Today's Topics

Monday, September 9, 2026 (Week 3, lecture 8) – Chapter "end of 3", 4.6, 5.

0. Newton's version of Kepler's 3rd law.

1. Gravitational potential energy

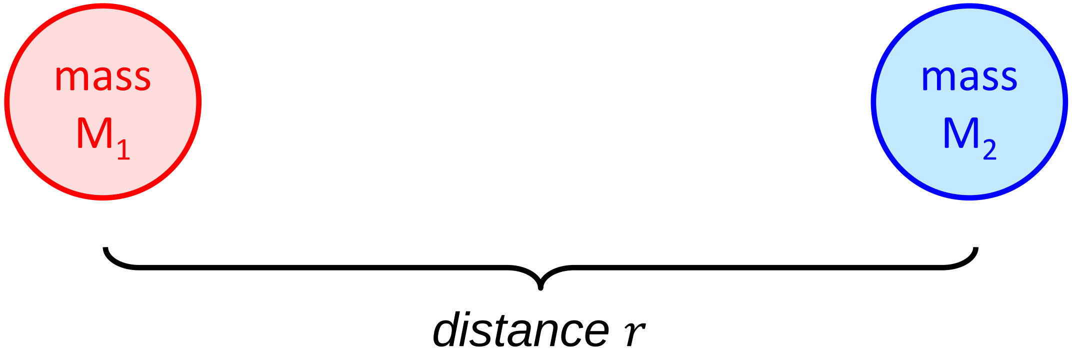
2. Escape velocity

3. Tides

4. Electromagnetic waves

Reminder: Problem Set #3 **part 1** is on ExpertTA and is due Friday, Feb. 13 by 9:00 am.
Problem Set #3 **part 2** is due in class on Friday, Feb. 13 (hard copy).

Gravitational Potential Energy



Stored gravitational energy $= E_{potential} = -\mathrm{G}\,\dfrac{M_1 M_2}{r}$

Total Energy $= E_{total} = E_{potential} + E_{kinetic}$

For 2 orbiting bodies (e.g. Sun + Earth): $E_{total} < 0$

For 2 unbound bodies (Earth + Mars rocket): $E_{total} > 0$

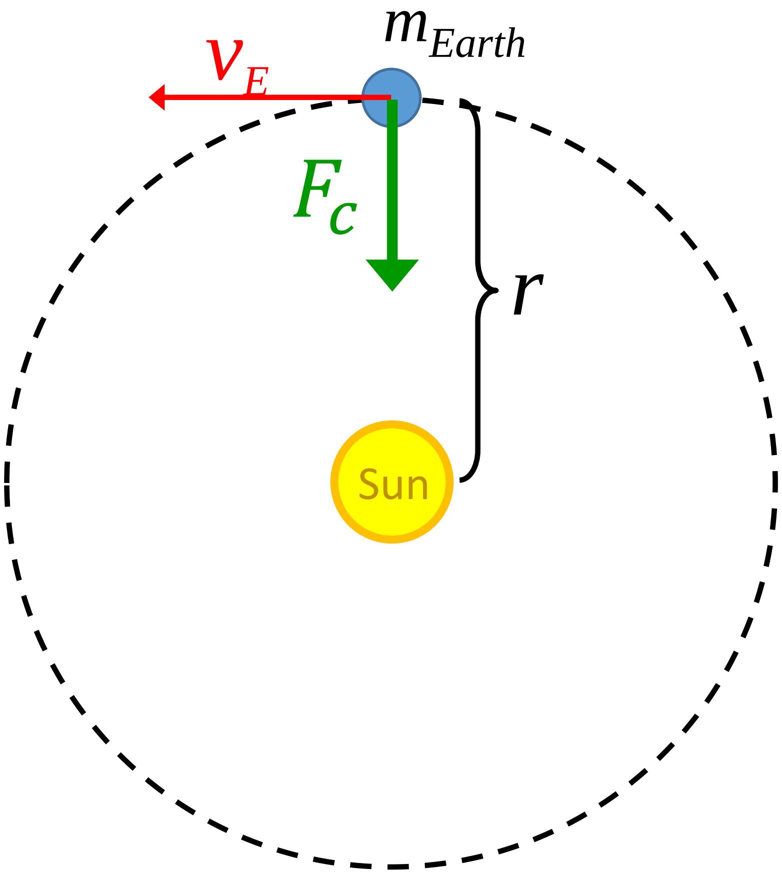
Bound Orbital Energy

Centripetal force needed to keep Earth on a circular orbit:

$$F_c = \frac{m_{Earth} v_{Earth}^2}{r}$$

Force of gravity on Earth from Sun:

$$F_{gravity,\,S\rightarrow E} = G\frac{m_{Earth} M_{Sun}}{r^2}$$



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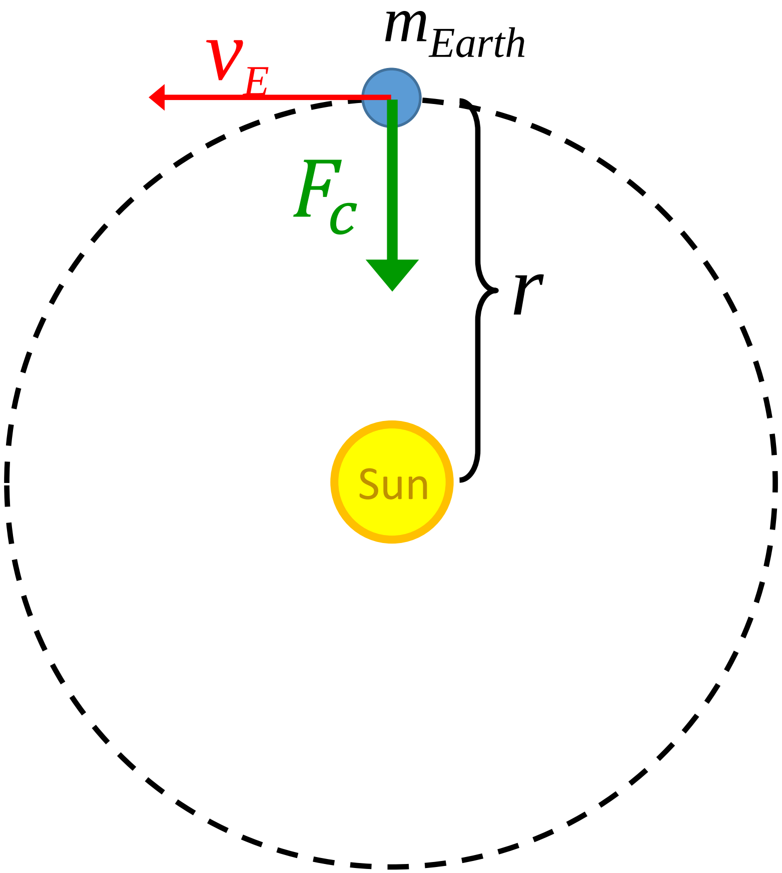

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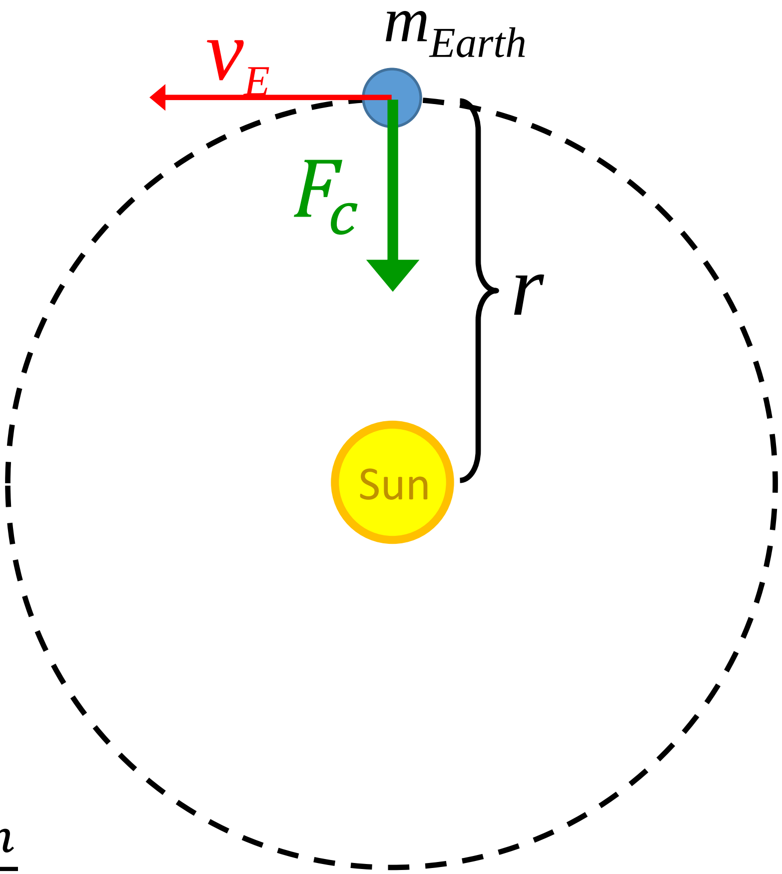

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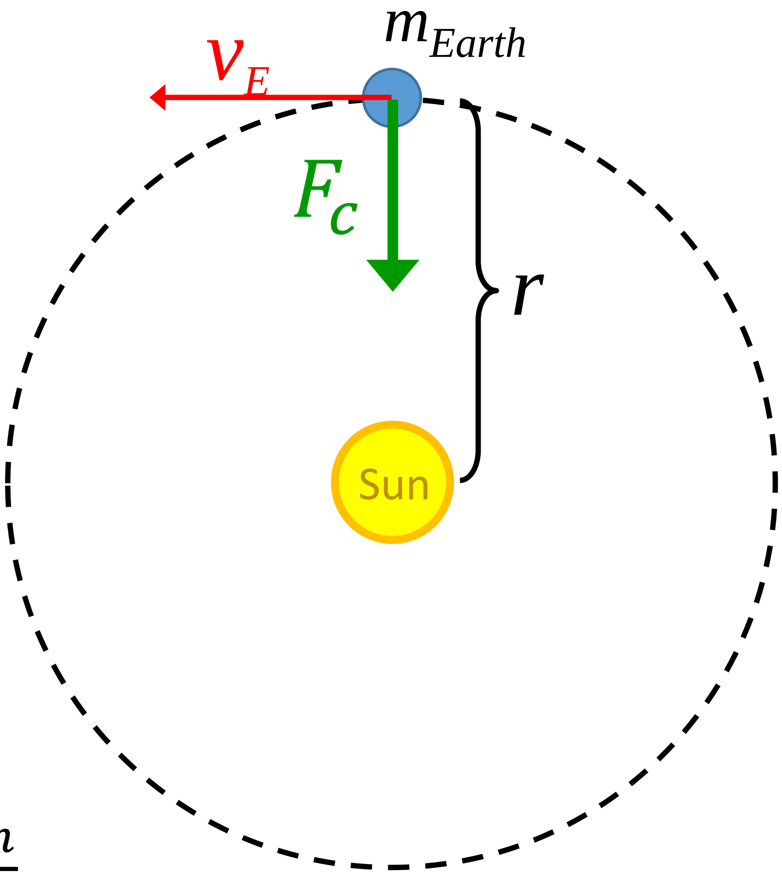

