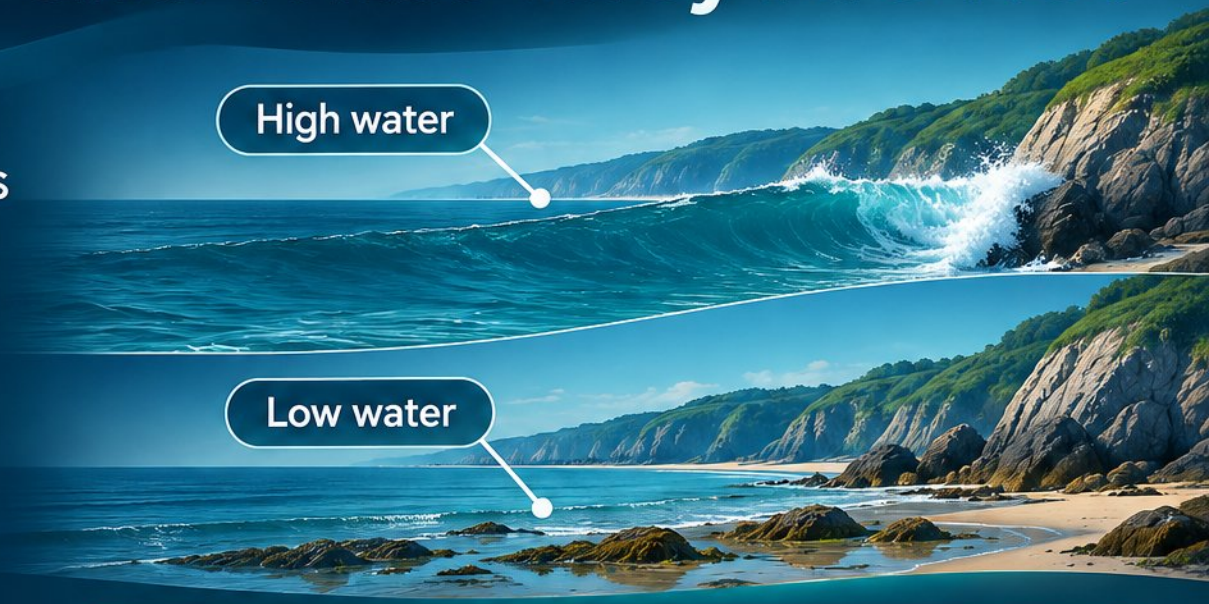
Tides Explained: How the Moon and Sun Pull the Oceans

- Tides: the ocean's reliable, twice-daily rise and fall
- Core question: why does water bulge toward and away from the Moon?
- Scope: tidal forces, two-bulge model, spring–neap cycle, real coasts
- Audience: students, natural-science learners, and science educators
- Roadmap: idealized model first, then real-world complications and applications



What Tides Are—and What They Are Not

- Tides: long-period ocean waves driven by the Moon's and Sun's tide-generating force
- High water = wave crest at the coast; low water = trough
- Tidal range = height difference between high and low water
- Vertical rise and fall comes with horizontal tidal currents (flood and ebb)
- Flag early: "Moon lifts water," rotation-only tides, one bulge, Sun must dominate
- Intuition check: Sun's gravity ≈ 177× the Moon's, yet its tidal force is only about half

