Rockets

Turn off all electronic devices

Observations about Rockets

- Rockets seem to ride torch-like flames
- Rockets can accelerate straight up
- Rockets can go very fast
- The flame only touches the ground initially
- Rockets can apparently operate in empty space
- Rockets usually fly nose-first

6 Questions about Rockets

1. What pushes a rocket forward?
2. How does the rocket use gas to obtain thrust?
3. What keeps a rocket pointing forward?
4. What limits a spaceship's speed, if anything?
5. Once in space, does a spaceship have a weight?
6. What makes a spaceship orbit the earth?

Question 1

Q: What pushes a rocket forward?
A: It's gaseous exhaust pushes it forward

- A rocket's momentum is initially zero
- That momentum is redistributed during thrust
  - Ship pushes on fuel; fuel pushes on ship
  - Fuel (now exhaust) acquires backward momentum
  - Ship acquires forward momentum
- Rocket's total momentum remains zero

$$momentum_{fuel} + momentum_{ship} = 0$$

Rocket Propulsion

- The ship and fuel have opposite momentums
- The ship's final momentum is

$$momentum_{ship} = -momentum_{fuel}$$

- The greater the fuel mass and backward velocity, the greater the ship's forward momentum

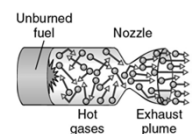## Question 2

Q: How does the rocket use gas to obtain thrust?
A: Redirects gas's thermal motion into a directed jet

- Combustion produces hot, high-pressure gas
- This gas speeds up in a de Laval nozzle
- Gas reaches sonic speed in the nozzle's throat
- Beyond the throat, supersonic gas expands to speed up further

Question 3

Q: What keeps a rocket pointing forward?
A: That depends on where the rocket is located

- On the ground, a rocket needs static stability
- In the air, a rocket needs aerodynamic stability
  - Center of aerodynamic forces behind center of mass
- In space, a spaceship is a freely rotating object
  - Orientation governed by angular momentum
  - Small rockets are used to exert torques on spaceship
  - Spaceship's orientation doesn't affect its travel

Question 4

Q: What limits a spaceship's speed, if anything?
A: The rocket's fuel to spaceship ratio

- Spaceship's ultimate speed increases as
  - the ratio of fuel mass to ship mass increases
  - the fuel exhaust speed increases
- If fuel were released with the rocket at rest,

$$\text{velocity}_{ship} = -\frac{\text{mass}_{fuel}}{\text{mass}_{ship}} \cdot \text{velocity}_{fuel}$$

Ship's Ultimate Speed

- But because rocket accelerates during thrust,

$$\text{velocity}_{ship} = -\log_e\left(\frac{\text{mass}_{ship} + \text{mass}_{fuel}}{\text{mass}_{ship}}\right) \cdot \text{velocity}_{fuel}$$

Question 5

Q: Once in space, does a spaceship have a weight?
A: Yes, but less than at ground level

- Earth's acceleration due to gravity
  - constant for small changes in height at ground level
  - decreases at large altitudes
- Actual weight of a spaceship at any altitude is

$$\text{weight} = \frac{\text{gravitational constant} \cdot \text{mass}_{ship} \cdot \text{mass}_{earth}}{(\text{distance between centers of ship and earth})^2}$$

Law of University Gravitation

Two masses attract one another with gravitational forces equal in amount to the gravitational constant times the product of their masses, divided by the square of their separation.

$$\text{force} = \frac{\text{gravitational constant} \cdot \text{mass}_1 \cdot \text{mass}_2}{(\text{distance between masses})^2}$$

Question 6

Q: What makes a spaceship orbit the earth?
A: An orbiting spaceship falls, but misses the earth
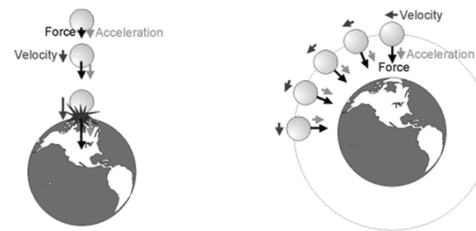
Orbits

- An object that starts with a sideways velocity
  - can miss the earth as it falls
  - follows a trajectory called an orbit
- Orbits can be
  - closed loops: circles and ellipses
  - open arcs: parabolas and hyperbolas
- Minimum speed for low-earth orbit
  - is about 28,000 km/h (17,400 mph)
  - requires far more thrust than merely reaching space

Summary About Rockets

- A rocket's fuel (as exhaust) pushes it forward
- Total rocket impulse is basically the product of exhaust speed times exhaust mass
- Rockets can be stabilized aerodynamically
- Rockets can be stabilized by thrust alone
- After engine burn-out, spaceships can orbit