideal for precise, on-demand maneuvers.

Hydrazine thrusters are classified as **monopropellant** systems because they use a single chemical that decomposes on its own, as opposed to bipropellant systems that mix a fuel and an oxidizer. This simplicity made hydrazine the go-to choice for satellite designers for over 50 years.

How Hydrazine Propulsion Works

Let's trace the path of propellant from tank to thrust. This simple block diagram shows the key components of a monopropellant hydrazine system — notice how few moving parts are involved, which is one reason for its legendary reliability.



Key Physics at Work

The entire system is governed by conservation of momentum. When hot exhaust gases are expelled at high velocity in one direction, the satellite receives an equal and opposite impulse. The specific impulse (Isp) of hydrazine thrusters is typically around **220–230 seconds**, which tells us how efficiently the propellant is being used. Higher Isp means more "bang for your buck" in terms of velocity change per kilogram of fuel.

Why No Igniter?

One of hydrazine's most useful properties is that it decomposes **catalytically** — the iridium catalyst triggers the reaction on contact, with no spark, flame, or electrical ignition required. This means the thruster can fire reliably even after sitting dormant in the cold of space for years. It's this "instant-on" reliability that made hydrazine the industry standard for so long.

Why Hydrazine Was the Standard

For more than half a century, hydrazine dominated satellite propulsion. Understanding its advantages helps us appreciate why the aerospace industry was slow to change — and what the newer alternatives had to overcome.



Highly Reliable

Catalytic decomposition means no complex ignition systems that could fail. Hydrazine thrusters have demonstrated reliability rates above 99.9% across thousands of missions.



Simple System Design

Minimal moving parts — just valves, a catalyst bed, and a nozzle. Fewer components mean fewer potential failure points, which is critical when repair is impossible.



Instant High Thrust

Produces enough thrust for rapid orbital corrections, emergency collision avoidance, and precise attitude adjustments — all on demand, within milliseconds.



Proven Track Record

Used on everything from small CubeSats to the largest GEO communications satellites, with decades of flight heritage backing every design decision.

Common Applications

Attitude Control

Keeping the satellite pointed in the right direction — antennas toward Earth, solar panels toward the Sun.

Orbit Adjustments

Correcting drift, changing altitude, or transferring between orbits after launch vehicle separation.

Emergency Burns

Rapid maneuvers to dodge tracked debris — sometimes with only hours of warning from ground tracking systems.

Problems with Hydrazine

Despite its long reign as the propellant of choice, hydrazine has serious drawbacks that have pushed the aerospace industry to seek alternatives. These disadvantages aren't minor inconveniences — they represent fundamental limitations that affect cost, safety, and mission capability.

Extremely Toxic

Hydrazine is a **known human carcinogen**. Even small exposures can cause severe chemical burns, organ damage, and long-term health effects. Any facility handling hydrazine must implement extraordinary safety protocols, including full hazmat suits, specialized ventilation, and contamination containment systems.

Expensive Handling

Because of its toxicity, fueling a satellite with hydrazine is one of the most expensive and time-consuming steps in launch preparation. Specialized teams, equipment, and procedures can add **millions of dollars** to mission costs and weeks to the launch timeline.

Moderate Efficiency

With a specific impulse of only ~220–230 seconds, hydrazine is far less fuel-efficient than electric propulsion systems (which can exceed 3,000 seconds). This means satellites must carry significantly more propellant mass to achieve the same total velocity change.

Large Propellant Mass

Because of its moderate efficiency, hydrazine-based satellites often dedicate **40–50% of their total launch mass** to propellant. That's mass that could otherwise be used for more capable instruments, larger solar arrays, or extended mission life.

 **Industry Trend:** The European Space Agency has classified hydrazine as a "Substance of Very High Concern" under REACH regulations, accelerating the push toward greener propellants and electric propulsion across the global space industry.