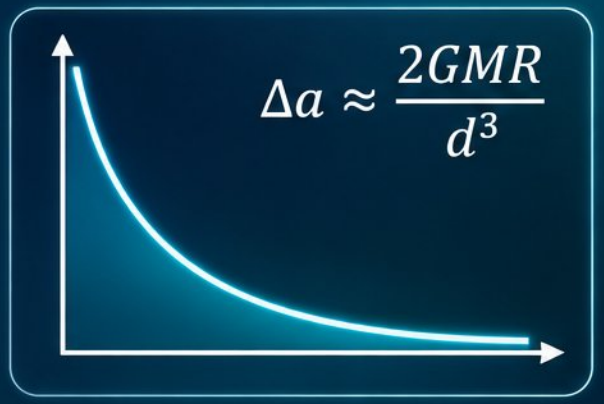


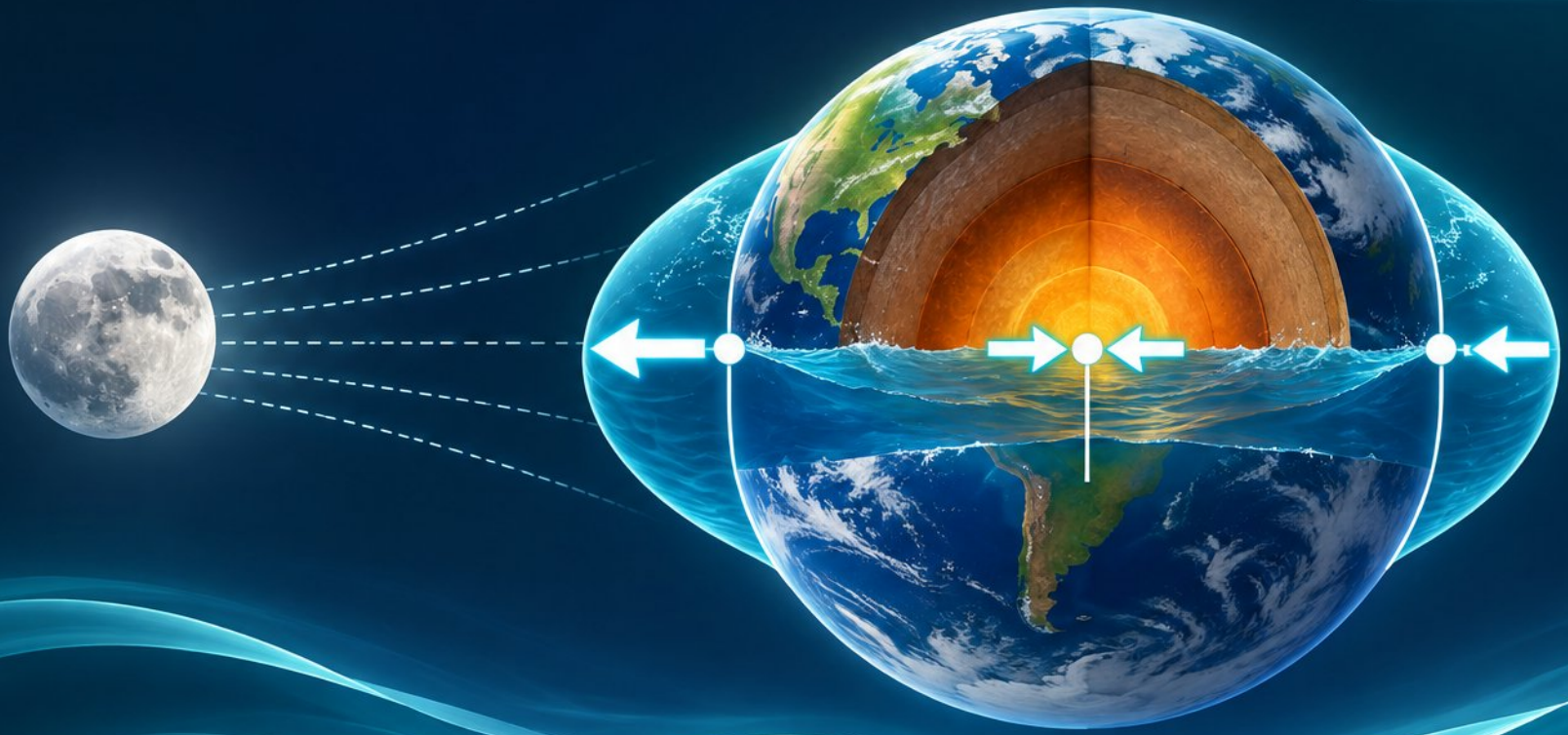




Gravity Is Not the Tide: The Differential Force

- Newton: gravity ∝ masses / distance²
- Tides come from a difference in pull, not the pull itself
- Only extended bodies feel tides; a point mass would not
- $\Delta a \approx 2GMR/d^3$ — tidal force falls as the inverse cube
- Lunar pull ≈ 1.1×10^{-7} g; solar ≈ 0.5×10^{-7} g — tiny yet persistent





Why the Moon Beats the Sun: The Distance-Cubed Effect

- Sun: ~27 million times the Moon's mass, but ~390 times farther away
- Tidal force scales as M/d^3, so distance is cubed: $390^3 \approx 59$ million
- Sun's tide-generating force ≈ 0.46 of the Moon's (about 31% vs 69%)
- Lunar/solar ratio ≈ 2.2 (range ~1.75 to ~2.9 with distance changes)
- Raw gravity ranks the Sun first; tidal force ranks the Moon first

