Announcements

- Exam #2: November 08
  - Covers Chaps: 5, S4, 14, 15, (16), 17, 18

Read: S2, S3, Chap 18
Announcements

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Today

1. Finish up Neutron Stars
2. Black holes
   - What they are
   - What they are NOT
   - Theories of relativity
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Today

1. Finish up Neutron Stars
2. Black holes
   - What they are
   - What they are NOT
   - Theories of relativity

Questions?

Read: S2, S3, Chap 18
A pulsar is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis.

The radiation beams sweep through space like lighthouse beams as the neutron star rotates.
Why pulsars must be neutron stars

- Circumference of NS = $2\pi (\text{radius}) \approx 60 \text{ km}$
- Spin Rate of Fast Pulsars $\approx 1000$ cycles per second
- Surface Rotation Velocity $\approx 60,000 \text{ km/s}$
  - $\approx 20\%$ speed of light
  - $\approx$ escape velocity from NS!
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  - $\approx \text{escape velocity from NS!}$

Anything else would be torn to pieces!
Magnetic fields in neutron stars

- Circulating electric currents in the Earth's molten metallic core generate a magnetic field
- Current loop
- Similar in Sun

Read: S2, S3, Chap 18
Magnetic fields in neutron stars

Announcements

- Pulsars

Thought question
- Neutron star limit
- Forming BHs
- Energy
- Escape velocity
- Schwarzschild
- Sizes of black holes
- Thought question
- Laws of physics
- Special Relativity
- Consequences
- Photon clock
- More consequences
- General Relativity
- Back to Black holes
- Event horizon
- Gravity around a black hole
- Gravitational redshift
- Not really Black!
- Evaporating Holes
- Other Predictions

Rapidly rotating:

- Frequency: 1000 rotations/second
  (1 rotation/month for the Sun)
- Due to conservation of ang mom (recall skater)
Magnetic fields in neutron stars

- **Rapidly rotating:**
  - Frequency: 1000 rotations/second
    (1 rotation/month for the Sun)
  - Due to conservation of angular momentum (recall skater)

- **Strongly magnetized:**
  - $10^{12}$ Gauss (1 and 0.5 Gauss for the Sun & Earth)
  - Why? Magnetic field lines are conserved and compressed as star collapses.
Magnetic fields in neutron stars

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Strongly magnetized:
- \(10^{12}\) Gauss (1 and 0.5 Gauss for the Sun & Earth)
- Why? Magnetic field lines are conserved and compressed as star collapses.

Very hot:
- \(10^6\) K at surface after collapse (5800 K for Sun)

Read: S2, S3, Chap 18
A pulsar is a rotating neutron star that beams radiation along its magnetic axis.
Could there be neutron stars that appear as pulsars to other civilizations but not to us?

(A) Yes

(B) No
Could there be neutron stars that appear as pulsars to other civilizations but not to us?

(A) Yes

(B) No
Quantum mechanics says that neutrons in the same place cannot be in the same state.

Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about $3M_{\text{Sun}}$.

Beyond the neutron star limit, no known force can resist the force of gravity.

Gravity crushes all the matter into a single point known as a singularity.
A star with $M > 18 M_{\text{Sun}}$ would leave behind an iron core more massive than 2-3 $M_{\text{Sun}}$

- Neutron degeneracy pressure would fail with nothing to stop its gravitational collapse
- Core would collapse into a singularity!
- Gravity becomes so strong that nothing, not even light, can escape
- Infalling matter is shredded by powerful tides

Black hole!

- Black because they neither emit nor reflect light
- Hole because nothing entering can ever escape
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Energy is conserved: a quick review

- **Definition:**
  
  *Energy* is the capacity of a physical system to do work

- **Definition:**

  *Work* is application of force over a distance
Example: \textit{kinetic energy} from accelerating an object

- Push an object with a constant force over a distance $d$: final velocity $v_f$

- Average velocity: $\bar{v} = \frac{v_f}{2} = \frac{d}{t}$

- Force required: $F = ma = m\frac{v_f}{t}$

- Work done (energy): $E = Fd = \frac{mv_f d}{t} = \frac{1}{2}mv_f^2$
Example: *potential energy* is energy that can be converted to kinetic energy by moving in a force field.

