Rocket Propulsion & Escaping Earth

Why is launching into space so difficult?

Today you will:

- Apply Newton's 3rd Law to rockets
- Analyze thrust vs weight
- Understand why rockets turn sideways
- Explain staging and efficiency
- Connect propulsion to orbital motion

Newton's 3rd Law and Rockets

"For every action, there is an equal and opposite reaction."

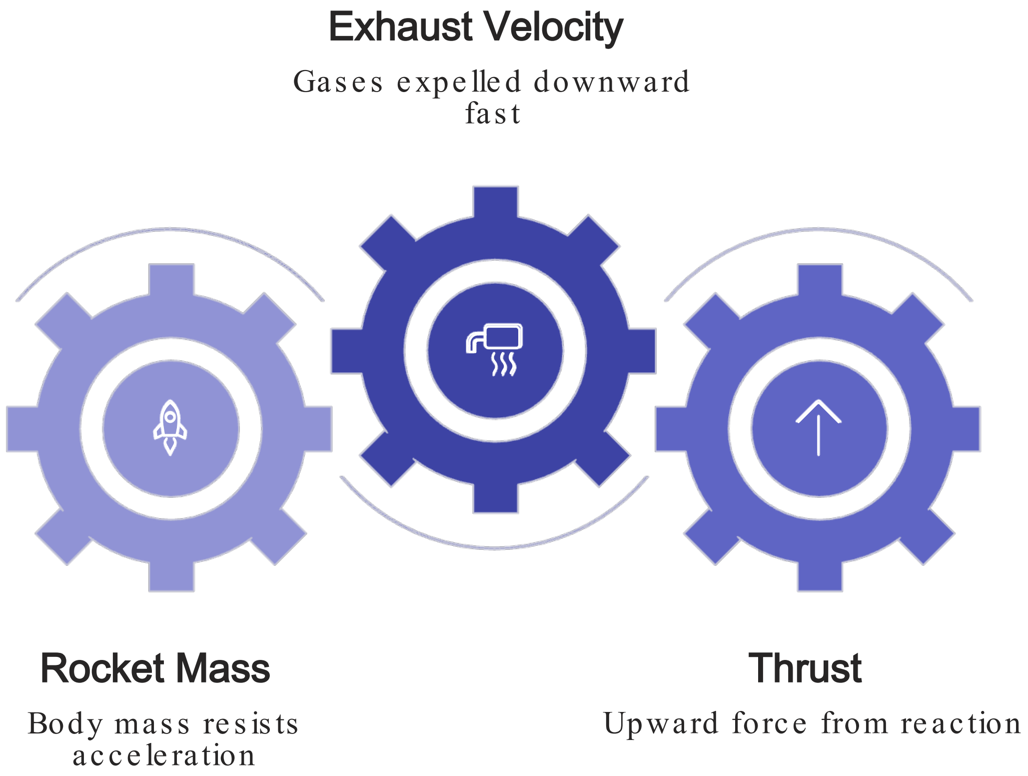
Rocket pushes exhaust gases downward.

Exhaust gases push rocket upward.

Important:

Rockets do NOT push against air.

They push against their own exhaust.