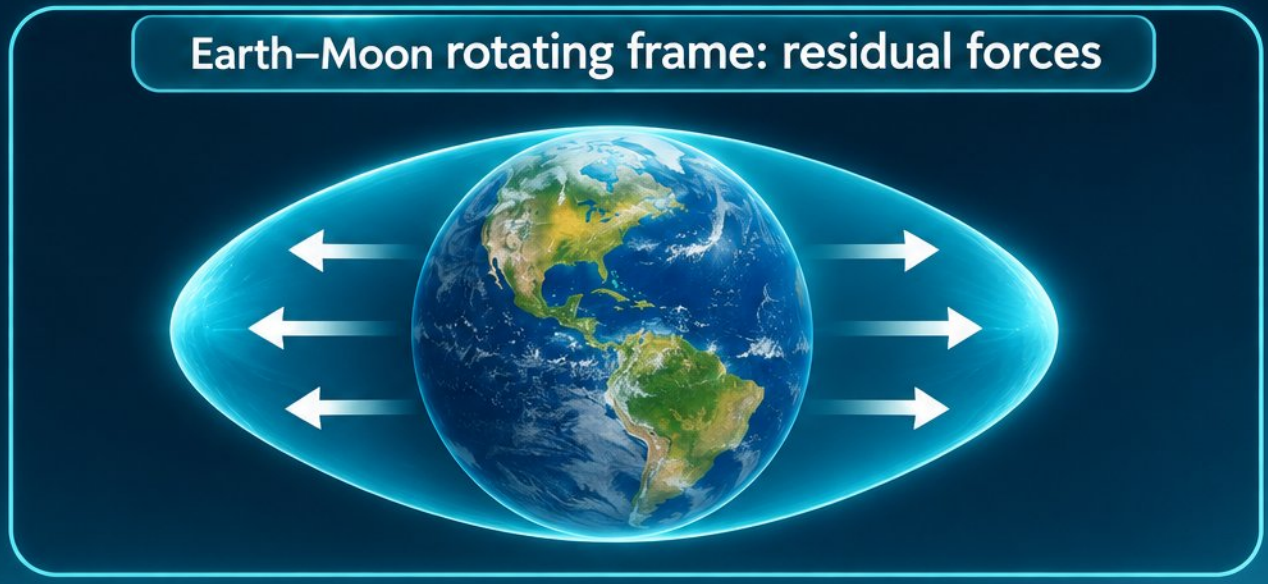




Two Bulges, Two High Tides: Explaining the Far-Side Bulge

- Near side: water is pulled more strongly than Earth's center, piling up toward the Moon
- Far side: pull is weaker than at Earth's center, so water lags behind and bulges
- Both bulges are essentially equal in height—no bulge floats free
- Work in the Earth–Moon rotating frame (barycenter inside Earth) for residual forces
- Water flows horizontally and piles up; avoid vague "inertia" or "centrifugal" shortcuts





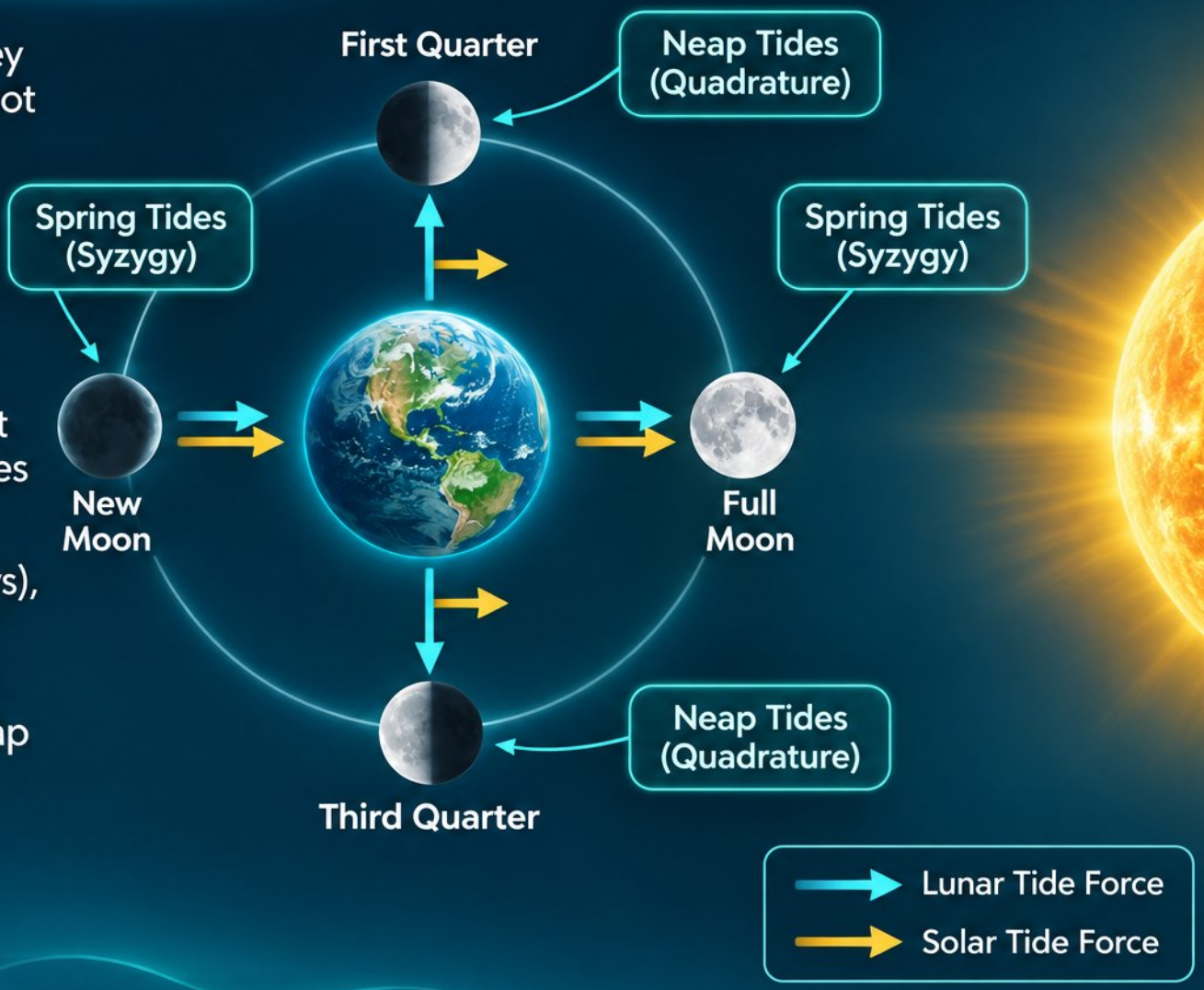
The Tidal Day: Why High Tide Comes About 50 Minutes Later