Electric / Ion / Plasma Propulsion

Welcome to the future of spacecraft propulsion. Electric propulsion represents a fundamentally different approach to generating thrust — one that trades raw power for extraordinary efficiency. Instead of burning chemicals, these systems use **electricity from solar panels** to accelerate ionized gas to extreme velocities.

01

Solar Energy Collection

Large solar arrays convert sunlight into electrical power — typically several kilowatts for modern electric propulsion systems. This is the energy source that replaces chemical combustion.

03

Electrostatic Acceleration

Powerful electric fields accelerate these ions through a potential difference of 1,000+ volts. The ions exit at speeds of **30–50 km/s** — roughly 10× faster than chemical exhaust.

The result? A faint, eerie blue glow that produces only about as much thrust as the weight of a sheet of paper on Earth — but does so with **10–15× the fuel efficiency** of chemical rockets. In the vacuum of space, that tradeoff is transformative.

02

Xenon Ionization

Xenon gas (chosen for its high atomic mass and chemical inertness) is fed into an ionization chamber where electrons are stripped from the atoms, creating positively charged xenon ions (Xe^+).

04

Ion Beam Expulsion

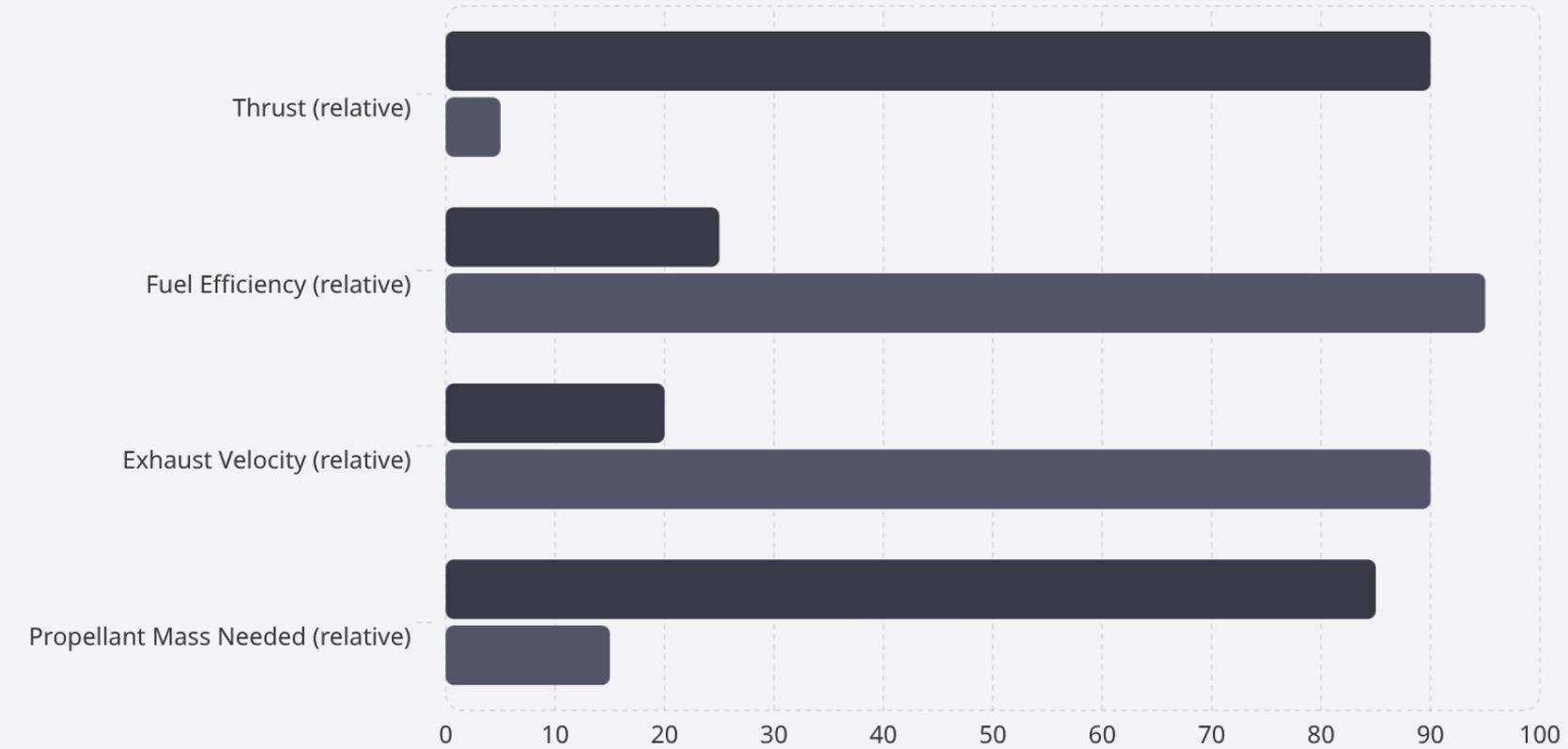
The high-velocity ion beam streams out the back of the thruster, and by Newton's Third Law, the spacecraft is pushed forward. A neutralizer emits electrons to prevent the spacecraft from building up charge.