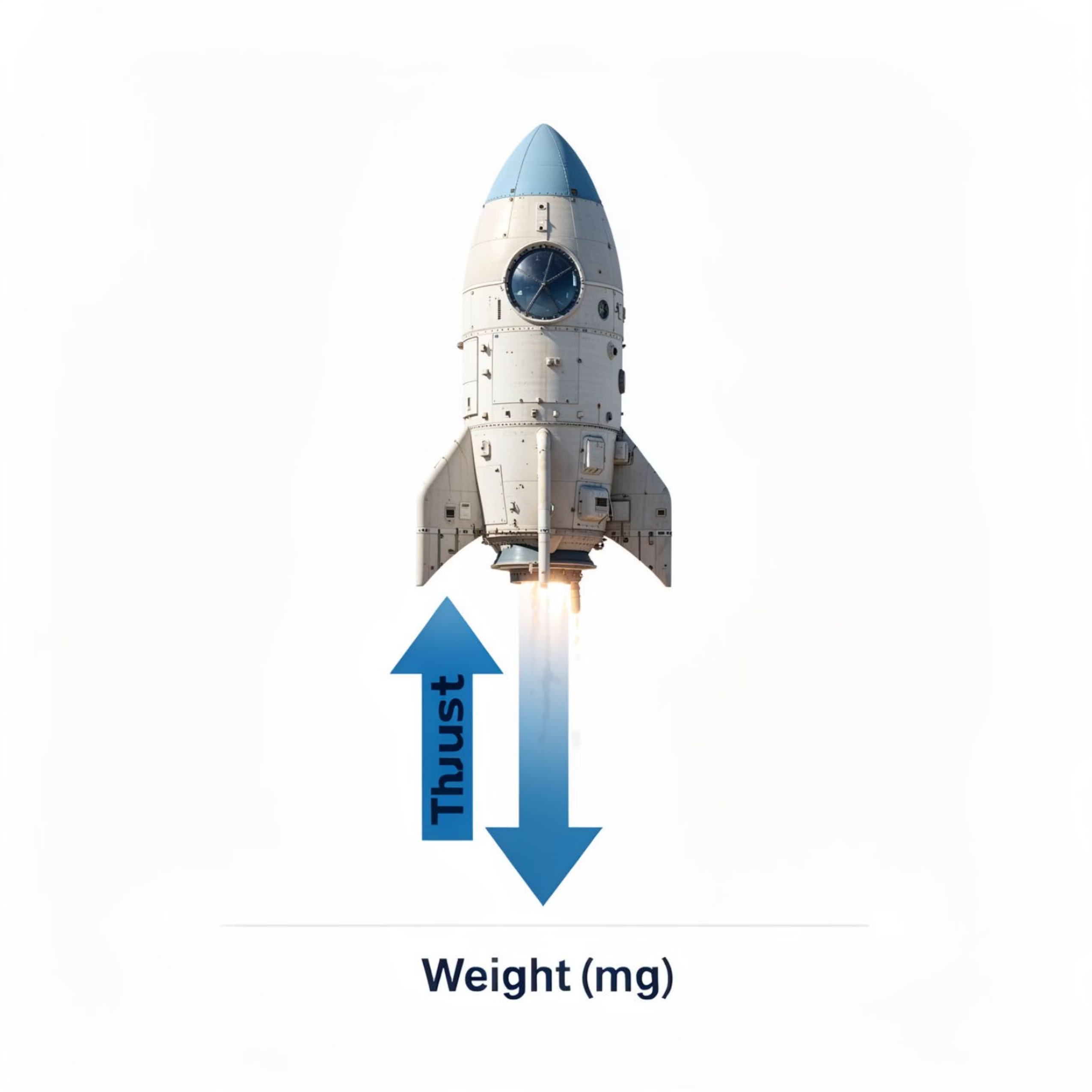
Thrust vs Weight

Forces acting on a rocket at launch:

- Upward: Thrust
- Downward: Weight (mg)

Conditions for rocket flight:

- If Thrust > Weight → Rocket accelerates upward
- If Thrust = Weight → Rocket hovers
- If Thrust < Weight → Rocket cannot lift off



Why Rockets Need So Much Fuel

At launch:

- Rocket mass is very large
- Weight = mg
- Must overcome gravity and drag

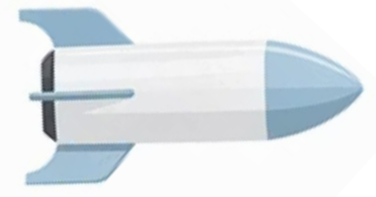
Most of a rocket's mass is fuel.

> Saturn V was ~85% fuel by mass.

Why Rockets Turn Sideways

Orbit requires horizontal velocity.
Going straight up only increases altitude.

To stay in orbit: You must move sideways fast enough to keep missing Earth .



Gradual Pitch Over

Horizontal Velocity Building

Vertical Ascent

Escape Velocity vs Orbital Velocity

Orbital velocity:

Speed needed to stay in orbit.

Key values:

- Escape velocity ≈ 11.2 km/s
- LEO orbital velocity ≈ 7.8 km/s

Conclusion: Escape velocity > orbital velocity.

Escape velocity:

Speed needed to completely escape Earth's gravity.