- Bulges stay roughly aligned with the Moon; Earth rotates underneath them
- Moon orbits in the same direction Earth spins, so Earth must catch up
- Lunar (tidal) day ≈ 24 h 50 min — an extra ~50 minutes per day
- Successive high tides ≈ 12 h 25 min apart; high-to-low ≈ 6 h 12.5 min
- Idealized result: two high and two low waters at nearly equal heights
- Equilibrium model assumes an ocean-covered Earth responding instantly — a teaching device, not a prediction tool

Spring and Neap Tides: The Sun Joins In

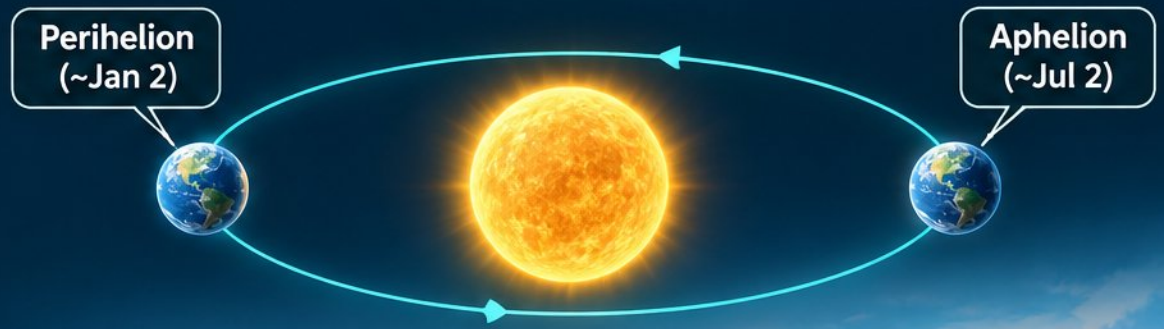
- Solar tides are smaller, but they modulate the lunar pattern—not a separate tide
- New and full Moon (syzygy): forces align, producing spring tides with the largest range
- First and third quarter (quadrature): forces act at right angles, partly cancel—neap tides
- Two springs and two neaps each synodic month (~29.5 days), about a fortnight apart
- Combined amplitude ≈1.46 vs 0.54 lunar units; spring-to-neap ratio ≈2.7
- "Spring" means the tide "springing forth"—no link to the season

