- The <u>Invariant</u> <u>Interval</u> (14)

Beware: notation different than text! Particularly signs.

- Define the <u>invariant interval</u> δs^2 between 2 events by
$$\delta s^2 = -c^2\delta t^2 + \delta\vec{x}^2 \qquad \delta\vec{x}^2 = \delta x^2 + \delta y^2 + \delta z^2, \text{ etc.}$$
  - This is like a Pythagorean distance but with a sign on the time part
  - What do we mean invariant?

    It's the <u>same</u> when calculated in any inertial reference frame.
  - Proof:

    What we want to show is
$$-c^2\delta t^2 + \delta x^2 + \delta y^2 + \delta z^2 = -c^2\delta t'^2 + \delta x'^2 + \delta y'^2 + \delta z'^2$$
    for any frames S + S' (inertial)

    + Use standard configuration
    + We know $\delta y = \delta y'$, $\delta z = \delta z'$, so need
$$-c^2\delta t^2 + \delta x^2 = -c^2\delta t'^2 + \delta x'^2$$
    + Start in S' and use Lorentz transformations
$$-c^2\delta t'^2 + \delta x'^2 = -c^2\gamma^2\left(\delta t - \frac{v\delta x}{c^2}\right)^2 + \gamma^2(\delta x - v\delta t)^2$$
$$= -c^2\delta t^2\gamma^2\left(1 - \frac{v^2}{c^2}\right) + \delta x^2\gamma^2\left(1 - \frac{v^2}{c^2}\right) + 2\gamma^2 v\delta t\delta x$$
$$- 2\gamma^2 v\delta t\delta x$$
$$= -c^2\delta t^2 + \delta x^2 \quad \checkmark$$

- We have 3 cases
  - $\delta s^2 > 0$. Consider 2 events separated by $\delta\vec{x}$, δt with $c\delta t < |\delta\vec{x}|$.

    Then you can go to a frame with $\delta t' = \gamma(\delta t - \frac{v}{c^2}\delta x) = 0$

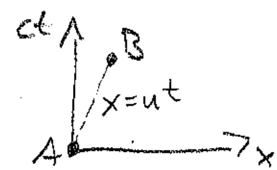
    How? Line up $\delta\vec{x}$ along x-axis. Choose $v = c^2\delta t/\delta x$.

    Then, in new frame,
$$\delta s^2 = (\delta x')^2$$
    Call this the (squared) <u>proper</u> <u>distance</u>. This is <u>spacelike</u> <u>separation</u>
  - [illegible]

- $\delta s^2 < 0$. This is time-like separation.
  We can choose a frame where $\delta \vec{x}' = 0$. So $\delta s^2 = -c^2 \delta t'^2$.
  We define $\delta \tau^2 = -\delta s^2/c^2 = +\delta t^2 + \delta \vec{x}^2/c^2 = (\delta t')^2$
  $\delta \tau$ is the proper time between the two events.
- $\delta s^2 = 0$. Imagine a light ray. Since light has $|\delta \vec{x}| = c\delta t$,
  $\delta s^2 = -c^2 \delta t^2 + \delta \vec{x}^2 = -c^2 \delta t^2 + c^2 \delta t^2 = 0$. That means light can travel between the two events. They are light-like separated

– Examples

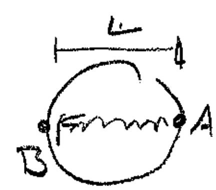
- Suppose A and B are timelike separated events. Then $|\delta \vec{x}/\delta t| < c$
  Some object moving at speed $u < c$ can go from A to B. Then



$$\delta s^2 = -c^2 \delta t^2 + \delta \vec{x}^2 = -c^2 \delta t^2 + u^2 \delta t^2$$

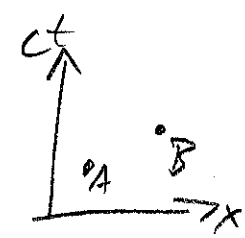
The proper time of the object's clocks is $\delta \tau = \sqrt{-\delta s^2/c^2} = \delta t \sqrt{1 - u^2/c^2}$
Familiar?

- Let's look at that galaxy & supernovae again
  We know that light from the explosion at A passes B when that star explodes.
  So these events are light-like separated.