Staging

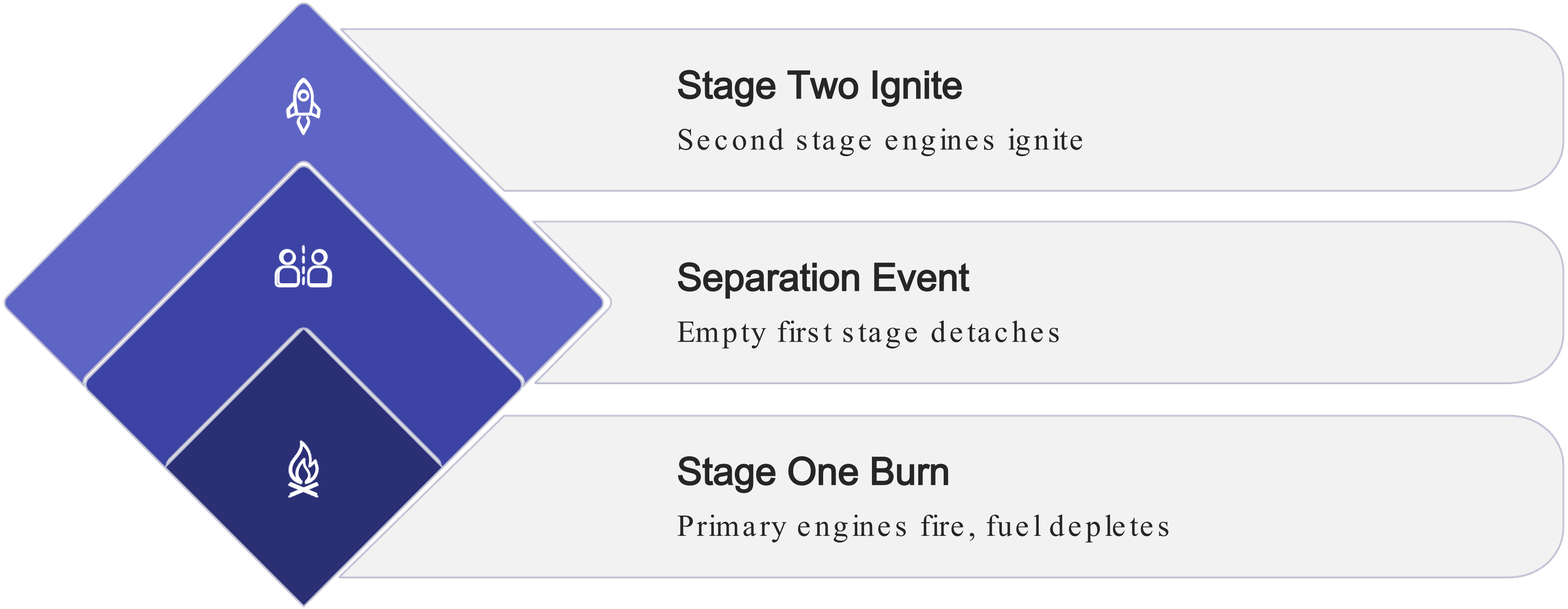
As fuel burns:

Rocket mass decreases.

Staging:

Drop empty tanks to reduce mass.

Less mass → easier acceleration.



Proportional Thinking

The Scenario

In rocket science, understanding proportionality is crucial. Consider these foundational principles:

1

Rocket Mass Changes

If the **rocket's total mass doubles** (e.g., due to increased payload or fuel), then...

2

Weight Increases

...its **weight in Earth's gravity also doubles**. This directly impacts the force required to lift it.

3

Acceleration Goal

To **maintain the same acceleration** (how quickly the rocket gains speed) as before...

4

Thrust Adjustment

...the engine's **thrust must also double**. More mass requires proportionally more force.

The Physics Explained

This proportional relationship is a direct application of Newton's Second Law of Motion.

Mass Doubles ($m \rightarrow 2m$)

A heavier rocket demands more force.

Weight Doubles ($W \rightarrow 2W$)

The gravitational pull increases.

Acceleration Constant (a = constant)

The desired rate of speed change remains unchanged.

Thrust Doubles ($F \rightarrow 2F$)

To overcome increased mass and maintain acceleration, the engine output must increase proportionally.

$$F = ma$$

Force equals mass times acceleration.

Why Planes Cannot Reach Orbit

Planes:

- Use air for oxygen
- Depend on lift
- Cannot reach orbital speeds
- Cannot operate in vacuum

Rockets:

- Carry oxidizer
- Do not need air
- Achieve much higher speeds

Why Escape Velocity Is Higher

In orbit:

You balance gravity.

To escape:

You must overcome all gravitational potential energy.

Escape means:

No return trajectory.