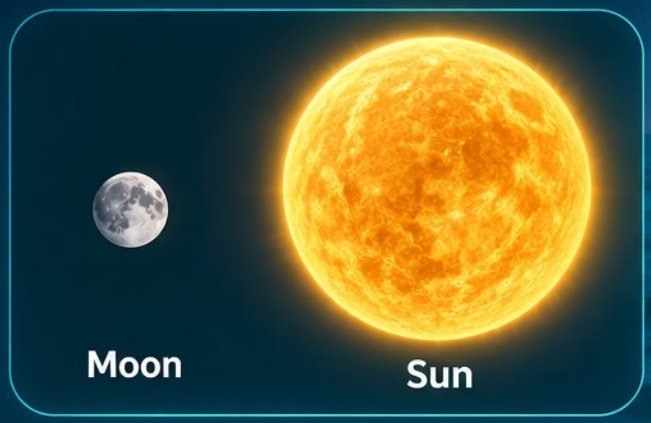


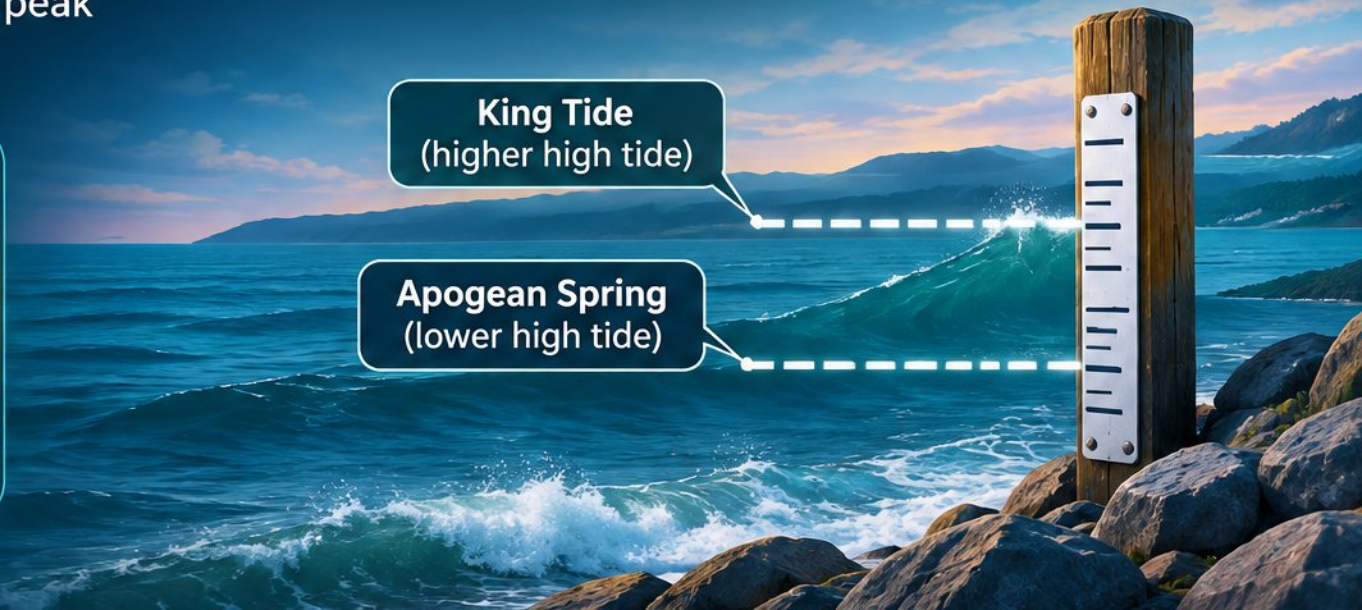
Distance Matters: Perigee, Apogee, and Perigean Spring Tides

- Lunar distance varies ~31,000 km each month; tidal force scales as $1/d^3$
- Perigee (closest) boosts tidal range; apogee (farthest) reduces it
- Earth's perihelion (~Jan 2) enhances solar tides; aphelion (~Jul 2) weakens them
- Perigean spring tides: new/full Moon near perigee, 6–8 times per year — "king tides"
- High tides can be >1 ft higher than apogean springs; at Anchorage, >3 ft
- Caution: not every king tide floods; sea level rise and seasons shift peak highs