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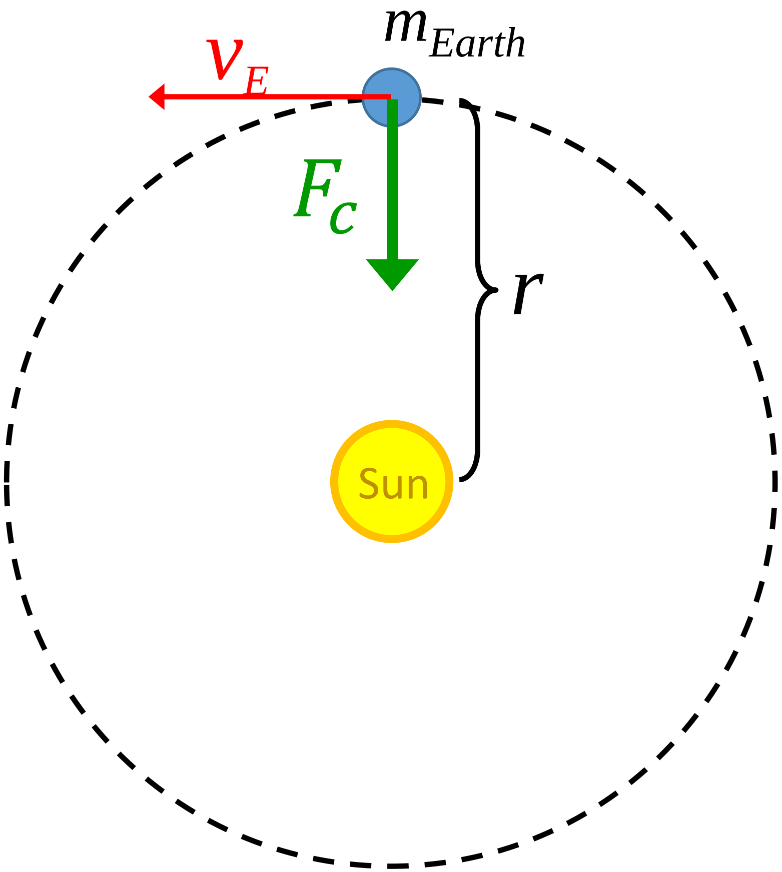

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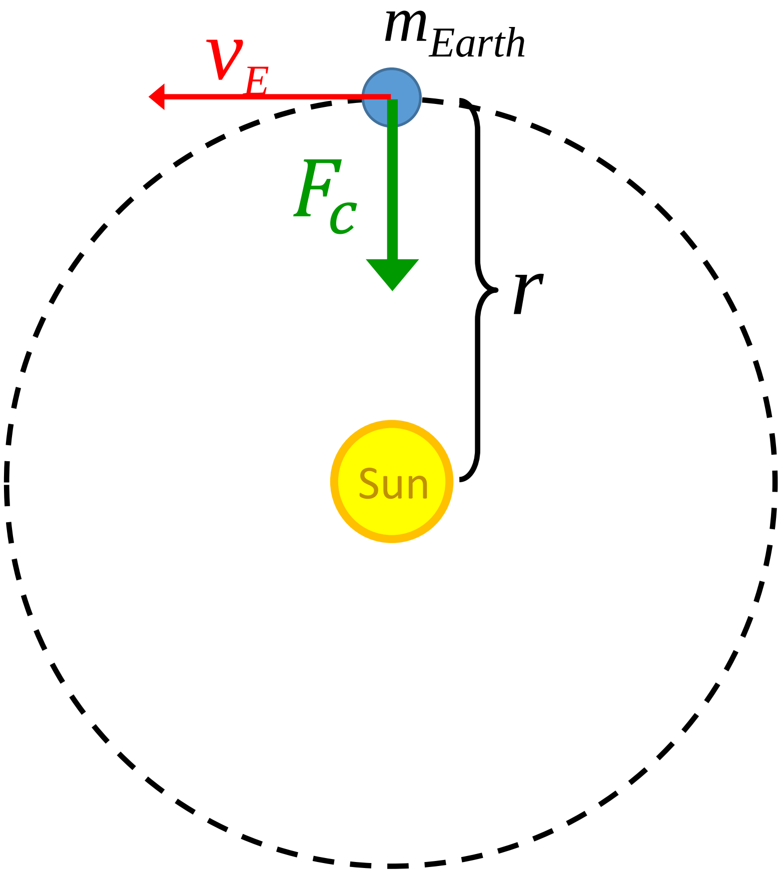

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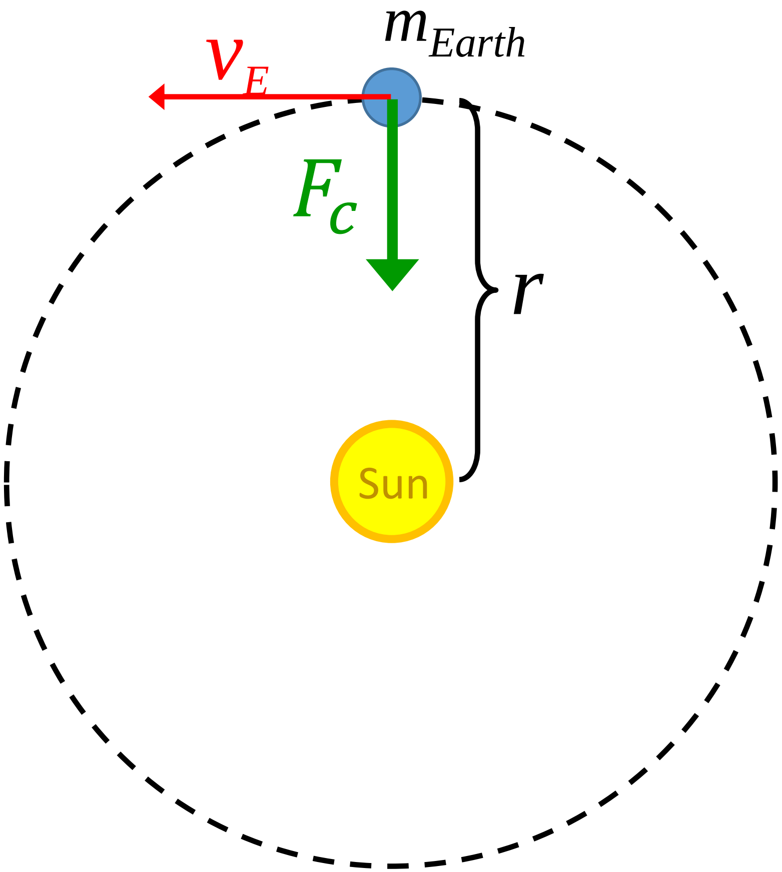

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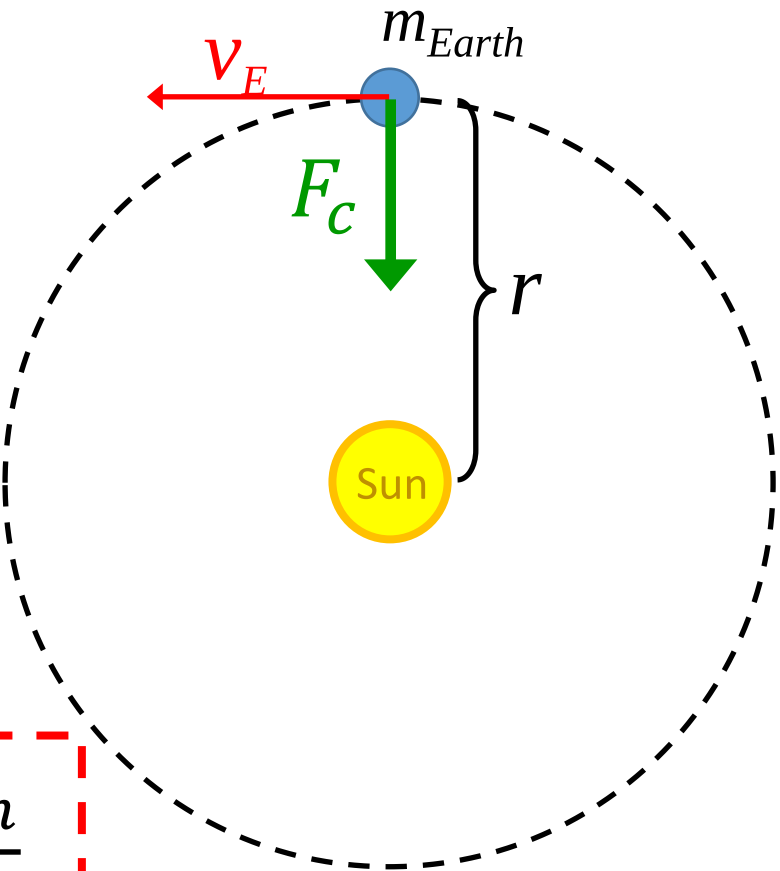

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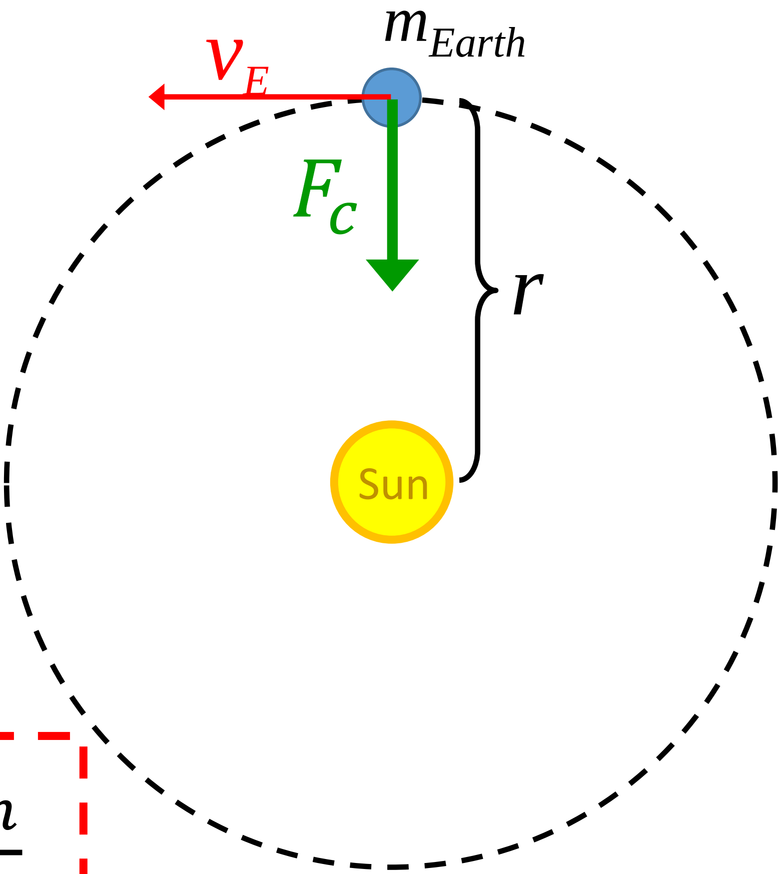