Gravity Turn Explained

As altitude increases:

- Air resistance decreases
- Rocket gradually tilts

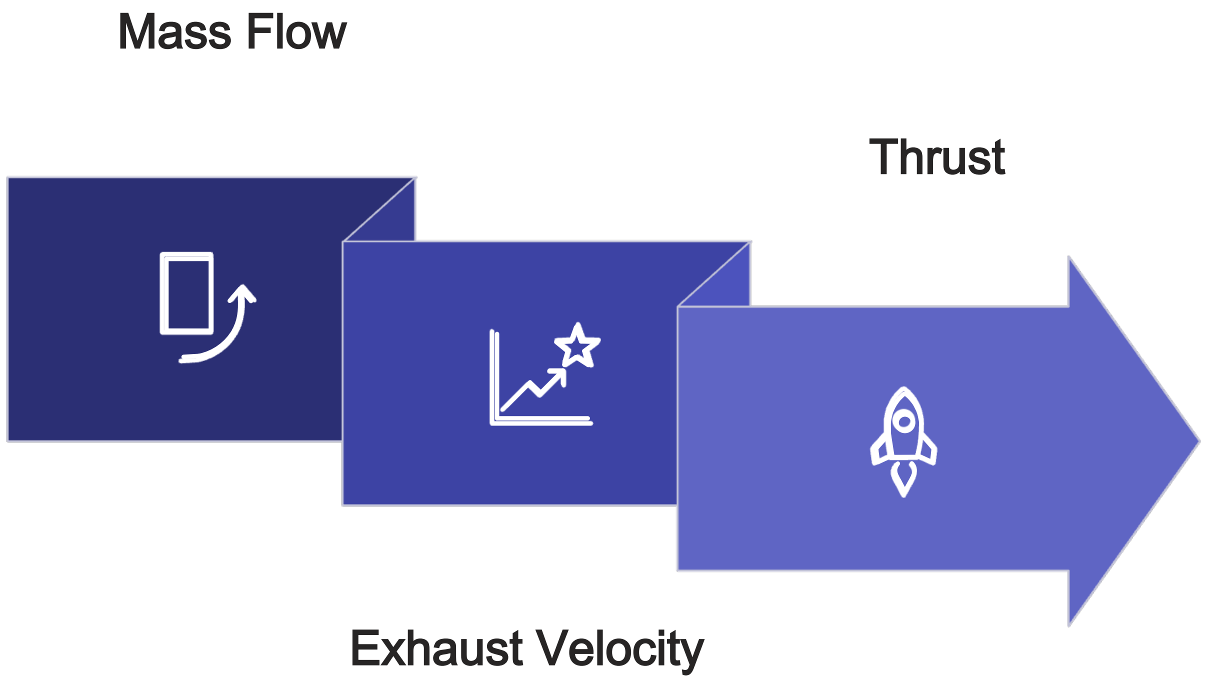
Goal: Build horizontal speed of ~7.8 km/s for LEO.

The Rocket Equation (Conceptual Only)

Thrust depends on:

- Rate of mass expelled
- Exhaust velocity

Key point: Higher exhaust velocity → more efficient propulsion.



We will not derive the full rocket equation, but understand: **Momentum must be conserved.**

Returning from Orbit

- Objects in orbit move ~7.8 km/s.
- Returning safely requires removing enormous kinetic energy.