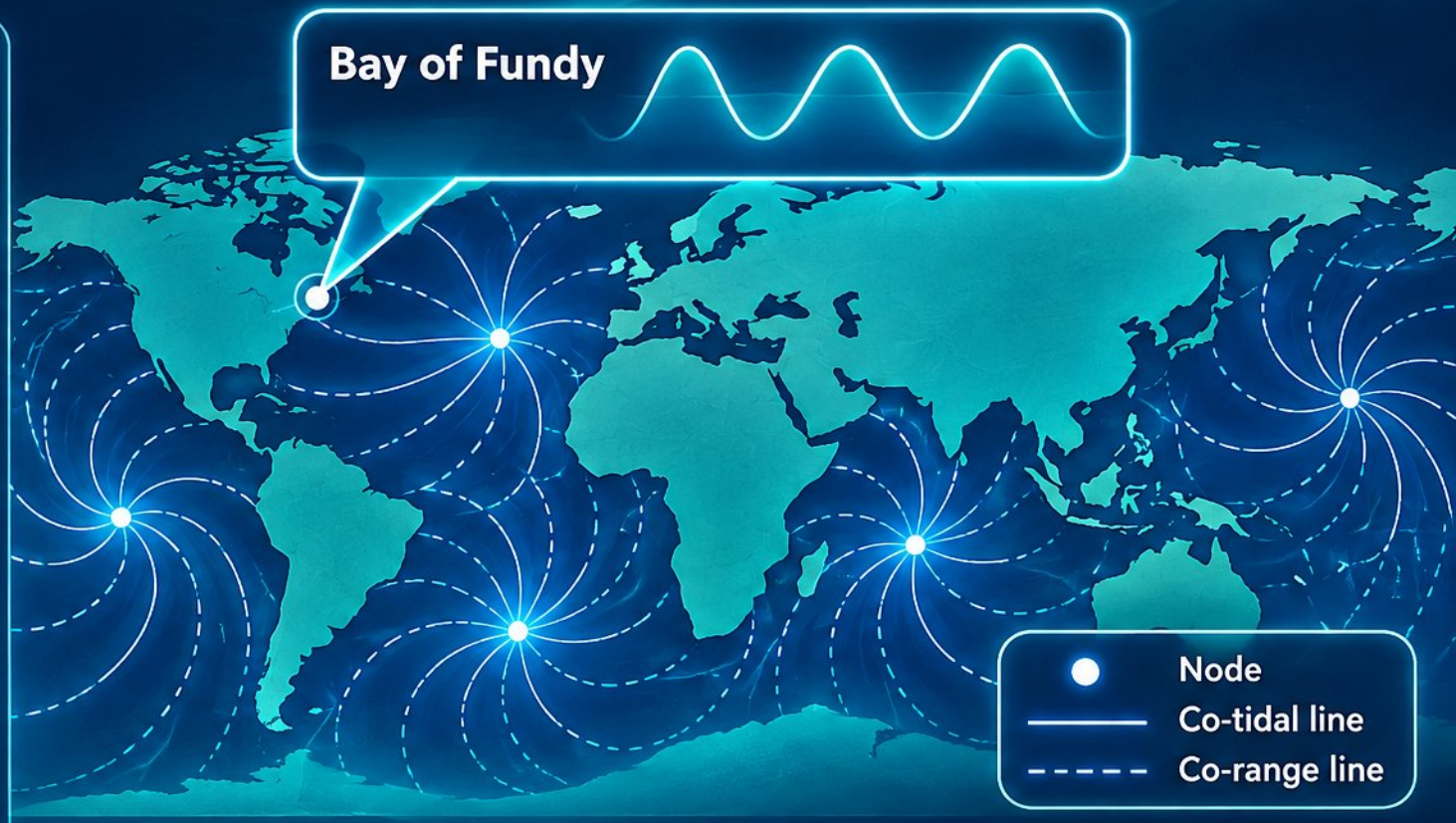


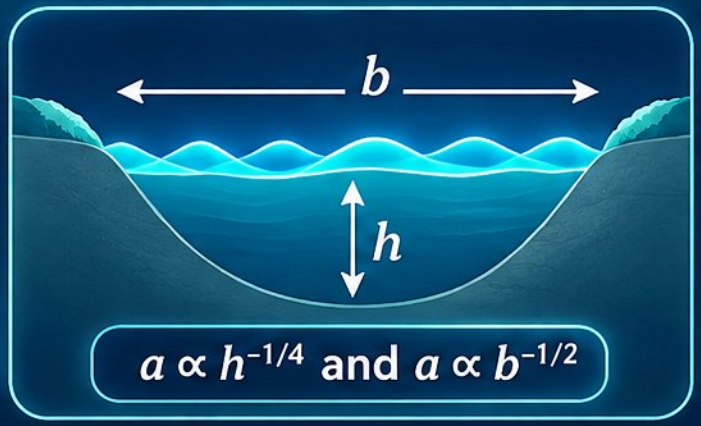




From Ideal Ocean to Real Coastlines: Resonance and Amphidromic Systems

- Continents block tidal bulges; each ocean basin develops its own pattern
- Coriolis turns tides into amphidromic systems: node plus co-tidal and co-range lines
- Shallow, narrowing basins amplify tides: $a \propto h^{-1/4}$ and $a \propto b^{-1/2}$
- Resonance: Bay of Fundy–Gulf of Maine ~12–13 h produces ranges up to 16 m
- Mediterranean, off resonance, has tidal ranges of only centimeters