Thrust vs. Efficiency: The Fundamental Tradeoff

This is one of the most important engineering concepts in spacecraft design. Chemical and electric propulsion each excel in different areas, and choosing between them defines the entire character of a mission. Let's compare them directly.



Performance Metric



Chemical Propulsion

- **High thrust** — Can perform rapid maneuvers in minutes
- **Lower efficiency** — Specific impulse ~220–230 s
- **Heavy fuel load** — Must carry large propellant mass
- **Best for:** Emergency maneuvers, launch, landing, quick orbit changes

Electric Propulsion

- **Very low thrust** — Maneuvers take weeks or months
- **Very high efficiency** — Specific impulse ~3,000+ s
- **Minimal fuel** — Dramatically reduces propellant mass
- **Best for:** Station keeping, orbit raising, deep space missions

Why Ion Engines Work in Space

If ion thrusters produce less force than the weight of a coin, how can they possibly move a spacecraft? The answer lies in the unique physics of the space environment — and it's one of the most elegant examples of **Newton's Second Law** in action.

On Earth: Useless

On Earth's surface, an ion thruster's tiny force would be completely overwhelmed by gravity and air resistance. You'd need thrust greater than the spacecraft's weight just to hover — and ion engines produce roughly **one-millionth** of that. They literally could not lift a pencil against Earth's gravity.

Additionally, atmospheric molecules would scatter the ion beam, making it even less effective. Electric propulsion is fundamentally incompatible with Earth's surface environment.

In Space: Transformative

Remove those obstacles, and everything changes:

- **No atmosphere** — No drag to overcome, so even tiny forces accumulate without resistance
- **No constant weight battle** — In orbit, the spacecraft is in freefall. There's no minimum thrust required to "stay up"
- **Continuous operation** — Ion engines can fire for months or even years without stopping

Small force × long time = big Δv A 90-millinewton ion thruster firing continuously for 6 months can achieve the same total velocity change as a chemical engine burning for just a few minutes — but using a fraction of the propellant.

DEEP DIVE

The Physics Behind Both Systems

At their core, **both** chemical rockets and electric thrusters obey the exact same physical laws. The difference is in *how* they apply those laws — specifically, in the mass and velocity of the particles they expel.

Chemical Rockets

Expel **large mass** at **moderate speed** Exhaust velocity: ~3–4 km/s
High mass flow rate

Electric Thrusters

Expel **small mass** at **very high speed** Exhaust velocity: ~30–50 km/s
Low mass flow rate

The Unifying Laws

Newton's Third Law

For every action, there is an equal and opposite reaction. When exhaust particles are pushed out the back of the engine, the spacecraft is pushed forward. This is true whether the "exhaust" is hot combustion gases or a beam of xenon ions.