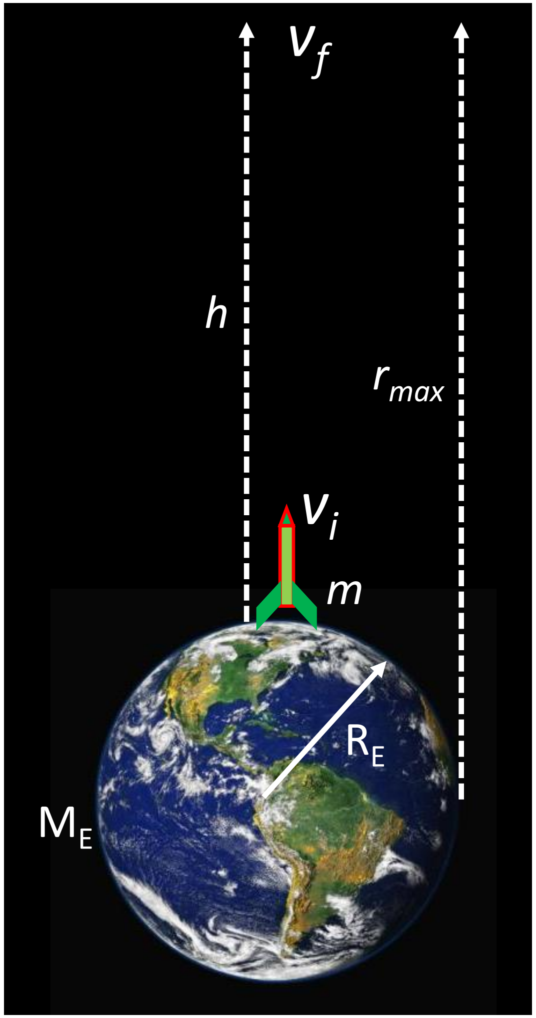
The bound orbital energy is negative: $E_{Total} < 0$

Example: *When a rocket wants to orbit another planet it has to slow down (lower its energy) in order to go into orbit.*

Escape Velocity

Question

What is the minimum velocity needed to escape Earth’s gravity?



$$\boxed{v_{escape} = \sqrt{\frac{2GM_E}{R_E}}}$$

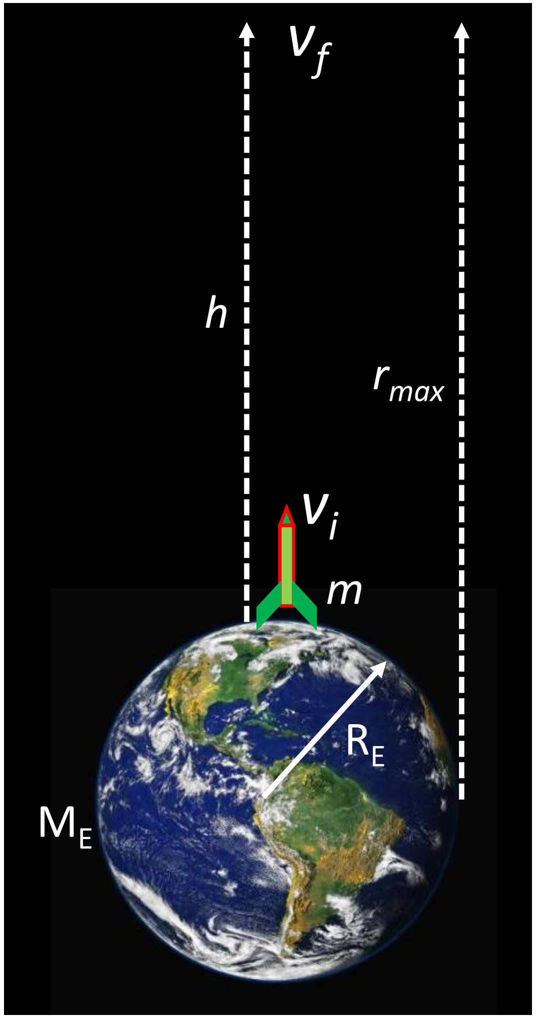
= 11.2 km/s on Earth

Note 1: escape velocity depends on your starting point.

Note 2: Since the Earth spins, objects at “rest” close to the equator already have a significant velocity.

→ Rockets are typically launched close to the equator (or in Florida … or in Texas).

Escape Velocity: Derivation



The projectile reaches its maximum altitude when

$$v_{final} = v_f = 0$$

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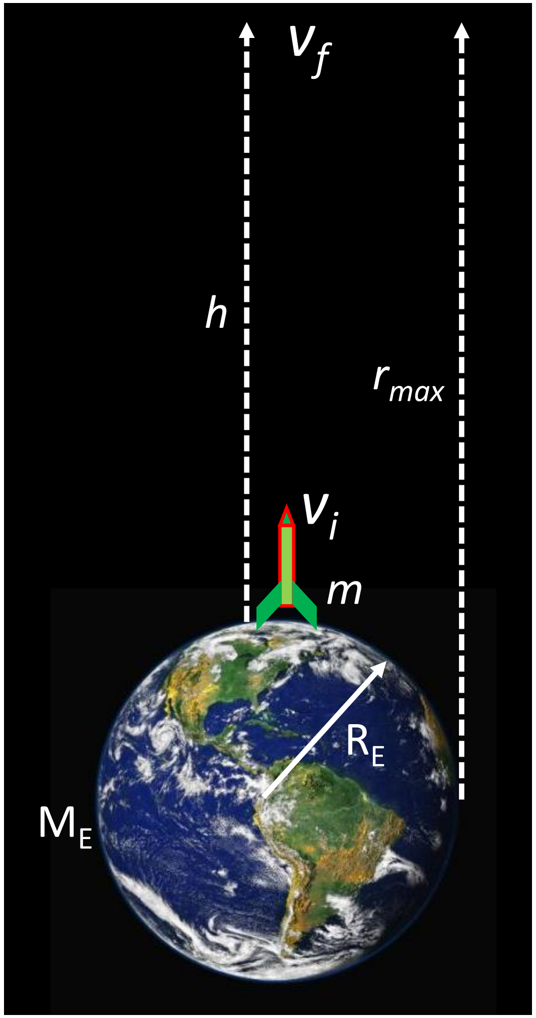

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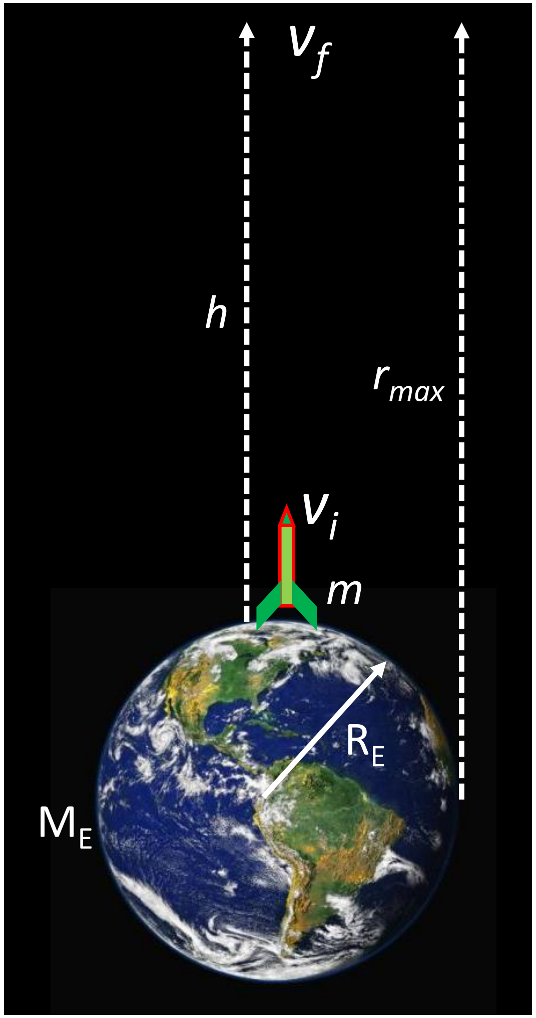

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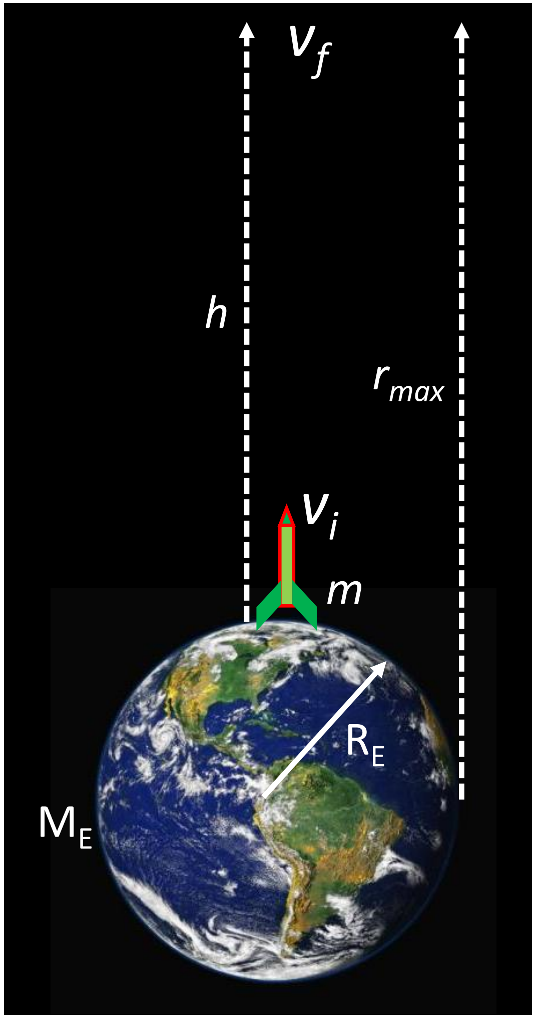

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Solve for v_i: $$\frac{1}{2}mv_i^2 = GM_Em\left(\frac{1}{R_E} - \frac{1}{r_{max}}\right)$$