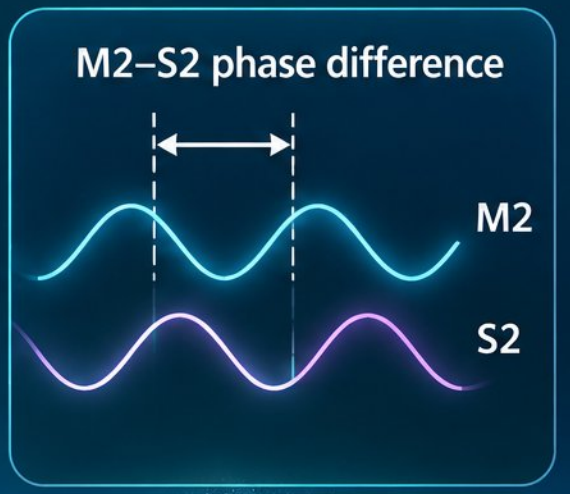
Tidal Timing: Lags, Age of the Tide, and Tidal Lag

- The ocean doesn't respond instantly: friction, inertia, and basin shape delay high water.
- Tidal lag (lunitidal interval): ~2 hours in the open Southern Ocean, ~2 days in the North Sea.
- Age of the tide: delay between new/full Moon and largest spring range, commonly 1–2 days.
- Quantitatively: age ≈ (phase M2 − phase S2) / 1.0163; largest where tidal dissipation is strong.
- Practical consequence: you cannot read tide times off the Moon—use local tide tables.









Three Tidal Patterns: Semi-diurnal, Mixed, and Diurnal

- **Semi-diurnal:** two highs and two lows of similar height each lunar day (U.S. East Coast, much of the UK)





Sample Tide Table

- **Mixed:** two highs and two lows that differ markedly in height (U.S. West Coast, Hawaii, San Francisco)





Sample Tide Table

- **Diurnal:** one high and one low per lunar day, typical of partly enclosed basins such as the Gulf of Mexico





Sample Tide Table



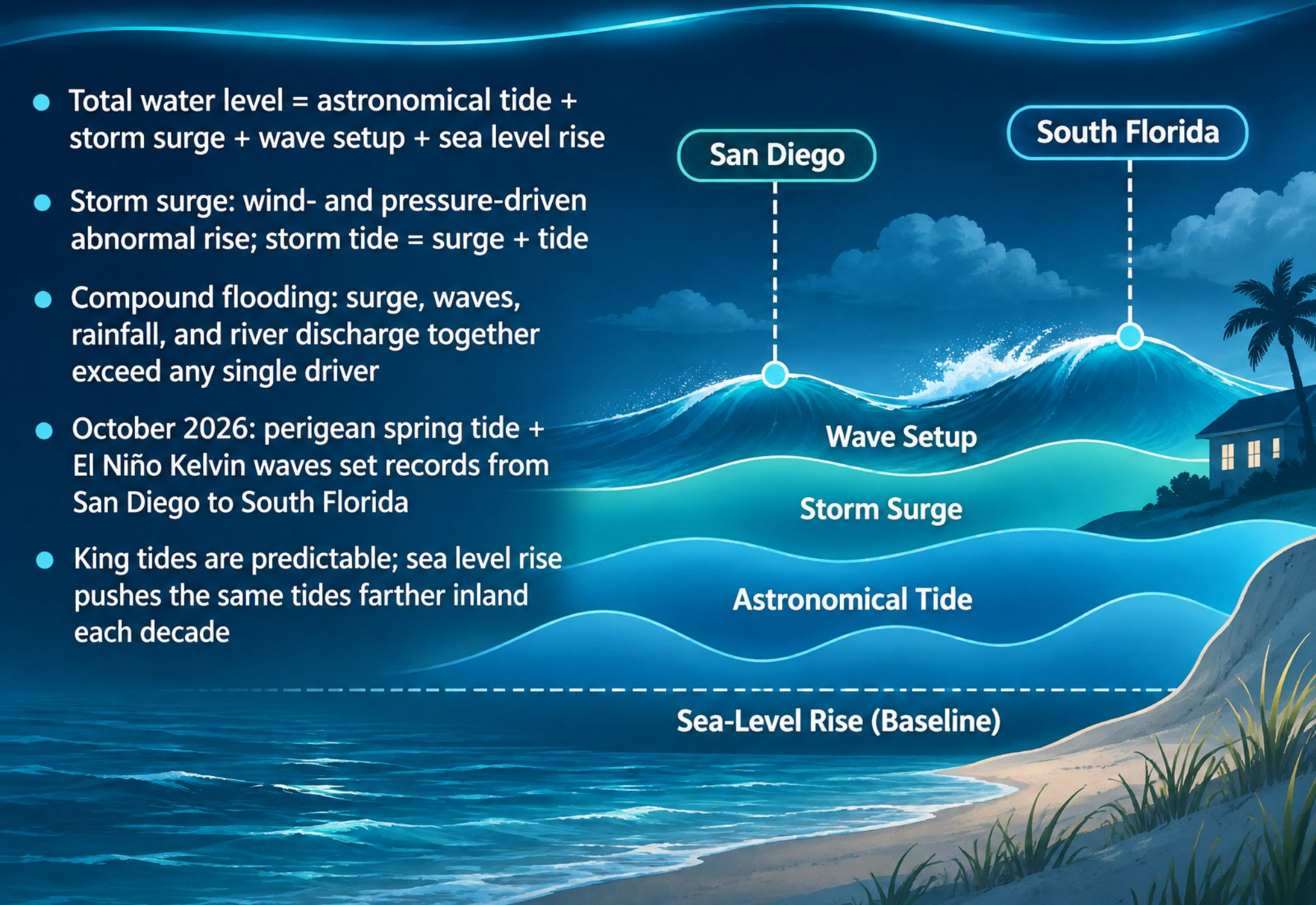
- **Cause:** the Moon's and Sun's declination tilts the tidal envelope, producing diurnal inequality — least near the equator, greatest at maximum declination