- Potential energy is *positive* to start.
- Kinetic energy is gained as ball rolls down hill.
- Potential energy is *zero* at bottom of hill.
Example: potential energy is energy that can be converted to kinetic energy by moving in a force field.

- Potential energy is zero at top of well.
- Kinetic energy is gained as ball rolls into well.
- Potential energy is negative at bottom of well.

Total energy (kinetic plus potential) is conserved.
Escape velocity

- Need a critical value of velocity to escape the surface of a gravitating body.
- To escape the gravitational pull of a planet, need an initial velocity that will make your total mechanical energy be unbound.
- Total mechanical energy of a blob the energy of motion added to the energy given up by falling in:

\[ E = KE + PE = \frac{1}{2}mv^2 - \frac{GMm}{R} \]
Energy must be greater than zero to be unbound:

\[
0 = \frac{1}{2}mv^2 - \frac{GMm}{R}
\]

\[
v_{esc} = \sqrt{\frac{2GM}{R}}
\]

[Just like ball rolling in the potential well]

Examples:

- Earth: \(v_{esc} = 11.2 \text{ km/s}\)
- Moon: \(v_{esc} = 2.4 \text{ km/s}\)
Escape velocity

Energy must be greater than zero to be unbound:

\[ 0 = \frac{1}{2}mv^2 - \frac{GMm}{R} \]

\[ v_{esc} = \sqrt{\frac{2GM}{R}} \]

[Just like ball rolling in the potential well]

Examples:

- Earth: \( v_{esc} = 11.2 \text{ km/s} \)
- Moon: \( v_{esc} = 2.4 \text{ km/s} \)
- Neutron star: \( v_{esc} = 160,000 \text{ km/s} = 0.53 c! \)
For a given escape velocity and mass, we can compute the radius we need to just escape:

\[ R = \frac{2GM}{v_{esc}^2} \]
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Nothing moves faster than the speed of light...
Schwarzschild Radius

For a given escape velocity and mass, we can compute the radius we need to just escape:

\[ R = \frac{2GM}{v^2_{\text{esc}}} \]

Nothing moves faster than the speed of light... Light cannot escape from a Black Hole if it comes from a radius closer than the Schwarzschild Radius, \( R_s \):

\[ R_s = \frac{2GM}{c^2} \]

where \( M \) is the mass of the hole.
Sizes of black holes

\[ R_s = \frac{2GM}{c^2} \]

Comparison:

- 0.6 $M_{\text{Sun}}$ White Dwarf: radius of 1 $R_{\text{earth}} = 6370$ km
- 1.4 $M_{\text{Sun}}$ Neutron Star: radius of 10 km
- A black hole with a mass of 1 $M_{\text{Sun}}$ has $R_s = 3$ km

Read: S2, S3, Chap 18
Newton’s law of gravity tells us how to compute gravitational force. Suppose that the distribution of mass changes in one part of the Universe.

How quickly does this information travel to another part of the Universe?

(A) Instantaneously.

(B) At the speed of light.

(C) At some speed slower than the speed of light.
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(A) **Instantaneously.** [According to Newton]

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Newton’s theory gravity implies that the force propagates infinitely fast \textit{(action at a distance)}
Implications for the Laws of Physics

- Newton’s theory of gravity implies that the force propagates infinitely fast (action at a distance)
- Need to modify laws of motion to think about velocities near the speed of light (Special Relativity)
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Also need to modify law of gravity to incorporate new laws of motion

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**Laws of physics**

Special Relativity
Consequences
Photon clock
More consequences
General Relativity
Back to Black holes
Event horizon
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Gravitational redshift
Not really Black!
Evaporating Holes
Other Predictions

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Read: S2, S3, Chap 18
Newton’s theory gravity implies that the force propagates infinitely fast \textit{(action at a distance)}

Need to modify laws of motion to think about velocities near the speed of light \textit{(Special Relativity)}

Also need to modify law of gravity to incorporate new laws of motion

\textbf{General Relativity:}

- Einstein’s theory of gravitation (1915)
- First solutions by Karl Schwarzschild (1916)
- Not taken seriously until the 1960s
Thought experiment. . .

Q: Two cars have a head-on collision. Each is moving at 45 mph. What is their relative speed?
Thought experiment...