Thrust = exhaust mass flow rate × exhaust velocity.

$$F = \dot{m} v_e$$

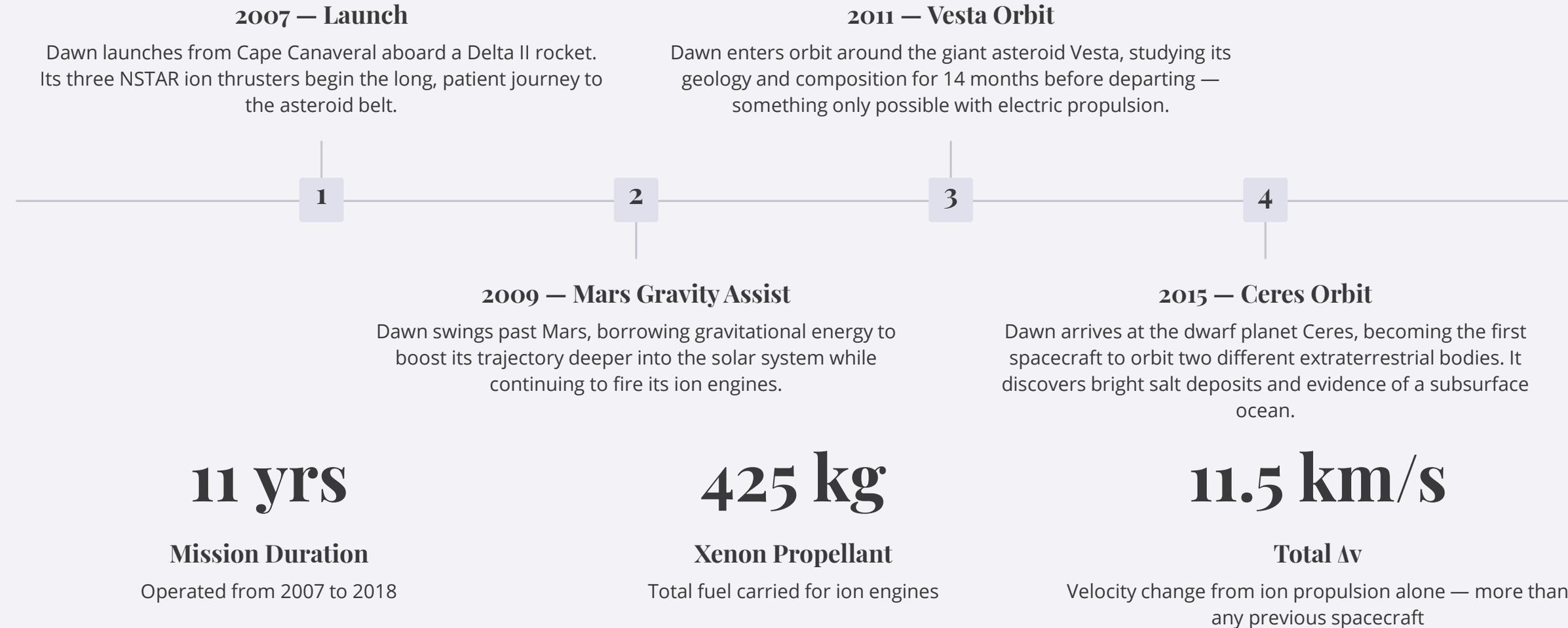
Conservation of Momentum

The total momentum of the system (spacecraft + exhaust) remains constant. As exhaust gains momentum in one direction, the spacecraft gains equal momentum in the opposite direction. Electric thrusters compensate for their low mass flow rate (\dot{m}) by dramatically increasing exhaust velocity (v_e), achieving similar impulse with far less propellant.

$$\Delta p_{spacecraft} = -\Delta p_{exhaust}$$

Real Example: NASA's Dawn Mission

The Dawn mission is one of the most spectacular demonstrations of what electric propulsion makes possible. Launched in 2007, Dawn achieved something no chemical-powered spacecraft could have done on a reasonable budget — it **orbited two different worlds** in the asteroid belt.