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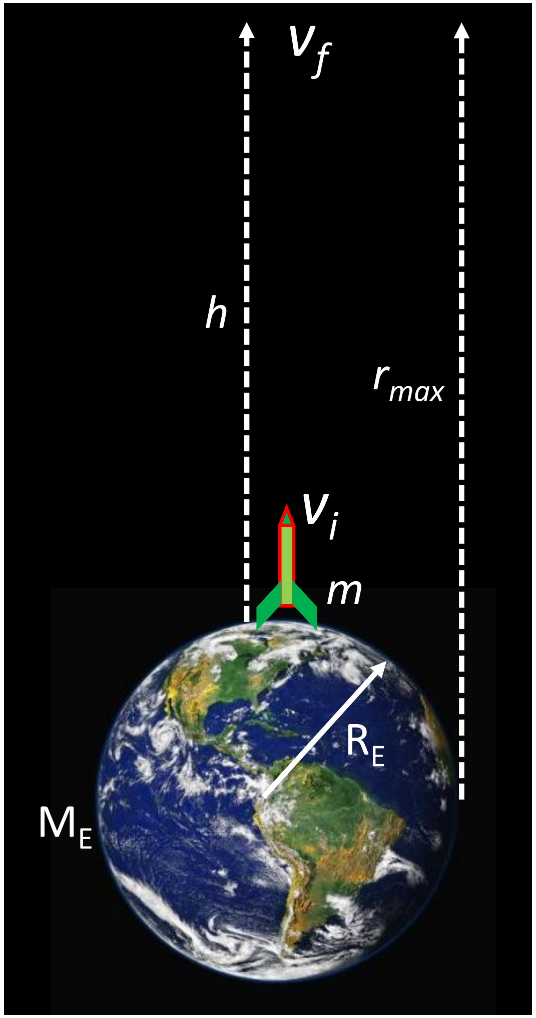

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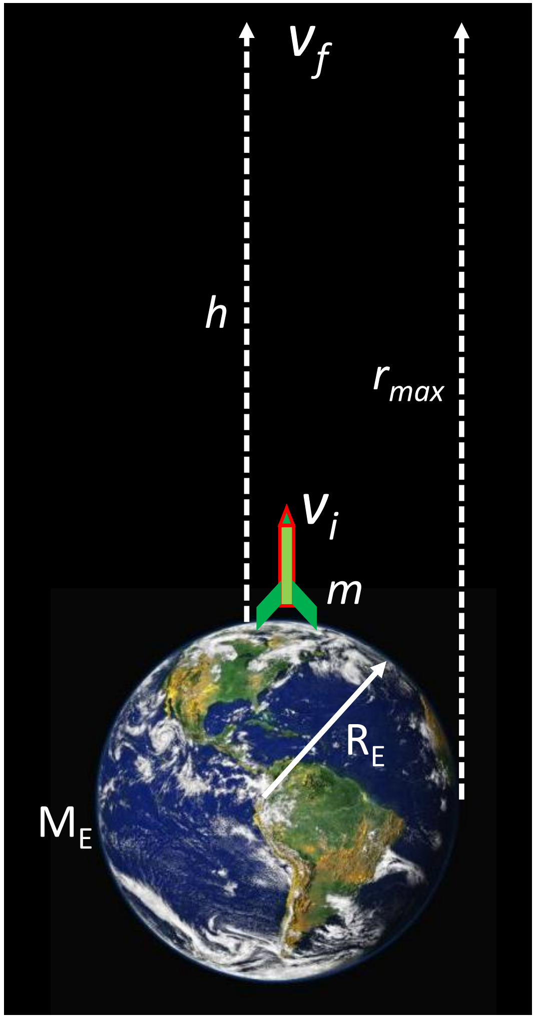

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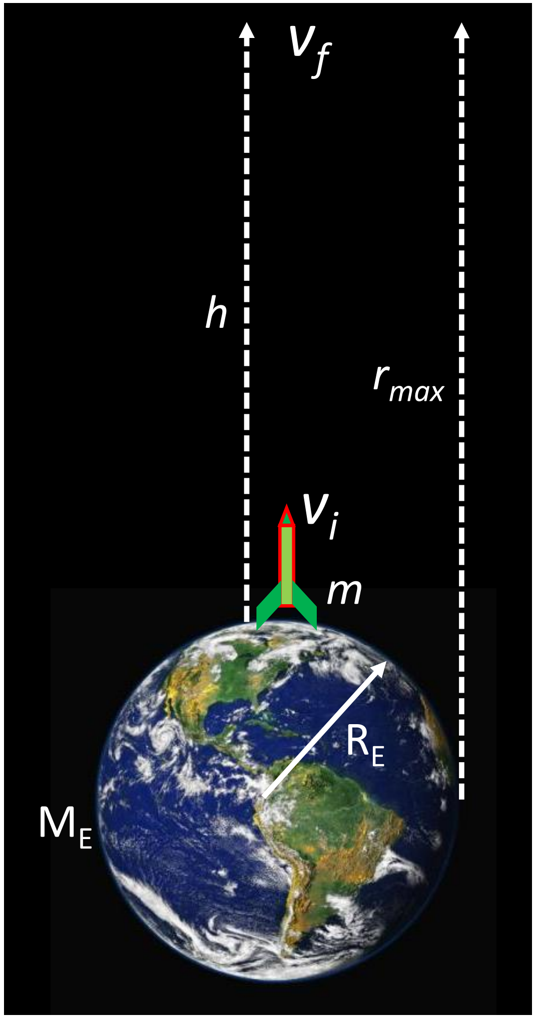

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$$v_{escape}^2 = 2GM_E\left(\frac{1}{R_E} - \frac{1}{r_{max\to\infty}}\right) \Rightarrow \boxed{v_{escape} = \sqrt{\frac{2GM_E}{R_E}}}$$

Tidal Force Example

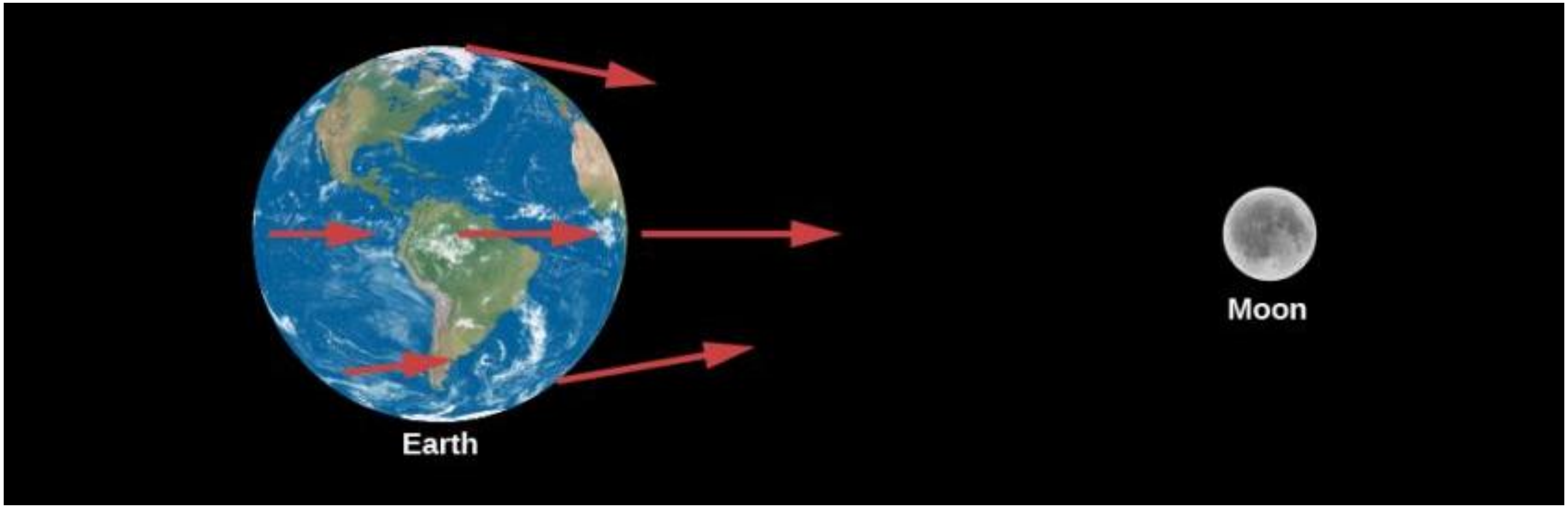
Ocean Tides

Ocean Tides

The force of **gravity** from the Moon is **not uniform** over the Earth.

→ gravity from Moon falls off as $1/r^2$.

→ Near face of Earth feels a stronger force than far face.



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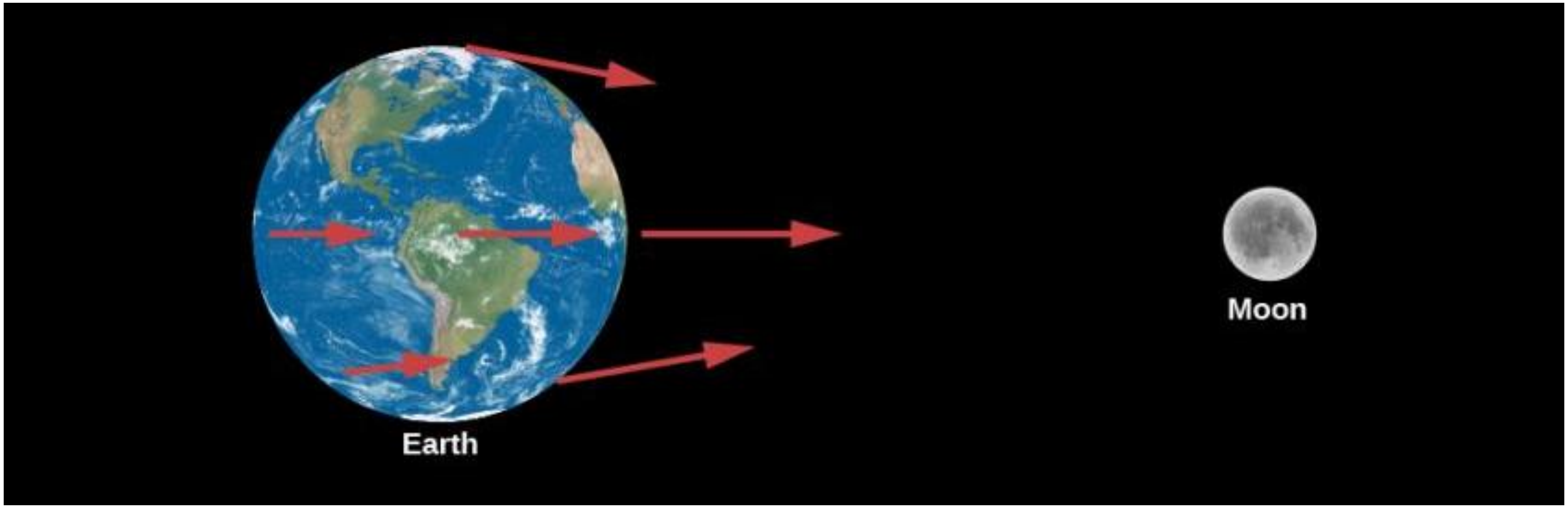


Result

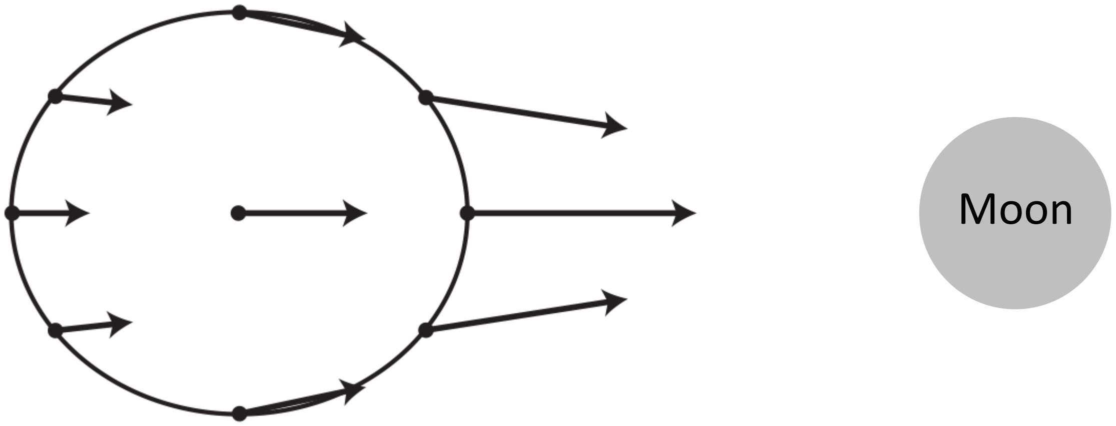
Water on **near side is pulled** towards Moon **more** than average Earth.