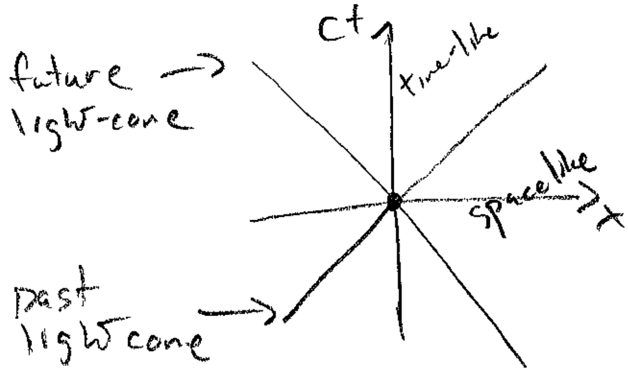


- Spacetime Diagrams

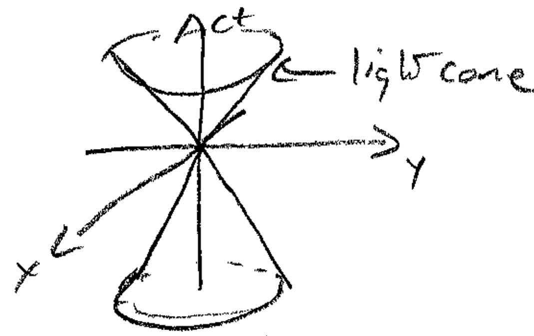
– For a while now, we've drawn diagrams as to the right, indicating events as points. But we can do more!



– First, if we take the origin as one event, we can divide the diagram into time-like, space-like, and light-like regions



Note: light travels at 45°

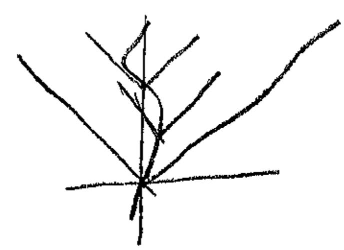


- The light-cone is all the light-like separated events.
- From an event, you can send a signal to anything on or in your future light cone
- And you can receive a signal from anywhere on or in your past light cone
- No matter your frame, the light-cone is at 45°!

— We can draw the trajectories of objects/particles through time. These are called world lines.

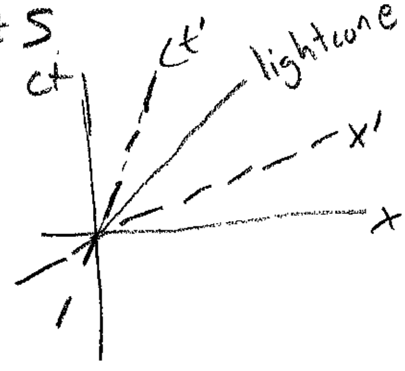
World lines can never bend out of the light cone at any point

Useful for illustration

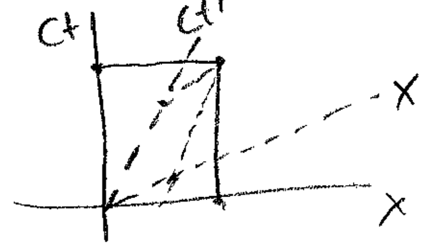


— Different frames in one diagram:

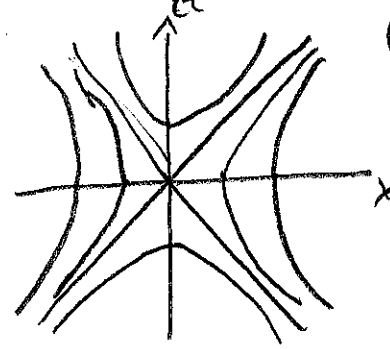
- Take S' in standard configuration w.r.t S
- What's the t' axis? That's just where $x'=0$, or $ct = x(c/v)$



- How about x' axis? That's where $t'=0$, or $ct = \left(\frac{v}{c}\right)x$
- The lightcone is still halfway between the axes
- To get coordinates, draw lines parallel to axes

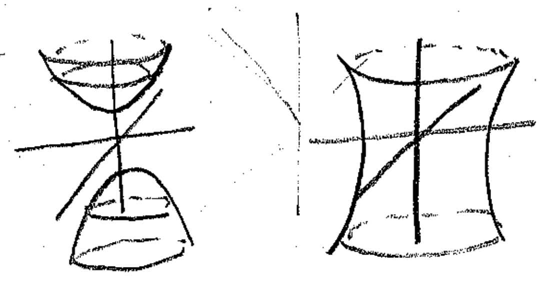


- Other invariant curves:



  - Just like δs^2 is invariant,
    $c^2t^2 - \vec{x}^2$ is invt
    (From the same Lorentz transformations)
  - Curves where this $=0$ are lightcones
  - Otherwise $= \pm(\#)$ are hyperboloids (hyperbolas in 2D)

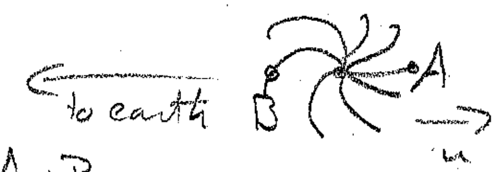
    Note that these rotate into y, z as well. like lightcones



  - By a Lorentz transformation,
    you can move any point on a hyperboloid to any other point on the same hyperboloid
    + Shows that space like separated events have no notion of "past", "future," or "simultaneity"! You can change time order
    + But time like separated events can't change order!
      There is a notion of past and future, but only inside the light-cone.
  - This shows us the causal structure of space time:
    which events can cause something to happen at other events.
    + Note: That's why you can't travel faster than c.
      If you could get outside the light cone, you could change frames and "time-travel" to the past.
      Then you could kill your grandparents before your parents are born!