A chemical-propulsion spacecraft attempting the same mission would have needed **many times more propellant**, likely making the mission unaffordable. Dawn proved that ion propulsion isn't just a lab curiosity — it's a mission-enabling technology for deep-space exploration.

Engineering Decision Activity

Now it's your turn to think like a spacecraft engineer. You've learned about two fundamentally different propulsion approaches, each with distinct strengths and weaknesses. Apply that knowledge to real mission scenarios.

Mission A: Weather Satellite in GEO

Your company needs to place a weather observation satellite in geostationary orbit at 35,786 km altitude. It must remain locked above the same longitude for **15 years**, performing regular station-keeping maneuvers. Rapid emergency collision avoidance may also be needed.

Mission B: Mars Probe

NASA has funded a deep-space science mission to study the Martian atmosphere. The spacecraft must travel approximately **225 million km** to reach Mars, enter orbit, and conduct observations for at least 2 years. Budget is limited.

Your Task

For Each Mission, Decide:

- Which propulsion system would you choose — chemical (hydrazine), electric (ion), or a **hybrid combination**?
- What are the physics-based reasons for your choice?
- What tradeoffs are you accepting?
- How does $F = \dot{m} \cdot v_e$ influence your decision?

Discussion Prompts

Consider these factors in your analysis:

- **Time sensitivity** — Does the mission need to get somewhere fast, or can it take a slow, efficient route?
- **Propellant budget** — How much mass can you afford to dedicate to fuel?
- **Power availability** — Is there enough sunlight where you're going to run ion engines?
- **Maneuver types** — Do you need quick bursts or long, steady burns?

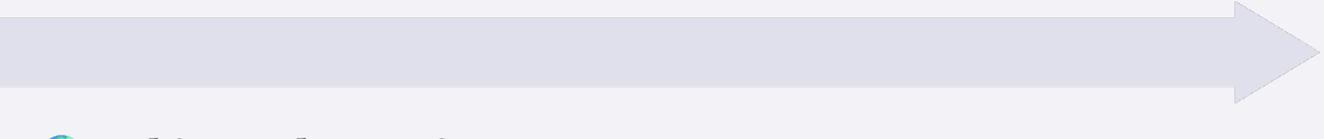
Synthesis: It's All Connected

Every phase of spaceflight — from the roar of launch to the silent glow of an ion engine — is governed by the same fundamental physics. Let's see how the entire journey connects through Newton's Laws.



Launch = High Thrust

Massive chemical engines produce enormous force to overcome Earth's gravity. Newton's Third Law in its most dramatic form — millions of pounds of exhaust pushing the rocket upward.



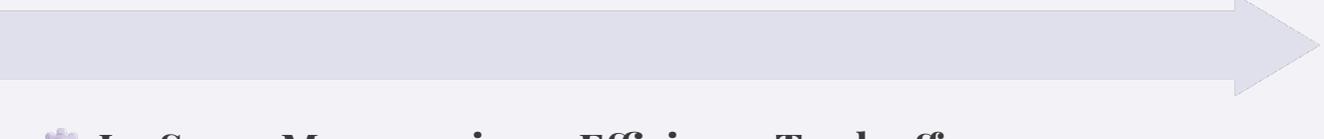
Orbit = Balance of Forces

Gravitational acceleration provides exactly the centripetal force needed for circular motion. The satellite is in continuous freefall, perfectly balanced at $v = \sqrt{GM/r}$.



Reentry = Energy Dissipation

All that kinetic and potential energy must go somewhere. Atmospheric friction converts it to heat — a thermodynamics challenge solved by heat shields and careful trajectory design.



In-Space Maneuvering = Efficiency Tradeoffs

Chemical vs. electric propulsion — high thrust vs. high efficiency. Engineers choose based on mission needs, always constrained by $F = \dot{m} \cdot v_e$ and conservation of momentum.

The Big Idea: Spaceflight isn't four separate topics — it's one continuous physics story told through Newton's Laws, conservation of energy, and conservation of momentum. Every decision, from engine selection to reentry angle, flows from these same fundamental principles.