Water on **far side is pulled** towards Moon **less** than average Earth.

Ocean Tides: Effective Moon Gravity

Recall:

- Moon is in "free fall" orbit around Earth.
- Earth is in "free fall" orbit around Moon (albeit small orbit).



[scijinks.gov]

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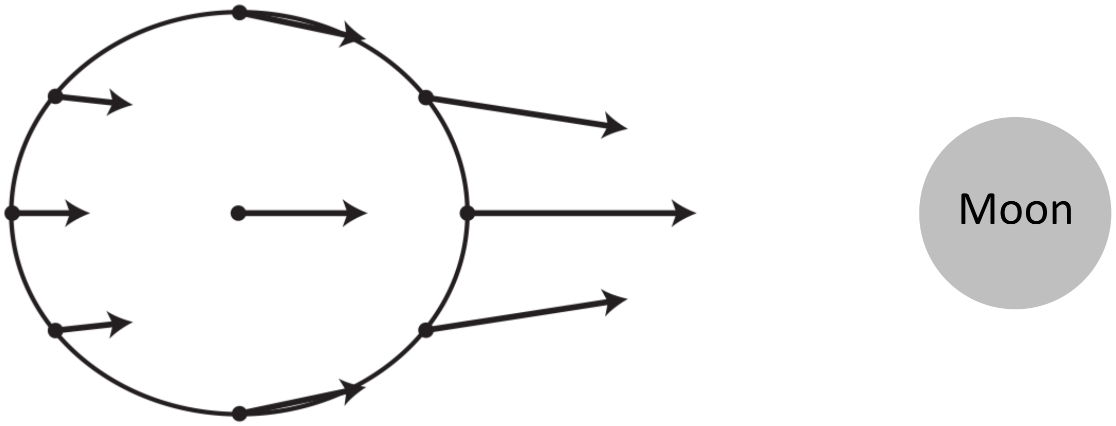

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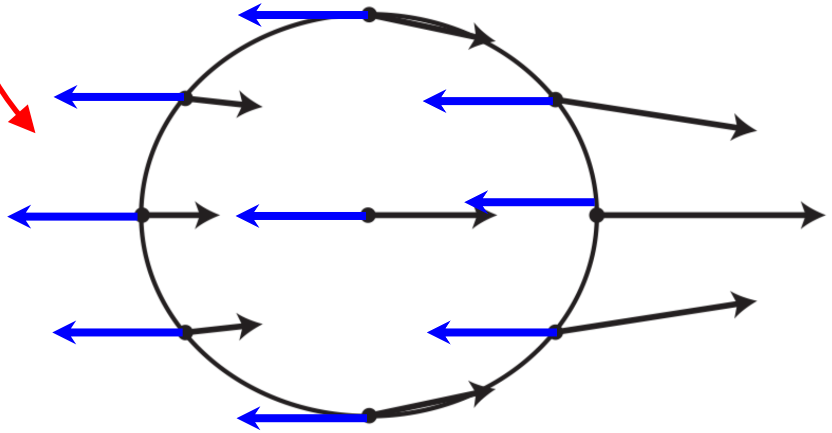
Subtract average gravitational force of Moon.

[since Earth is in “free fall” around Moon.]



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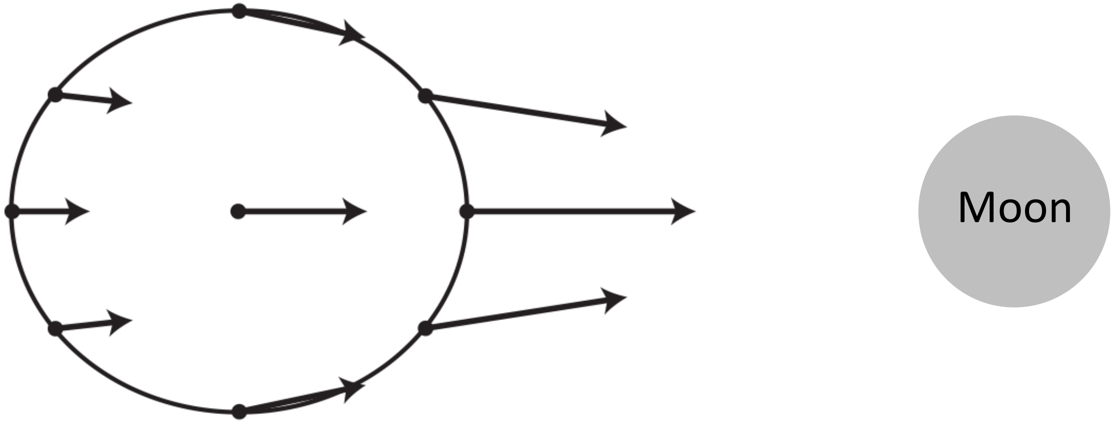

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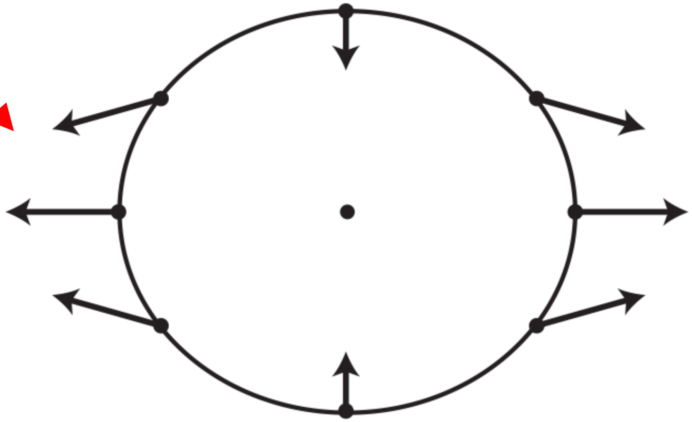

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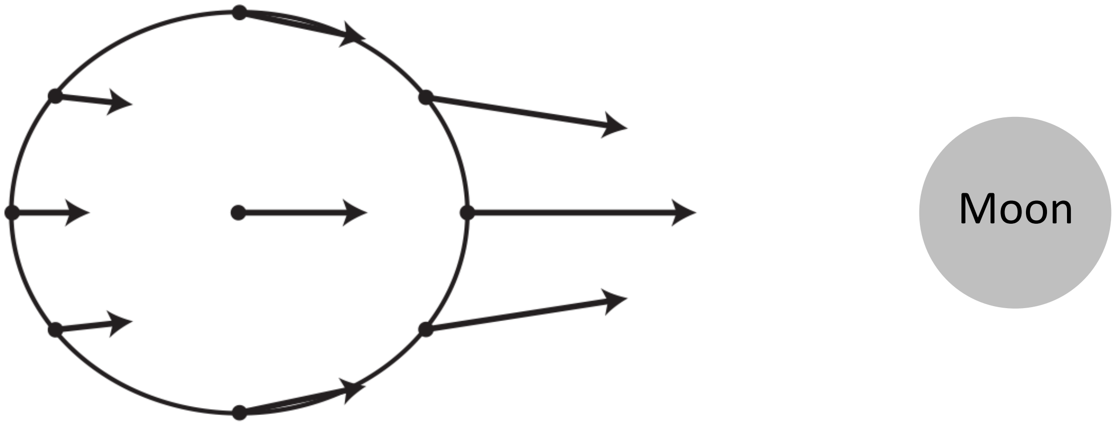

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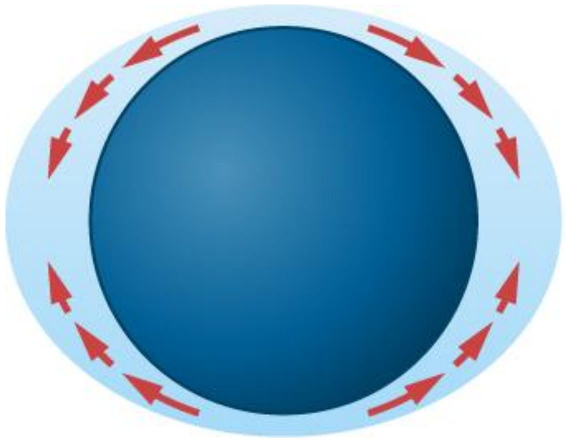
Ocean water is pulled by the effective force



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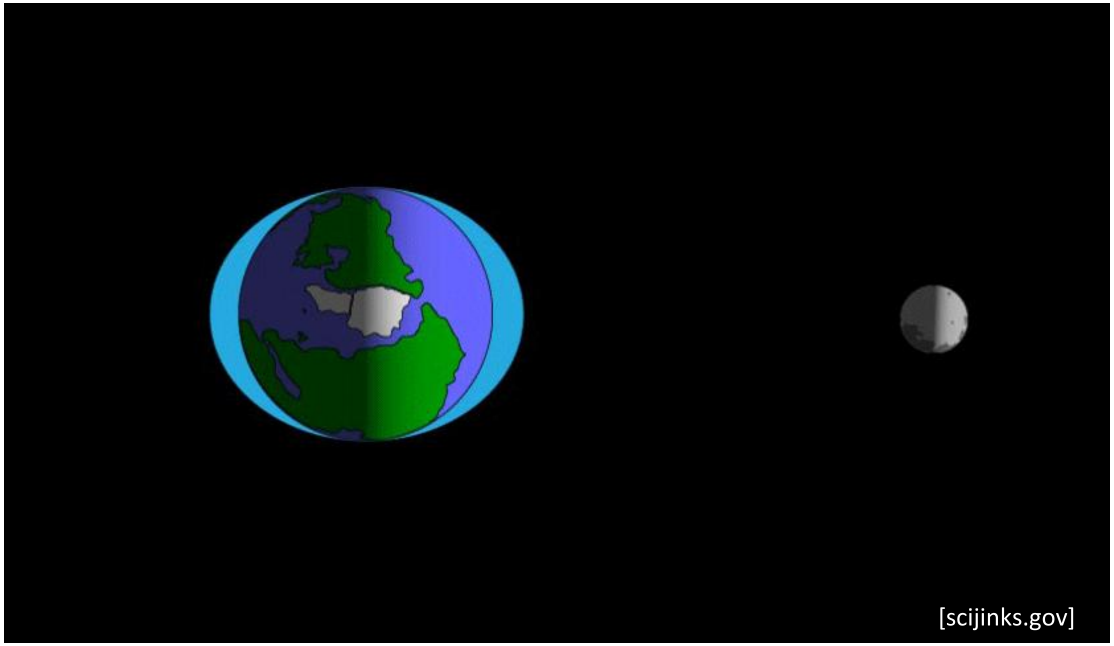
[scijinks.gov]

Animation of Earth and Oceans as seen from above North Pole.