- **Practical skill:** read a local tide table — heights, times, and the chart datum they reference

Extreme Tides and Compound Coastal Flooding

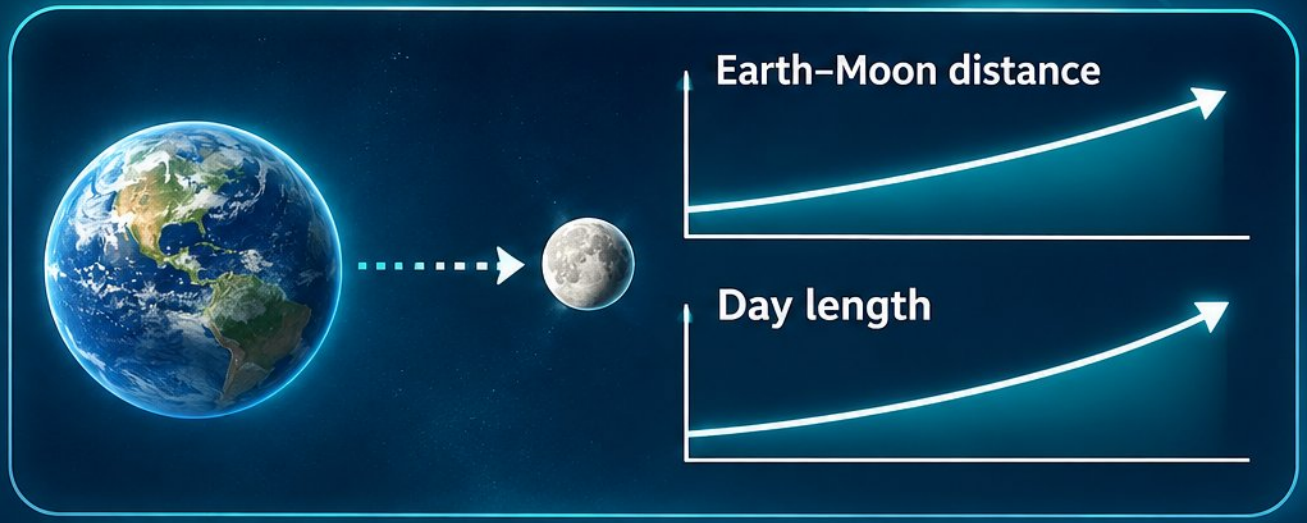
- Total water level = astronomical tide + storm surge + wave setup + sea level rise
- Storm surge: wind- and pressure-driven abnormal rise; storm tide = surge + tide
- Compound flooding: surge, waves, rainfall, and river discharge together exceed any single driver
- October 2026: perigean spring tide + El Niño Kelvin waves set records from San Diego to South Florida
- King tides are predictable; sea level rise pushes the same tides farther inland each decade



Tides Through Deep Time and as a Resource



- Tidal friction slows Earth's spin and pushes the Moon outward
- Lunar laser ranging: recession 38.30 ± 0.09 mm/yr; day lengthens ~2.4 ms/century
- Climate change may add ~1 mm/yr recession via ocean stratification and sea level
- Measured with tide gauges, satellite altimetry, and harmonic tide models
- Tidal stream energy: 140 devices, 172 MW planned by 2030; MeyGen record 372 MWh (March 2025)





Teaching Tides: Demonstrations, Misconception Repair, and Assessment

- **Research:** single-bulge, 'gravity lifts water', and ignoring differential force persist—even in preservice teachers
- **Do:** start from force difference; only extended bodies feel tides; stress the dominant horizontal component
- **Don't:** rely on centrifugal/inertial shortcuts or radial-only diagrams—misleading visuals stick
- **Demos:** stretch a balloon; model the frozen tide; let students estimate the spring–neap period, then simulate
- Extend with local tide charts and king-tide photo projects; check five core takeaways
- **Assessment:** distractors target the flagged misconceptions









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