GENERAL RELATIVITY & COSMOLOGY

A Quick Guide

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1 Overview and Review

General relativity is a theory of gravity, replacing Newton's gravity law for heavy masses to give more precise predictions. However, we should keep in mind that general relativity is not yet compatible with quantum mechanics. There are numerous open problems in physics related to reconciling gravity and quantum mechanics.

1.1 Review of Special Relativity

Special relativity studies the kinematics and dynamics in relatively moving inertial reference frames. Most of special relativity and its consequences are encoded in the Lorentz transformations. A classic example of a Lorentz transformation that is often focused on in introductory special relativity is called the "Lorentz boost" in the x-direction. Note that there is nothing special about x or y or z. The x-Lorentz boost is essentially a coordinate transformation, i.e. given coordinates an event A in frame (S), we can calculate the coordinates of A in frame (S').

$$\begin{pmatrix} ct' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} = \begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix},$$

where $\beta = v/c$ and the Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}.$$

Since we are studying relativity, it is important to look at "invariants" - quantities that do not change under transformations. In special relativity, one such invariant is the spacetime invariant:

$$\begin{aligned} (\Delta S)^2 &= (c\Delta\tau)^2 \\ &= (c\Delta t)^2 - (\Delta x)^2 - (\Delta y)^2 - (\Delta z)^2 \\ &= (c\Delta t')^2 - (\Delta x')^2 - (\Delta y')^2 - (\Delta z')^2 \\ &= (\Delta S')^2 = (c\Delta\tau')^2. \end{aligned}$$

This can be readily shown. In fact, we have verified this in *Special Relativity: A Quick Guide*. This quantity, roughly speaking, is a measure of **proper** distances and times. If we go to a rest frame of event A, such that $\Delta x' = \Delta y' = \Delta z' = 0$, then we get $\Delta t' = \Delta\tau$, where τ denotes the **proper time**, which is the time measured in the rest frame. This gives $(\Delta S)^2 = (c\Delta\tau)^2$.

In relativity in general and in Minkowski spacetime in particular, we are interested in two types of objects: **scalars** and **vectors**. Scalars are invariant under general coordinate transformations. An example of a scalar is the spacetime invariant. Another scalar, which we probably will not see again in this text, is the metric signature ($\mathrm{sgn}([\eta_{\mu\nu}] = -2)$). Vectors, on the other hand, are a different type of objects, which transform in the same way under coordinate transformations, but are not invariant under general coordinate transformations in general, i.e., their components are not necessarily the same in different coordinate systems. In 4-dimensional spacetime, we work with 4-vectors, which simply means 4-component vectors.

In special relativity, we often talk about position vectors $\mathbf{x} = (ct, x, y, z)^\top = (ct, \vec{x})^\top$ and energy-momentum vectors $\mathbf{p} = (E/c, p_x, p_y, p_z)^\top = (E/c, \vec{p})^\top$. These vectors transform under the Lorentz transformation. For example, for the x-Lorentz boost applied to $\mathbf{p}$ gives

$$\begin{pmatrix} E'/c \\ p'_x \\ p'_y \\ p'_z \end{pmatrix} = \begin{pmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} E/c \\ p_x \\ p_y \\ p_z \end{pmatrix}.$$

Notice that E/c transforms like ct (time) and $\vec{p}$ transforms like $\vec{x}$ (space). We also have the following invariant

$$\frac{E^2}{c^2} - p_x^2 - p_y^2 - p_z^2 = \frac{E^2}{c^2} - \vec{p} \cdot \vec{p}.$$

But recall that $(mc)^2 = E^2/c^2 - \vec{p} \cdot \vec{p}$, so

$$\frac{E^2}{c^2} - p_x^2 - p_y^2 - p_z^2 = (mc)^2.$$

If we go to a rest frame, such that $\vec{p} = \vec{0}$, then we obtain the famous rest mass-energy equivalence: $E = mc^2$.

Some quantities associated with a vector can be invariant (scalar), such as their norm. In fact, the spacetime invariant in Minkowski space is nothing but a dot product of a vector with itself:

$$\mathbf{a} \cdot \mathbf{a} = a^0 a^0 - a^1 a^1 - a^2 a^2 - a^3 a^3,$$

where $0, 1, 2, 3$ are indices, and $\mathbf{a}$ implies a 4-vectors, which should be distinguished from the 3-vector $\vec{a} = (a^1, a^2, a^3)^\top$. Notice that the dot product in Minkowski spacetime is defined differently from that in flat 3-dimensional Cartesian coordinate system. In the following chapters, we will explore how dot products are defined in general. Hint: the metric tensor plays an important role.

1.2 The Equivalence Principle

In 1907, Albert Einstein had the "happiest thought of his life" when he realized that in a freely falling frame (non rotating and/or accelerating), the effects of gravity go away, i.e., there is an equivalence between gravity and acceleration such that they can "undo" each other. For example, the following two situations are equivalent in terms of the acceleration experienced by the observer: (i) a person standing on Earth, and (ii) a person inside an elevator accelerating upwards at rate g in free space (no gravitational field). Likewise, the following two situations are also equivalent: (iii) a person floating in free space, and (iv) a person inside an airplane free falling towards Earth (this is commercially known as "zero-G flight"). we arrive at the statement of the Equivalence Principle:

"*A small, non-rotating, freely falling frame in a $\vec{g}$ field is an inertial frame.*″

The above statement is a direct result of Galileo's discovery that all objects have the same acceleration due to gravity. This result may seem a little bit *circular*, because it is actually a coincidence that the two roles of **mass**: (i) to cause gravitational force like charge in an electric field:

$$\vec{F} = \frac{GMm_G}{r^3}\vec{r} = m_G\vec{g}$$

and (ii) to measure inertia:

$$\vec{F} = m_I\vec{a}$$

are the same, i.e., $m_I = m_G$. It could have been that "gravitational mass" m_G and "inertial mass" m_I are not the same, in which case $\vec{a} \neq \vec{g}$, and the equivalence principle does not hold. However, the famous Eötvös experiment, which measured the correlation between inertial mass and gravitational mass, has shown that

$$\frac{|m_G - m_I|}{m_I} \leq 10^{-10}.$$

While the observations we have made so far can seem self-apparent, the consequence of the equivalence principle is the bending of light around massive objects. Consider a light ray going horizontally (left to right) pass an upward-accelerating elevator with an observer inside. For the observer, since he is accelerating upwards, he sees the light beam as bent, entering at the top-left of the elevator and exiting at the bottom-right. Now, according to the equivalence principle, because the upward-accelerating scenario is equivalent to the existence of a massive object (such that the observer experiences the same acceleration). This means that the observer, now no longer in the elevator, "sees" the light as bent around this massive object. Fig. 1. illustrates this postulate.

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General relativity predicts that light going pass Earth's surface will "fall" by approximately 1Å, which is not observable. However, for a much more massive object like the Sun, general relativity predicts a bending of $1.75''$ (arc sec). This prediction was verified by the glorious experiment of Arthur Eddington.

Note that we could argue for the bending of light, using Newtonian physics. However, in order to get the correct predictions for the bending of light, we need general relativity. We will explore the reason behind this discrepancy in the following chapter. But roughly speaking, spacetime is assumed to be flat in Newtonian physics, while spacetime is curved by massive objects, according to general relativity.

One might ask: "How do we view falling objects on Earth as due to the curvature of spacetime?" The answer requires bringing back Minkowski spacetime diagrams.

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