Sun’s gravity gradient affects tides as well: 46% of Moon’s contribution.

- Tides are largest when Sun-Moon-Earth are aligned.
- Tides are weakest when Sun & Moon are at 90° to each other.
- Shape of ocean basins & winds also affect the strength of tides.
- The atmosphere also experiences tides.

PollEv Quiz: PollEv.com/sethaubin

Week 3
Light & Matter

1. Electromagnetic waves & photons

2. Spectroscopy and atoms

3. Particles, nuclei, and fusion

REMINDER: **Midterm #1** is on Friday, February 20 (in class).

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Speed of Light

The speed of light in **vacuum** is always $c = 3.0 \times 10^8$ m/s.

$= 300{,}000$ km/s

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The speed of light does NOT depend on the observer:

- **If observer A is at rest** and measures the speed of light of their laser pointer, then they will measure $\mathbf{c = 3.0 \times 10^8}$ **m/s**.
- **If observer B is moving at 290,000 km/s**, then they will measure the speed of light of observer A's laser pointer to be $\mathbf{c = 3.0 \times 10^8}$ **m/s**.

Speed of Light in Matter

The speed of light ***in matter is slower*** than in vacuum

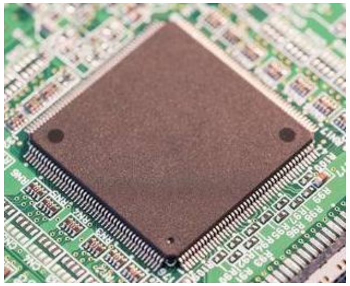
Speed of light in **air** = **99.97% of c**

Speed of light in **water** = **75% of c**

Speed of light in **glass** = **67% of c**

Speed of light in **diamond** = **41% of c**

Speed of light in **silicon** ≃ **25% of c**

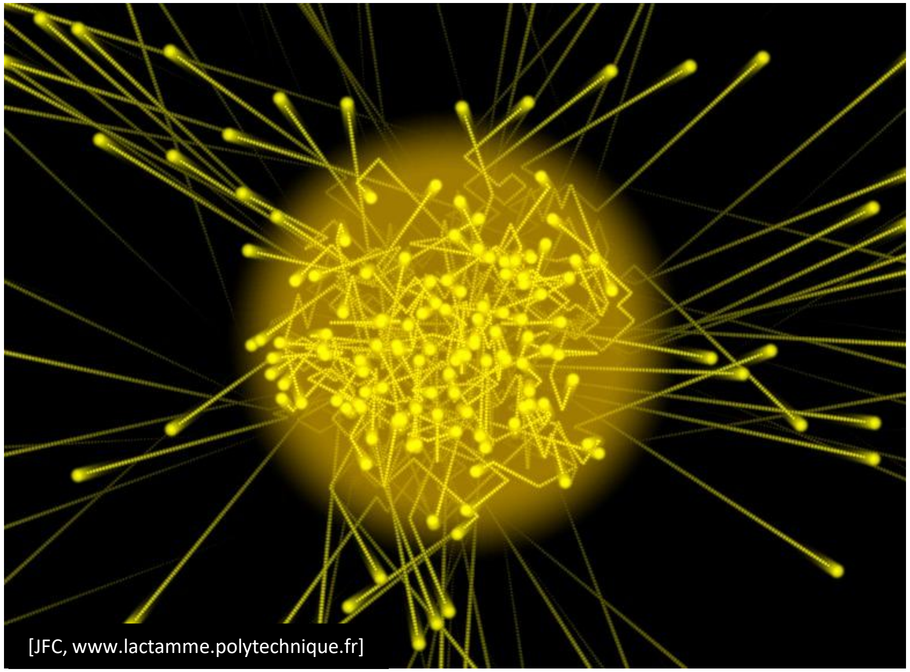


[123RF.com]

Note: In engineered atomic gases, light can be brought ~ 10 m/s and even stopped. (Novikova Lab at W&M)

Light:

Particle or Wave?



[JFC, www.lactamme.polytechnique.fr]

[Zachary Wilson, CK-12 Foundation, CC BY-NC 3.0]

Electromagnetic Waves

James Clerk Maxwell (1831-1879) worked on electricity and magnetism:

- They are different facets of the same phenomenon.
- Light is a wave of electric & magnetic fields.

[OpenStax]

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oscillating electric field

⬇

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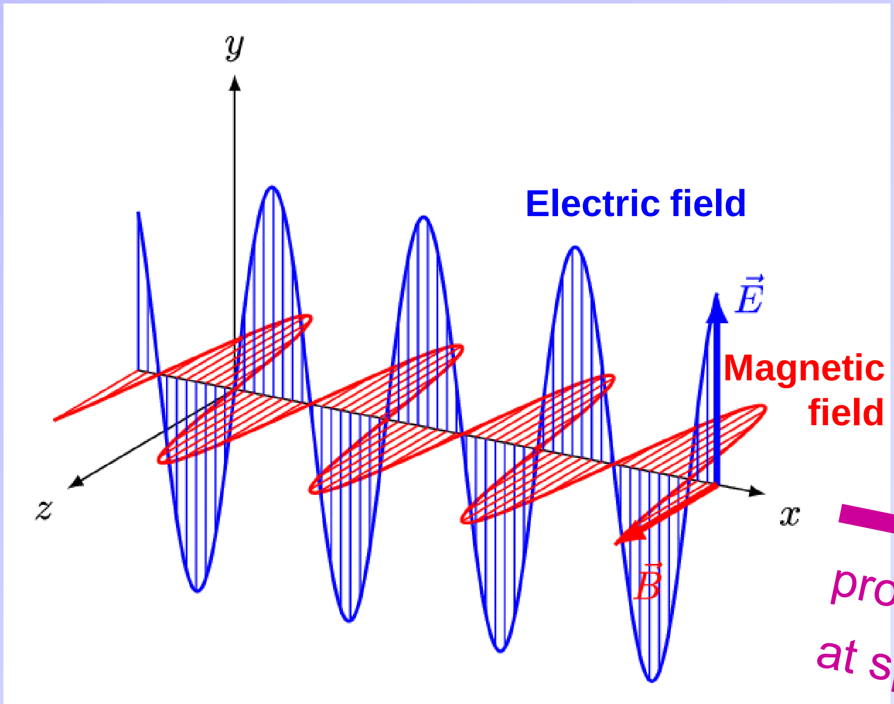


[And1mu, wikimedia commons]