Q: Two cars have a head-on collision. Each is moving at 45 mph. What is their relative speed?

A: 90 mph
Thought experiment... 

Q: Two cars have a head-on collision. Each is moving at 45 mph. What is their relative speed?

A: 90 mph

Q: Two spaceships have a head-on collision. Each is moving at 0.9 c. What is their relative speed?
Thought experiment . . .

Q: Two cars have a head-on collision. Each is moving at 45 mph. What is their relative speed?
A: 90 mph

Q: Two spaceships have a head-on collision. Each is moving at 0.9 c. What is their relative speed?
A: 1.8 c? No, it is 0.99 c (according to special relativity)
What is the medium that propagates light?

- c. 1900: scientists look for differences in the speed of light in different directions
- Michelson-Morley experiment: no difference
- Einstein showed that this can be explained assuming the speed of light is constant for all observers
What is the medium that propagates light?

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Two principles:

- The laws of physics must be the same in all reference frames
  (True in Galilean relativity, Newton's Laws, too)
- Speed of light must be constant in all reference frames
  (New!)
Consider two observers moving at near the speed of light relative to each other.

At the instant that they are at the same place, one observer fires a flash bulb or strobe.

Sphere of light propagates from this point.

What does each observer see?
Each observer must see a sphere of light. How can this be?

Stationary observer A sees

- B’s length contracts: \( L = L_o \sqrt{1 - v^2/c^2} \)
- B’s clock dialates: \( T = T_o / \sqrt{1 - v^2/c^2} \)
- B’s energy increases: \( E = E_o / \sqrt{1 - v^2/c^2} \)

From B’s point of view, the same thing happens to A.

Both observers A & B see light sphere from the flash bulb.
Photon clock

- Clock ticks when pulse arrives, sends new pulse
- Pulse from laser travels 3 meters to receiver
- \[ t = \frac{3m}{3 \times 10^8 m/s} = 10^{-8} s \]

Read: S2, S3, Chap 18
Photon clocks in moving frames

As seen by spaceship pilot (B) at $v = 0.8c$
Photon clocks in moving frames

As seen by mission control (A)

v = 0.8 c
More consequences

- Lengths and clocks
- Simultaneous events in one frame are not simultaneous in another
- *Pole and barn paradox*
More consequences

- **Lengths and clocks**
- **Simultaneous events in one frame are not simultaneous in another**
- **Pole and barn paradox**
  - 80 m pole, 40 m barn with doors at both ends
  - Runner runs through barn at $v = 0.5c$
  - In barn frame: $L = 80\sqrt{1 - 0.5^2} = 34.9$ m
  - Runner: barn is $L = 40\sqrt{1 - 0.5^2} = 17.4$ m
  - Barn doors close and open simultaneously in barn’s frame but not in Runner’s frame

- **Twin paradox**

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Read: S2, S3, Chap 18

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More consequences

- Lengths and clocks
- Simultaneous events in one frame are not simultaneous in another
  - *Pole and barn paradox*
- *Twin paradox*
More consequences

- **Lengths and clocks**
- **Simultaneous events in one frame are not simultaneous in another**
- **Pole and barn paradox**
- **Twin paradox**
  - One twin travels at $0.99c$ to star 10 ly away
  - Travelling twin sees length to star contracted: $L = 10 \text{ly} \sqrt{1 - 0.99^2} = 1.41 \text{ly}$
  - Time to get there and back:
    $T = 2 \times 1.41 \text{ly} / c = 2.82 \text{ years}$
  - Twin on Earth sees: $2 \times 10 \text{ly} / c = 20 \text{ years}$

Read: S2, S3, Chap 18
A uniform gravitational field (like that near the Earth) is equivalent to a uniform acceleration.

A person cannot tell the difference between

1. Standing on the Earth, feeling the effects of gravity as a downward pull.
2. Standing in a very smooth elevator that is accelerating upwards at $g$ (32 feet per second per second).
General Relativity

- Back to action at a distance!
- Led Einstein to come up with a new way of describing gravity
  1. Space-time is curved by mass
  2. The motion of the mass is determined by the curvature of space-time
- In this view, gravity is no longer a force!
- Trajectories of objects in space-time move along the shortest path
Back to **action at a distance!**

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General Relativity

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Pulsars
Thought question
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Read: S2, S3, Chap 18
**General Relativity**: Light travels along the curved space taking the shortest path between two points. Therefore, light is deflected toward a massive object! The stronger the local gravity is, the greater the light path is bent.
If the Sun shrank into a black hole, its gravity would be different only near the event horizon.