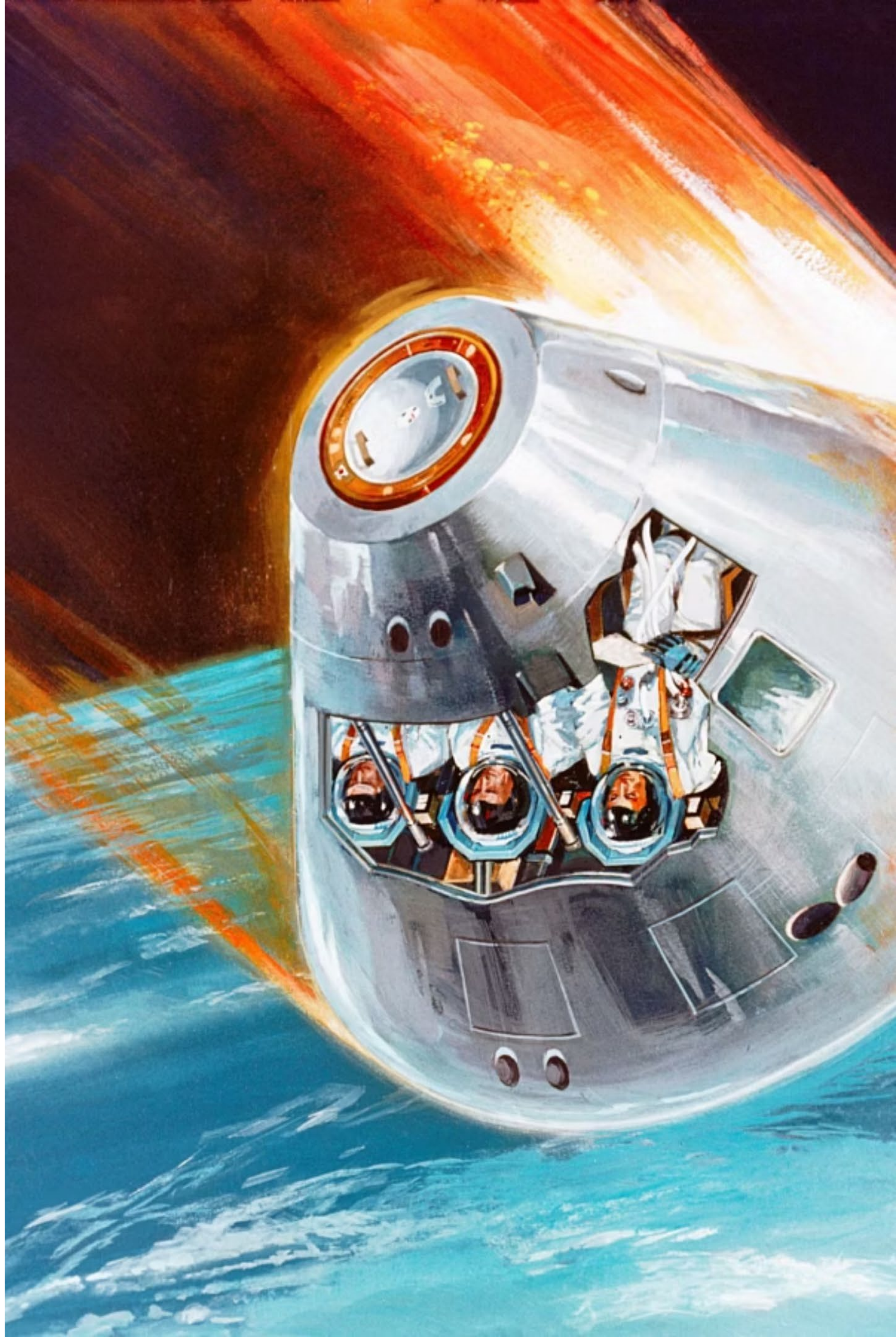
What Causes Reentry Heating?

Many believe reentry heating is caused by friction, but the primary mechanism is far more dramatic:

Important Clarification:

Reentry heating is primarily caused by air compression, not friction! This is a common misconception.

- As the spacecraft slams into the atmosphere, the air in front of it is compressed incredibly rapidly.
- This rapid compression of air generates immense heat, akin to a diesel engine's ignition.



Reentry Temperatures

Typical temperatures during reentry:

Shock layer air

1,500 °C – 3,000 °C

Apollo heat shield surface

~2,700 °C (5,000 °F)

Space Shuttle leading edges

~1,650 °C

Steel melts around 1,500 °C.

Without protection, spacecraft would fail instantly.

Reentry Angle

The angle at which a spacecraft reenters Earth's atmosphere is critical for a safe return. Too steep, and the vehicle will experience extreme heating and structural stress. Too shallow, and it risks bouncing off the atmosphere back into space.

Too Steep

Excess heating

Burn up

Too Shallow

Skip off atmosphere

Miss landing zone

There is a narrow safe reentry window.

Ablative Heat Shields (Capsules)

Ablative heat shields protect spacecraft during reentry by burning away and carrying heat with them.

Used by:

- Mercury
- Apollo
- Dragon

Heat shield material:

Chars, burns away (ablates), carries heat away.