propagation at speed **c**

oscillating electric field

⬇

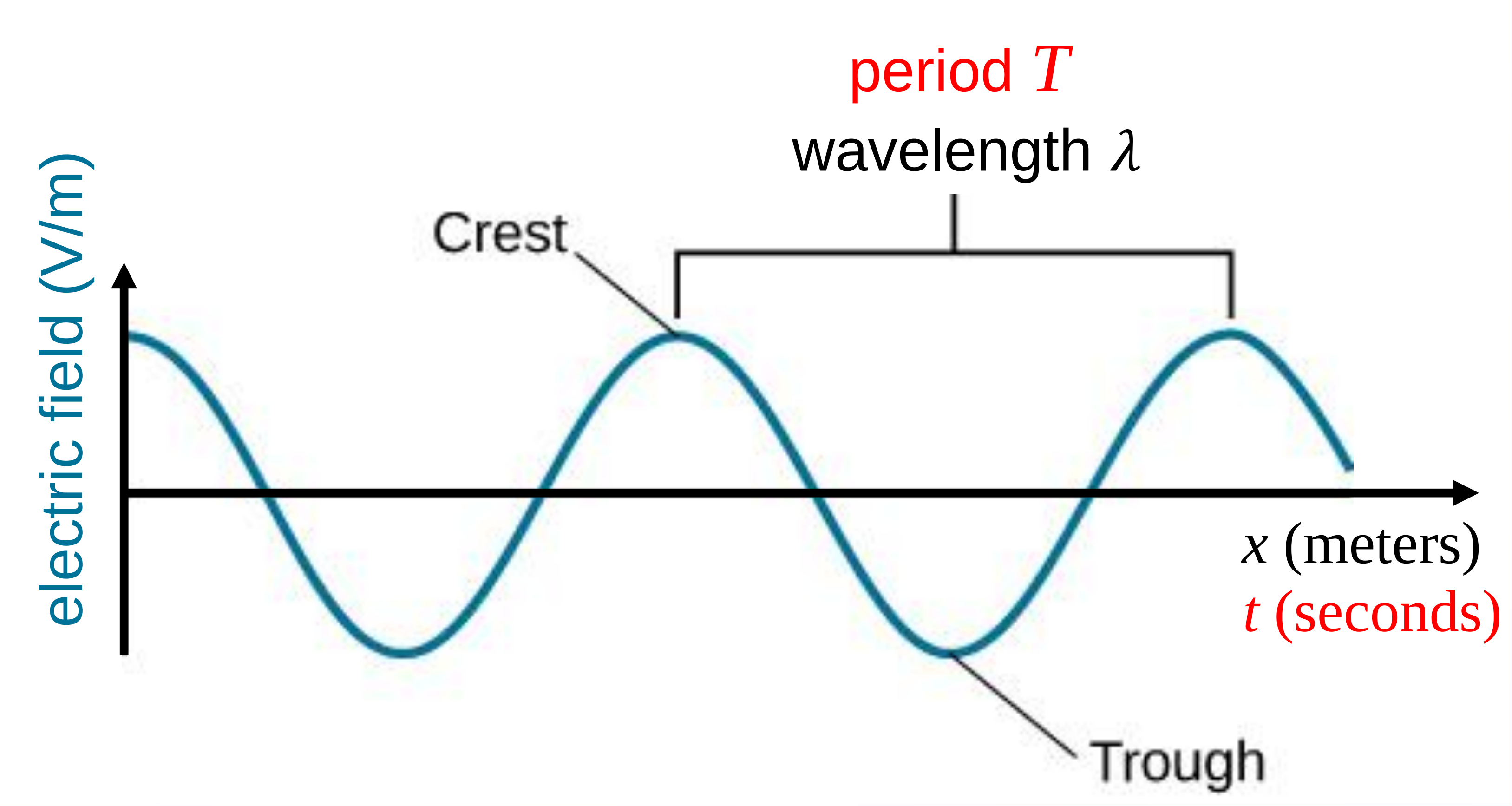
oscillating magnetic field

⬇

oscillating electric field

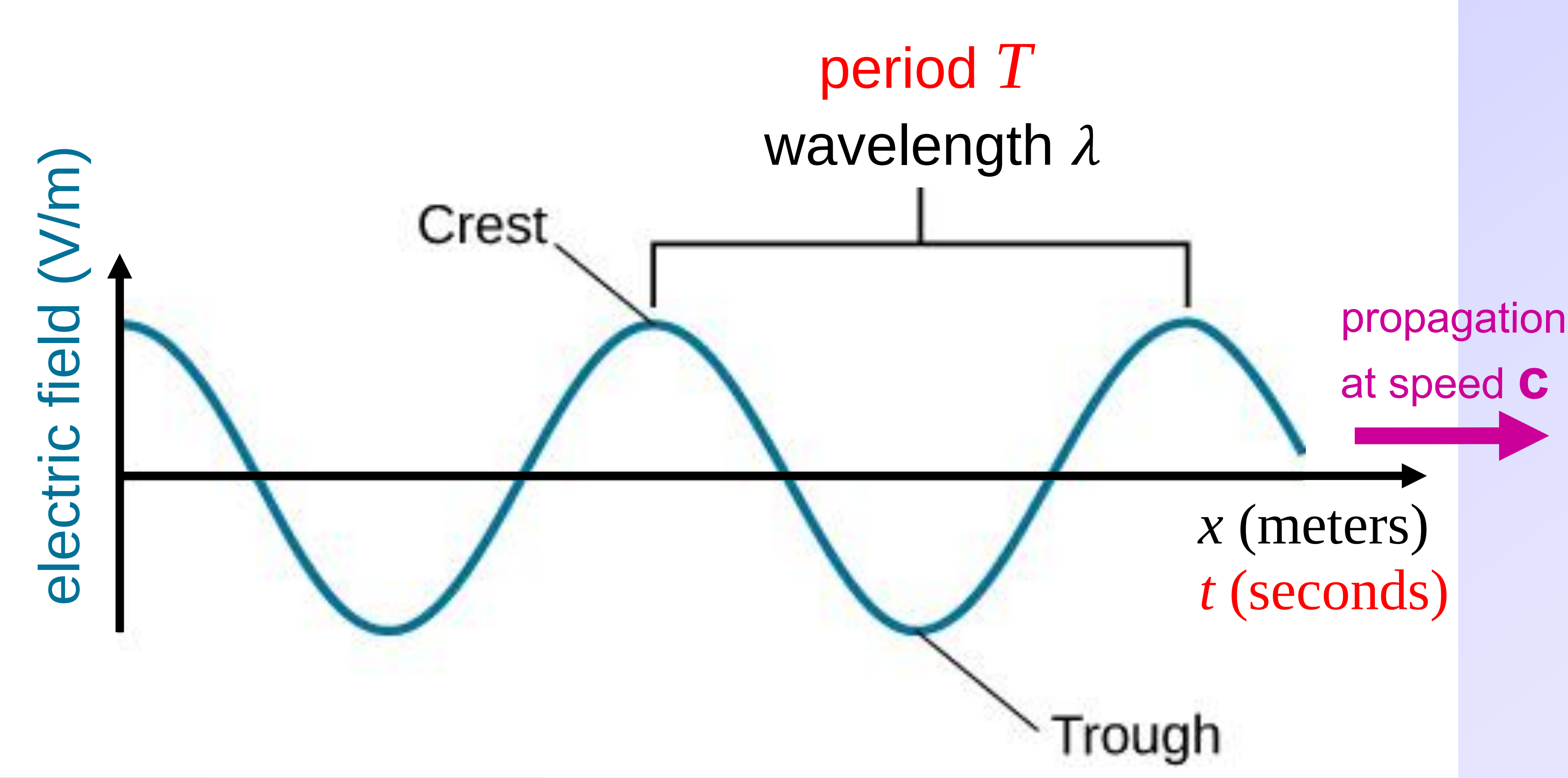
⬇

Wave Properties



Frequency: $f = \frac{1}{T}$ = oscillations per second

Wave Properties



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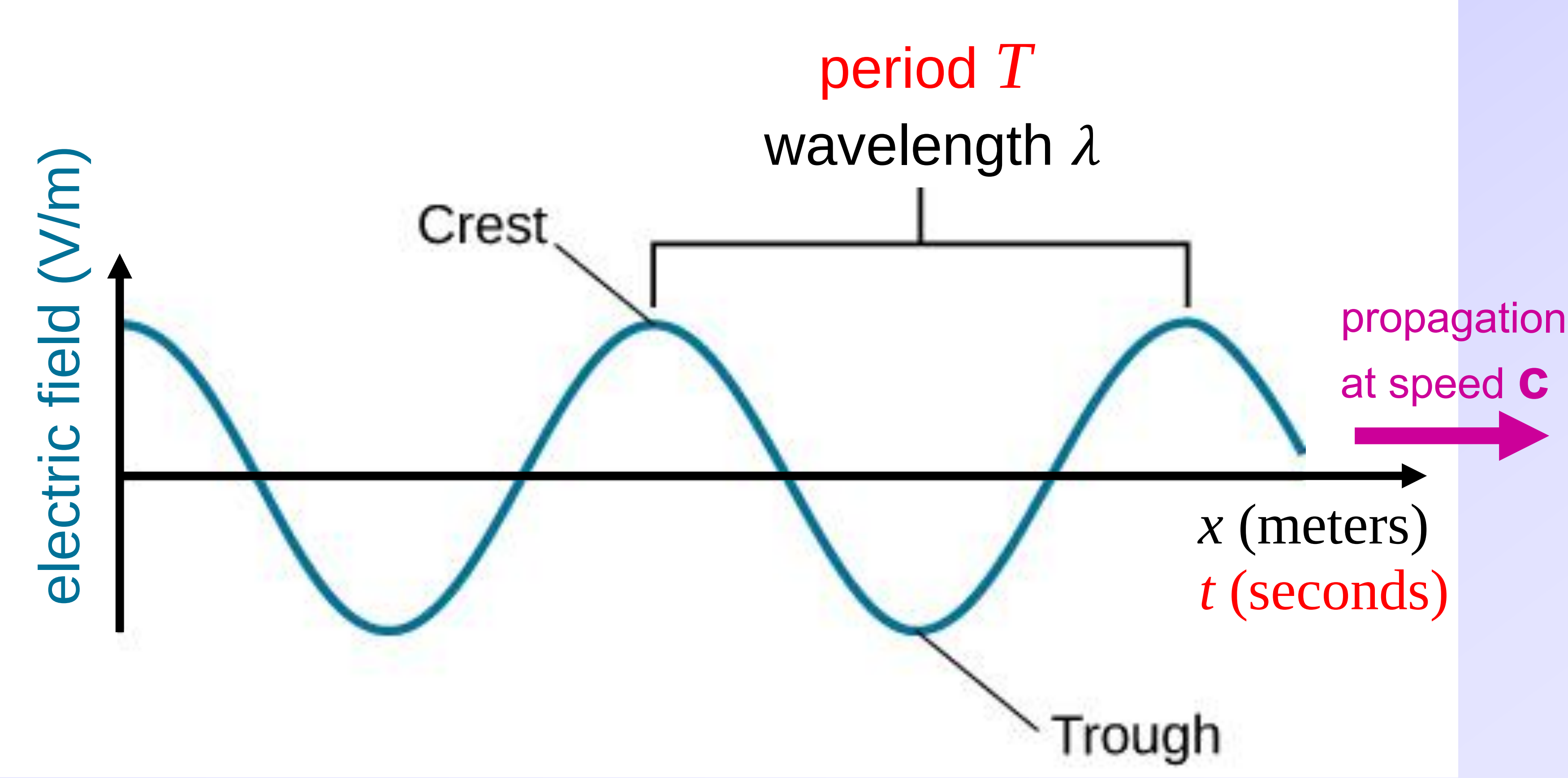

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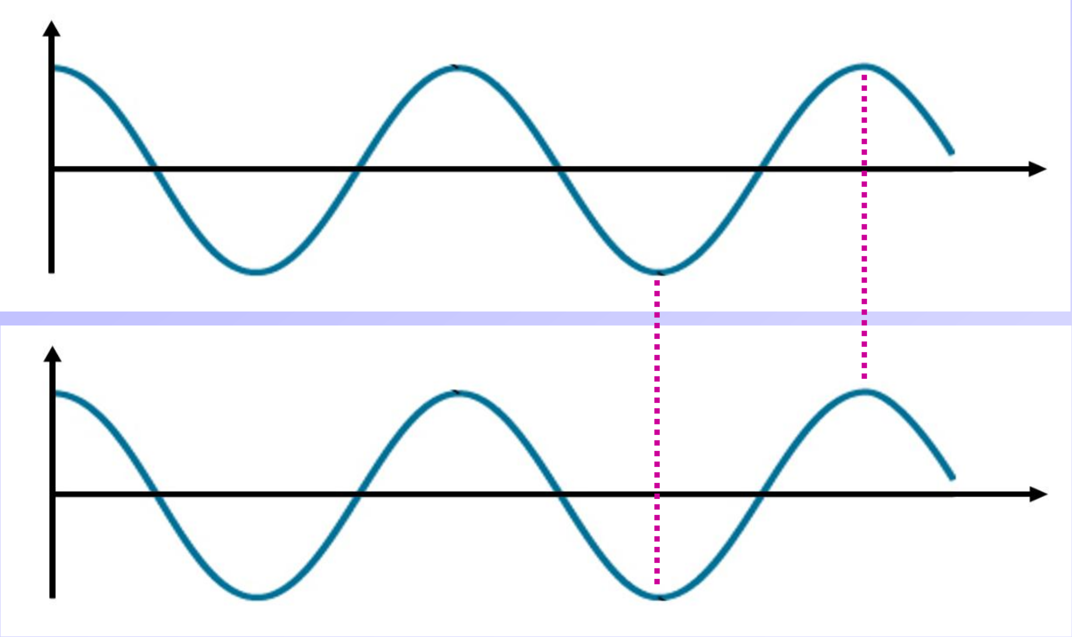
Traveling wave formula: $\boxed{\lambda f = c}$

