9/5/2024

PHY 565* - Advanced Topics in General Relativity

Announcements & Reminders

- Welcome back to school! I hope you had a great summer

- My contact information:
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  - Hours: M/W 11 – 12; also by appointments…or just coming to chat with me!

- Syllabus and course schedule at at https://dkagan.sites.umassd.edu

- In-person versus Zoom-based classes

CONCEPTUAL BUILDING BLOCKS OF GR [Standard Approach]

* INERTIAL FRAMES EXIST [Newton's 1st Law]
* Relativity postulate
  ↳ Fundamental laws of physics do not pick out a preferred ref. frame [Galileo]
* Speed postulate / Interaction rate postulate [Einstein]
  ↳ There is a universally invariant speed that limits the rates of interactions / signals

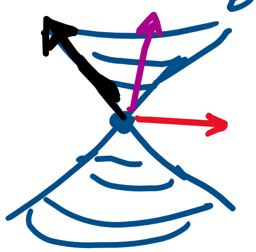
"speed of light"

$$c = 2.99792458 \times 10^8 \ \frac{m}{s} \approx 3 \times 10^8 \ \frac{m}{s}$$

Conceptual Building Blocks of GR [Standard Approach]

Speed postulate gives us a structure that underlies causality in space through time

↳ lightcone



future shell expanding

past shell converging

3 types of vectors:
timelike
spacelike
null/lightlike

↳ Symmetries of the light cones are $\underbrace{\text{Lorentz symmetries}}_{\text{Relate different inertial frames}}$

[Aside : c can be reinterpreted as a conversion factor relating dimensions of distance & time

↪ we can naturalize it : $c = 1$]

Conceptual Building Blocks of GR [Standard Approach]

Lorentz symmetry preserves "Lorentz invariants"

$\shortparallel$

"Lorentz scalars"

$\shortparallel$

"Invariants"

$\rightsquigarrow$ Example: proper time

* Another special invariant of this symmetry is the Minkowski tensor η [This is an invariant tensor not a scalar!]

Conceptual Building Blocks of GR [Standard Approach]

* Postulate : Space and time are homogeneous
  [no point in space or any instant in time are preferred by underlying laws of physics]

  Implies conserved quantities of energy + momentum

  Lorentz symmetry requires energy and momentum of particles to form a SPACETIME VECTOR

CONCEPTUAL BUILDING BLOCKS OF GR [Standard Approach]

We can form an invariant out of energy & momentum

↳ REST MASS of a particle

↳ inertial mass in the particle's rest frame

3 categories : $m \neq 0$, $m > 0$ [massive, physical particle] ← particles that can be brought to rest

$m = 0$ ← particles that cannot rest

↳ light-like

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$\left.\begin{array}{l} m \neq 0 \\ m \notin \mathbb{R} \\ m \in i\mathbb{R} \end{array}\right\}$ tachyonic and unphysical

GRAVITATION : (First pass)

↳ due to a field that "couples" to [gravitational mass]

NOT ASSUMING (YET!) any relation to inertial mass

Observation :

Weak Equivalence Principle (WEP)

In non-relativistic (Newtonian) regime inertial mass is equivalent to gravitational mass

*Postulate

Strong Equivalence Principle (SEP)

* Uniform gravitational field is physically indistinguishable from the effects of a uniformly accelerated ref. frame

→ If field is non-uniform then simply restrict to small enough distances and short enough time scales

* SR lives on locally in sufficiently restricted reference frames [only exact in infinitesimal frames]

$\underbrace{\hspace{10em}}_{\text{Principle of minimal coupling}}$

Principle of minimal coupling

MATH CONCEPTS

* Manifold : Local Minkowski spaces can be stitched together into a global geometric object that no longer exhibits the postulated symmetries at large scale

- Free motion is described by <u>geodesics</u> of the manifold

↳ by comparing two nearby geodesics and how they diverge we get at the underlying CURVATURE

↕

Associate this with the physical effects of gravity

The curvature has to be dynamical and non-rigid in order to respect the local limits of signaling due to the speed postulate. Changes in matter/energy distribution thus need to be communicated by distortions in the curvature that propagate no faster than the speed of light.

So we postulate that these gravitational signals are governed by a relativistic wave equation. The constraints imposed by local SR and the linking of gravitation with curvature almost pick out the Einstein field equations as the dynamical equations that describe the link between local matter/energy distributions and local curvature. Nevertheless, we cannot uniquely pick these field equations out without simply asserting them in some way or other.

Still, we come to the final, standard form of general relativity from a very beautiful, tightly knit set of arguments and postulates.

In this course, we will review this development, but also examine other approaches, some of which may ultimately point in the direction of whatever ultimately goes beyond GR in describing the fundamental laws of our universe.