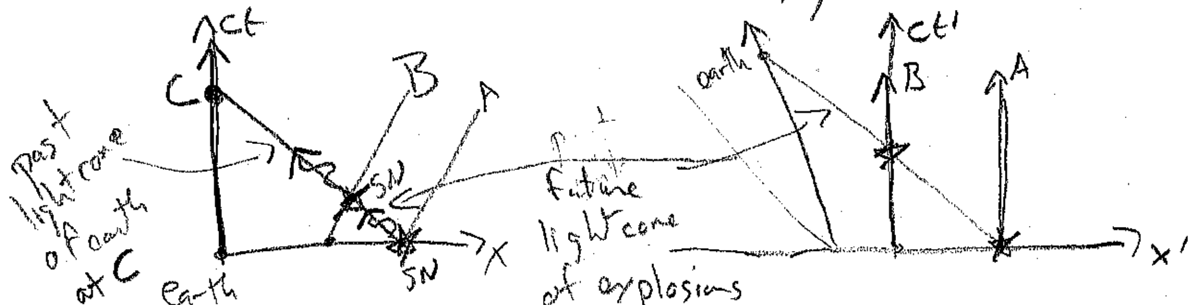
Examples of Spacetime Diagrams

- Back to the Moving Galaxy and 2 supernovae
- Recall the problem: Galaxy moves away from us at constant speed.

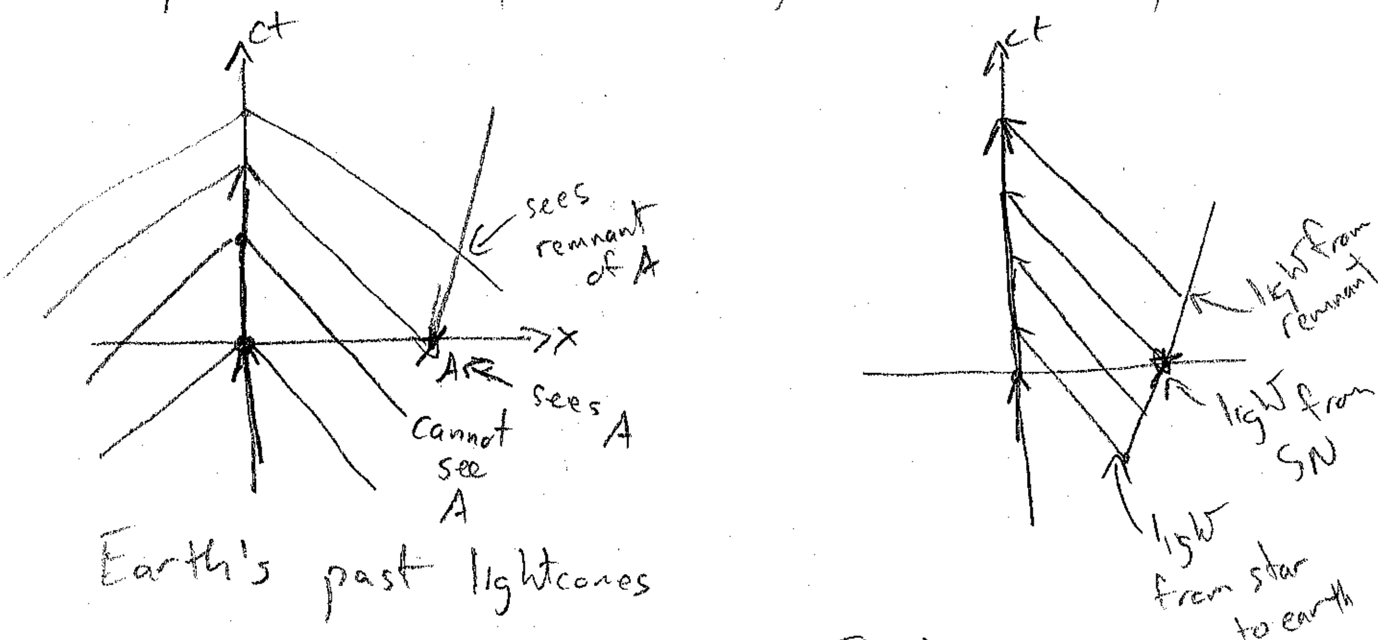


Explosions occur at spacetime points A + B
Light from them reaches earth at the same time

- Earth's frame Galaxy's frame



- One more point. Earth's worldline + explosions are spacelike separated at some points, then lightlike + timelike separated



Earth's past lightcones

Star's future lightcones

Just looking at the star / SN from A.

- Hopefully this gives you a picture of the problem