Wave Addition: Constructive Interference

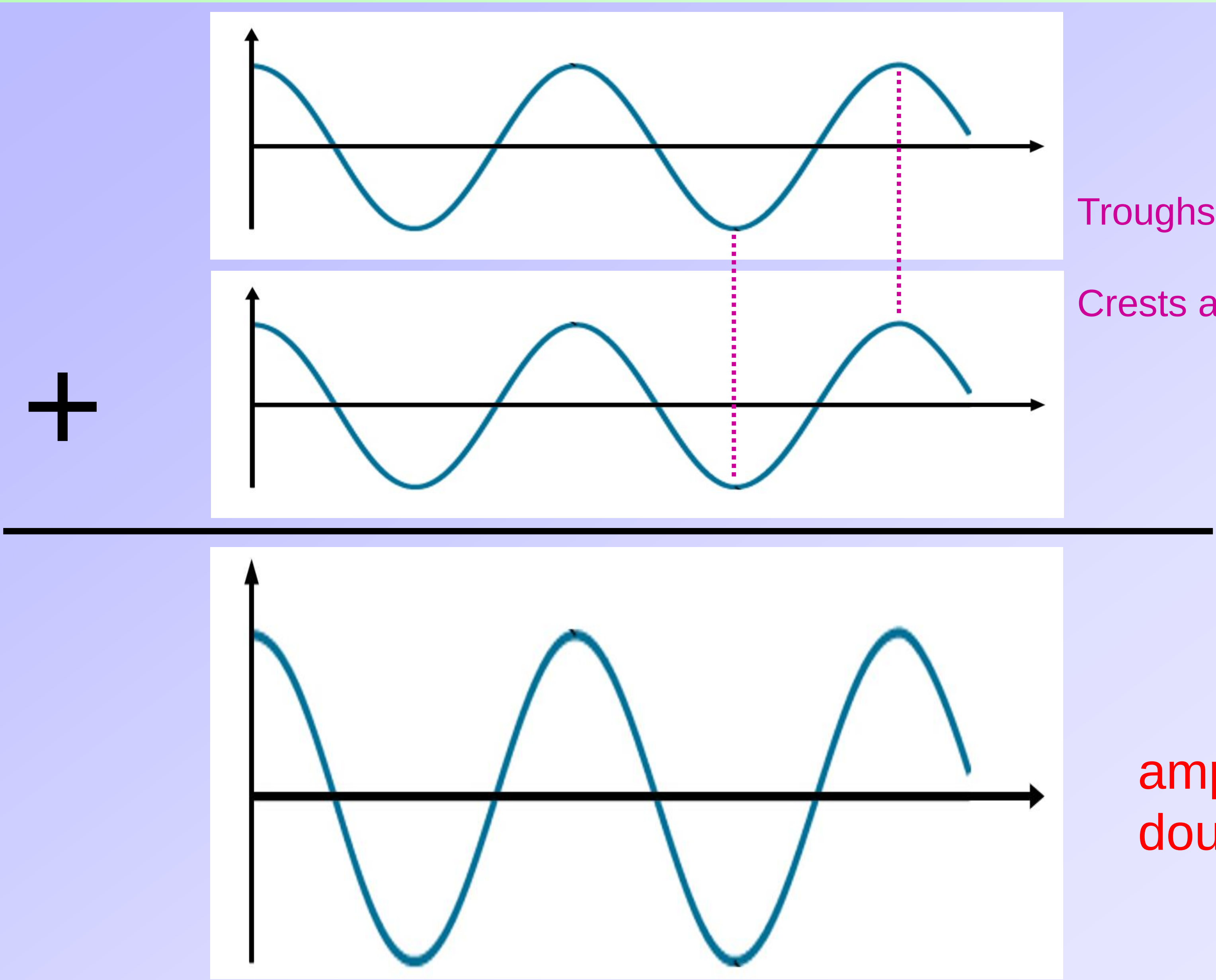


Troughs are in sync

Crests are in sync

+

Wave Addition: Constructive Interference

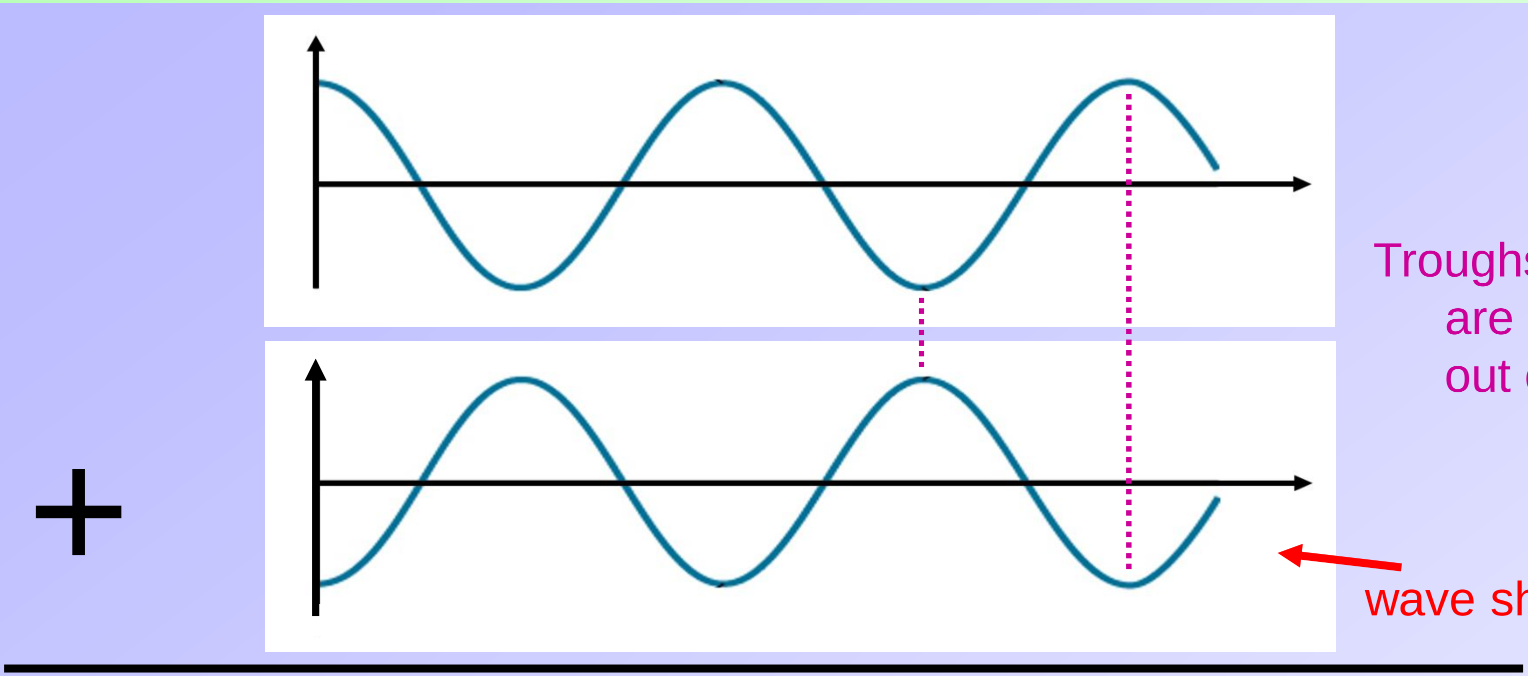


Troughs are in sync

Crests are in sync

amplitude
doubles

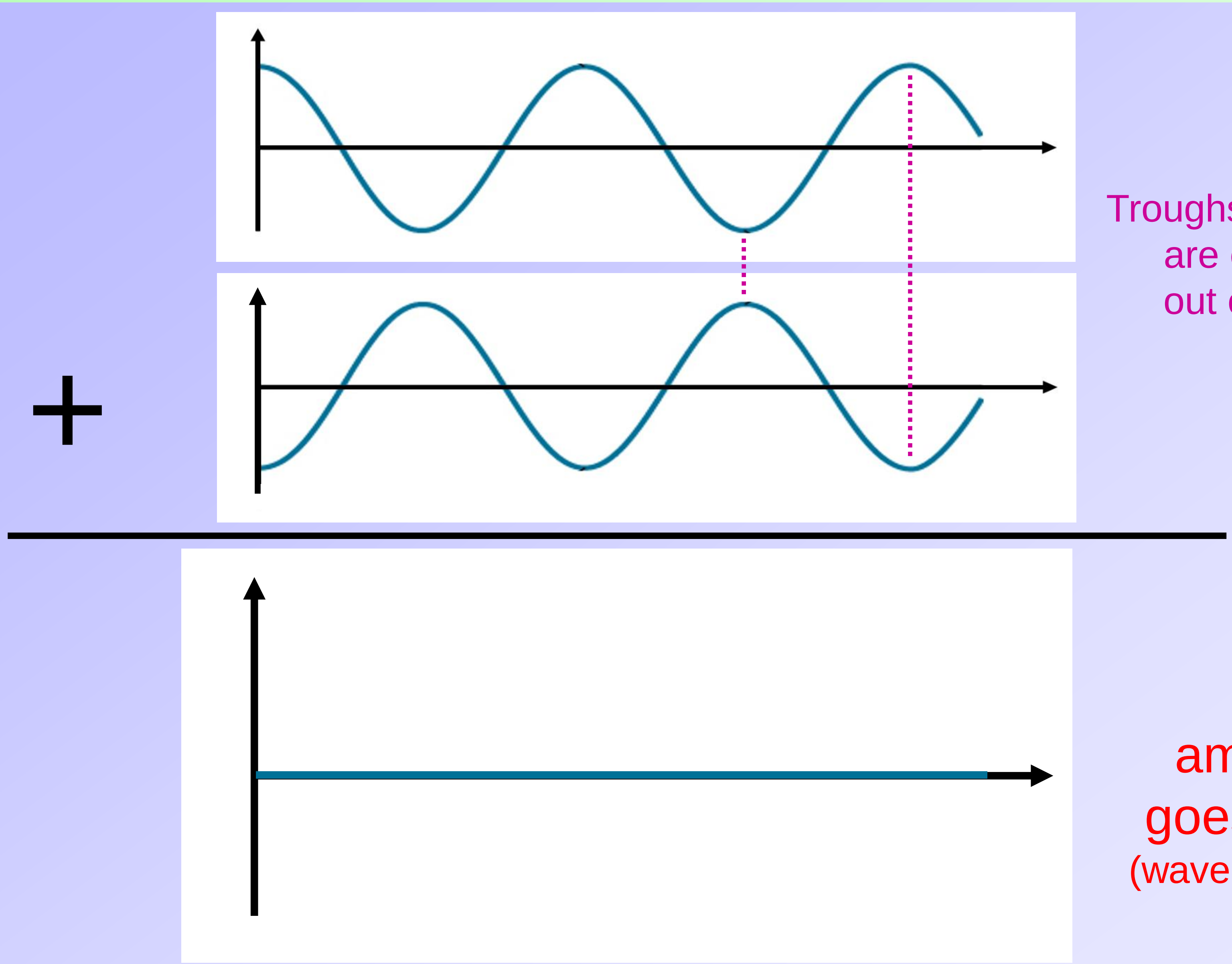
Wave Addition: Destructive Interference



Troughs & crests
are exactly
out of sync

wave shifted by 180°

Wave Addition: Destructive Interference



Troughs & crests
are exactly
out of sync

amplitude
goes to zero
(wave disappears)