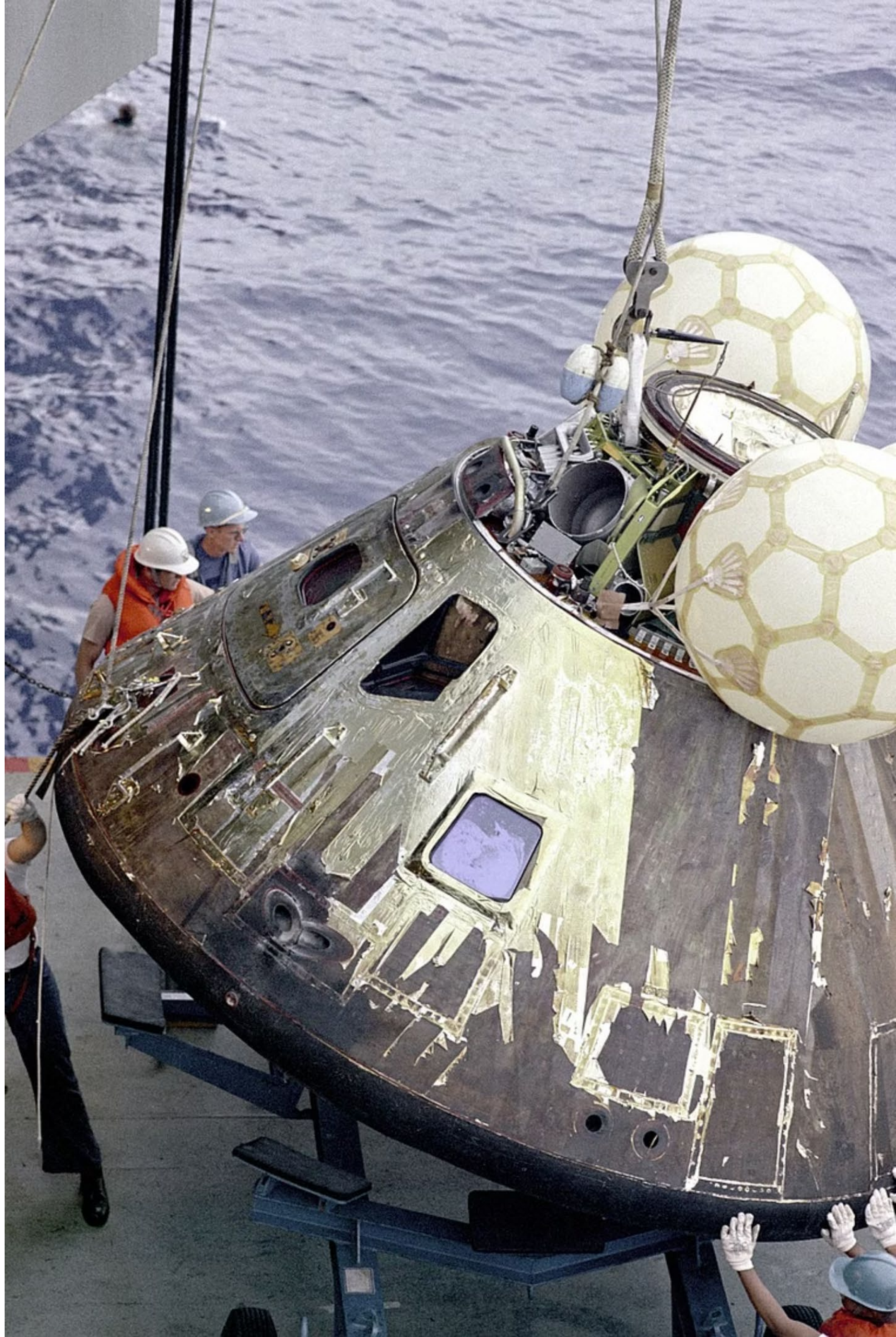
Advantages:

- Extremely reliable
- Excellent heat protection

Disadvantage:

- Single-use

Interior remains near room temperature.



Space Shuttle Thermal Protection

The Space Shuttle did NOT use ablative shielding.

It used:

- Silica insulation tiles
- Reinforced carbon - carbon panels

These materials:

- Did not burn away
- Reflected and absorbed heat
- Allowed reusability

However: They required careful maintenance.

Engineering Tradeoffs

Capsule

- Single-use
- Simpler
- Very safe

Shuttle

- Reusable
- Complex
- Higher maintenance risk

Modern spacecraft have returned to capsule designs.

Engineering always involves tradeoffs.

Homework

Complete the Day 2 Homework Worksheet.

Show all reasoning clearly.