- A two-dimensional representation of “flat” spacetime. Each pair of circles is separated by the same radial distance.
- A mass affects the rubber sheet similarly to the way gravity curves spacetime. The circles become more widely separated — indicating greater curvature — as we move closer to the mass.
- The curvature of spacetime becomes greater and greater as we approach a black hole, and a black hole itself is a bottomless pit in spacetime.
If the Sun shrank into a black hole, its gravity would be different only near the event horizon.

**Event horizon**

If you shrink the Sun into a black hole, its gravity will be different only near the event horizon.

**Gravity around a black hole**

- A two-dimensional representation of “flat” spacetime. Each pair of circles is separated by the same radial distance.
- A mass affects the rubber sheet similarly to how gravity curves spacetime. The circles become more widely separated indicating greater curvature as we move closer to the mass.
- The curvature of spacetime becomes greater and greater as we approach a black hole, and a black hole itself is a bottomless pit in spacetime.

Black holes do not suck!

Read: S2, S3, Chap 18
$R_s$ defines the Event Horizon surrounding the black hole’s singularity:

- Events occurring inside $R_s$ are invisible to the outside universe
- Anything closer to the singularity than $R_s$ can never leave the black hole
- The Event Horizon hides the singularity from the outside universe

The Event Horizon marks the “Point of No Return” for objects falling into a Black Hole.
Black holes do not suck!

- Far away from a black hole:
  - Gravity is the same as a star of the same mass.
  - If the Sun became a Black Hole, the planets would all orbit the same as before.

- Close to a black hole:
  - $R < 3R_s$, there are no stable orbits—matter falls in
  - At $R = 1.5R_s$, photons would orbit in a circle!
Gravitational redshift

- Wavelength of light increases when climbing out of a gravitational well
- Think of a baseball hit high into the air, slowing as it climbs
- Photon also loses energy
Gravitational redshift

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Gravitational redshift is observable:

- 1960, observed in elevator shaft Jefferson Tower physics building at Harvard University
- Observed in solar radiation, neutron stars
- GPS system!
Look for the effects of their gravity on their surroundings

- **Search for stellar-mass black holes in binary star systems by looking for:**
  - A star orbiting around an unseen massive companion
  - X-rays emitted by gas heated to extreme temperatures as it falls into the black hole
  - High velocities
How to find a black hole?

- **X-Ray Binaries**
  - Bright, variable X-ray sources identified by X-ray observatory satellites:
  - Spectroscopic binary with only one set of spectral lines - the second object is invisible.
  - Gas from the visible star is dumped on the companion, heats up, and emits X-rays.
  - Estimate the mass of the unseen companion from the parameters of its orbit.
Some X-ray binaries contain compact objects of mass exceeding $3M_{\text{Sun}}$ which are likely to be black holes.

Read: S2, S3, Chap 18
Black Holes are not really Black!

“Classical” General Relativity says:

- Black Holes are totally black
- Can only grow in mass and size
- Last forever (nothing gets out once inside)

But: General Relativity does not include the effects of Quantum Mechanics!

Read: S2, S3, Chap 18
Stephen Hawking looked at the problem by considering quantum effects occurring near the event horizon of a Black Hole. He showed that:

- Black holes slowly “leak” particles with a blackbody spectrum.
- Each particle carries off a little of the black hole’s mass.
- The smaller the mass of the black hole, the faster it leaks.
Black Holes evaporate slowly by emitting subatomic particles and photons via *Hawking Radiation*.

The smaller the mass, the faster the evaporation.

For black holes in the real universe, the evaporation rate is VERY slow:

- A $3 M_{\text{Sun}}$ black hole would require about $10^{63}$ years to completely evaporate.
- This is about $10^{53}$ times the present age of the Universe.
Wormholes? A theoretical possibility.
Other Predictions

Wormholes? A theoretical possibility.

Can the whole universe be curved? Definitely ... see cosmology.

Read: S2, S3, Chap 18