Relativity and Cosmology PHY312

Simon Catterall

Whats the course about ?

- Modern Physics stands on 2 pillars: Quantum Mechanics and Relativity
- All current theories of fundamental physics assume that these theories are correct (and almost all efforts at improving our understanding (of non-gravitational physics) assume them too)
- Theory of relativity has 2 parts: special and general theories.

Special Relativity

- Inseparable with name of Einstein. 1905.
- Radically new way of describing and understanding motion.
- Relates observations of motion from special frames of reference – inertial frames.
- From rather modest assumptions – provides a radical new view of world - challenges ideas about time and space.
- In most situations provides a accurate description of the world.
- Mathematics straightforward.

General Relativity

- Generalizes the special theory to all frames of reference. 1916.
- Provides a new theory of gravity (more accurate than Newton). Needed to understand cosmology, black holes, etc
- Mathematics more involved. Curved spacetime. Will try to avoid most of this. Focus on motion in simplest spacetimes.

Cosmology

- For a long time this was barely physics .... A mathematical theory of the Universe based on solutions to GR.
- OK not quite fair – Hubble's law, Big Bang nucleosynthesis, ...
- Now it has become a bustling experimental subject with lots of new, precision data arriving every year.
- This data is radically altering our picture of the structure and evolution of the Universe ...
- Dark matter, dark energy, cosmic acceleration ...

To do list

- Lot of time on special theory. Key to all that follows. Most useful.
- Much less time on general theory. Enough to talk about motion in black hole spacetimes – Schwarzschild solution.
- A very little on cosmology. Big Bang picture. Successes and failures. New ideas ..

Mechanics of class

- Here, Tuesdays and Thursdays 11-12:20
- Lecture. Work examples in groups.
- 1 homework per week. On Thursday. Back week later.
- Course page will have homeworks, lectures, project suggestions, announcements.
- Final grade based on homeworks, midsemester and final exams and a final project.
- Need PHY211/212 and calculus.

Relativity in Newton's mechanics

- Philosophiae Naturalis Principia Mathematica 1686

  I do not know what I may appear to the world; but to myself I seem to have been only like a boy, playing on the sea-shore, and diverting myself, in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me

- Newton's laws of motion:
  1. Every body remains in a state of rest or uniform motion unless acted on by a force
  2. $F = ma$.
  3. Two bodies in interaction exert equal and opposite forces on one another.

What these laws tell us

- This set of laws can be used to describe and predict the motion of material bodies.
- Revolutionary ! no precedent in history of science. Still in wide use today (eg. cars, bridges, planes, washing machines ...)
- Only when you ask detailed questions about the structure of atoms, about particles traveling at very high speeds or the behavior of exotic objects like black holes or neutron stars do you need anything else ...
- What does it tell us implicitly

Frames of reference

- Newton's first law seems benign but is perhaps the most important.
- It implicitly says that I can find a frame of reference (FOR) in which certain types of motion look very simple.
- A frame of reference is just some system for measuring distances between objects and time intervals. eg. fill space with set of Cartesian axes and place a series of clocks at each point.
- Suppose I find such a frame – then I can immediately find many others by taking my original frame of reference and moving it at constant speed in some direction.

Inertial frames

- Such frames are called inertial frames.
- Newton's first law really says that such frames exist and motions looks very simple when seen from such a frame.
- In fact all such frames are equally good for describing some physical situation.
- One *can* use accelerating frames, rotating frames (and indeed this is what GR allows/needs) but motions are necessarily more complicated when viewed from such frames.

Events

- Consider some physical occurrence at some place and some time as measured in particular FOR. Eg cartesian grid plus time (x, t)
- Call this an event.
- Everything that happens in the Universe is a collection of such events. eg
- As a ball moves it traces out a succession of positions at certain times – a series of events. Called the worldline of the ball.

Everything is relative

- Notice I cannot really make the statement – “the ball is at rest”. I can only say the ball is at rest relative to me. But is it absolutely at rest ? No, I am standing on a spinning planet which is orbiting the Sun, which is orbiting the center of Milky Way, which has some motion relative to distant stars etc etc
- Newton realized this. As far as we know there is no fundamental FOR for the Universe to which all motion can be refered. And even if there was how could we find out what it was.
- Therefore, it is necessary to couch all mechanics purely in terms of relative motion.

Things to do

- What is your speed relative to the center of the Earth ?
- What is your speed relative to the Sun ?
- How big are these speeds relative to the speed of light (3×10^8 m/s)

Relating different inertial FOR

Seems obvious .... (Galilean transformation)

(1) $$x' = x - vt$$

(2) $$t' = t$$

Right ? Newton assumes absolute time

Absolute, true and mathematical time, of itself, and from its own nature , flows equably without relation to anything external

Einstein was forced to change this to make theory compatible with experiments done at end of 19th century. But he chose to keep the Principle of Relativity

Principle of (Newtonian) Relativity

All inertial FOR are equally good for discovering the laws of mechanics and for predicting motion