GENERAL RELATIVITY BRIEFING

THE FOLLOWING TWO PAGES WILL BE FACING PAGES INSIDE THE BACK COVER

Please goto next page

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GENERAL RELATIVITY BRIEFING

(Inside back cover, left and right sides)

EVENT

An occurrence, such as your birth, that we can locate at a point in space at an instant of time. Events are the elemental nails on which physics hangs. An event exists independent of any method we use to locate it.

SPACETIME

The arena in which events occur. Newton thought that time is universal, the same for all observers. Einstein realized that different observers typically measure different values of time between a pair of events, along with different values of their spatial separation. Einstein combined space and time to provide a spacetime measure of separation between events on which all observers agree. [See INTERVAL and METRIC.]

SPACETIME REGION

A volume of space during a period of time, for example the vicinity of a black hole during one Earth-year.

SPECIAL RELATIVITY

A theory of motion in a spacetime without gravity or curvature.

GRAVITY

In Newtonian physics, a universal *force* arising from mass. For Newton, a force may be real (such as gravity) or fictitious (such as centrifugal force or Coriolis force) and we can correctly analyze gravity in a single *global* inertial reference frame. [See INERTIAL FRAME.] In general relativity, however, gravity is *always* a fictitious force which we can eliminate anywhere by changing to a local frame that is in free fall (a different free-fall frame for each event).

CURVATURE

A measure of those properties of spacetime which prevent us from having a global inertial frame. Sources of curvature include mass-energy and pressure.

GENERAL RELATIVITY

A theory of curved spacetime and motion.

SINGULARITY

A spacetime location at which curvature is so extreme that general relativity fails.

PATCH

A spacetime region purposely limited in size and duration so that curvature does not noticeably affect a given measurement or observation. A patch can have uniform gravity (which generates no curvature). We can approximate curved spacetime to any desired accuracy with a set of patches, in the same way that the curved surface of the space shuttle was covered with many small flat tiles.

STONE

A particle whose location at each instant is described by an event and whose mass warps spacetime too little to be measured. A stone has nonzero mass and moves slower than light with respect to every local inertial frame.

WORLDLINE

The path of a stone through spacetime. We can mark on a worldline a chain of intermediate events, such as ticks of the stone's wristwatch. The **wristwatch time** is the reading on the stone's wristwatch at any event along its worldline.

GLOBAL COORDINATE SYSTEM

Any system that assigns unique numbers ("coordinates") to every event in order to locate it in an extended spacetime region. General relativity frees us to use (almost) any global coordinate system in a given spacetime region. In this book we usually analyze events that occur on a single spatial plane, for which three coordinates, such as (t, x, y) or (t, r, ϕ), suffice to locate an event.

FRAME

A local coordinate system of our choice installed on a patch. This local coordinate system is limited to that single patch. We may construct a frame at any event except on a singularity such as that inside a black hole.

INERTIAL or FREE-FALL FRAME

A local coordinate system in which special relativity is valid, typically Cartesian spatial coordinates and synchronized clocks. A free stone moves with constant velocity as measured in coordinates of an inertial frame. In general relativity every inertial frame is local; spacetime curvature precludes a global inertial frame.

ROOM

A room is a physical enclosure of fixed spatial dimensions in which we make measurements and observations over an extended period of time measured in that room.

OBSERVER

An observer is a person or machine that moves through spacetime making measurements, each measurement limited to a local inertial frame. Thus an observer moves through a series of local inertial frames.

WORLDTUBE

A worldtube is a bundle of worldlines of objects at rest in a room and worldlines of the structural components of that room. Think of a worldtube as sheathing the worldline of an observer at work in the room.

INTERVAL

Any one of three possible alternative directly-measured **spacetime separations** between any pair of adjacent events. If a free stone can travel directly from one event to the other, the time lapse on that stone's wristwatch is called the **wristwatch time** or **timelike interval**. If only a light flash is fast enough to travel directly from one event to the other, we say there is a **null interval** or **lightlike interval** between them. If nothing is fast enough to move between the two events, then the separation is a **spacelike interval**. In this case there exists an inertial frame such that the two adjacent events are simultaneous in that frame. The distance between the events measured along a ruler at rest in that frame is called the **ruler distance**.

GLOBAL METRIC

A function that satisfies Einstein's field equations, whose inputs are global coordinates and global coordinate differentials (such as dt, dr, $d\phi$) between an adjacent pair of events and whose output is the interval between the events. The global metric (plus the topology of the region) completely determines local spacetime and gravitational effects within the global region in which it applies. The global metric combines with the Principle of Maximal Aging [see entry] to predict the global motion of stones and massless particles in curved spacetime.

FRAME METRIC or LOCAL METRIC

A metric expressed in local coordinates on a spacetime patch and valid only on that patch. A frame metric is *always* distinguished from a global metric by the notations: (1) increment Δ instead of differential d, (2) an approximately equal sign $\approx$, (3) a one-word subscript label on every local coordinate increment (such as Δt_{shell}) that identifies the local frame. In contrast, a global differential such as dt *never* carries a one-word subscript.

INVARIANT

A physical quantity that has the same value, whether measured or calculated, with respect to any possible frame or global coordinate system. Examples include the interval between two infinitesimally close events, the wristwatch time along a worldline, the mass of a stone, and the mass of a center of gravitational attraction.

PRINCIPLE OF MAXIMAL AGING

A free stone follows the worldline of maximal wristwatch time (maximal aging) across any two adjoining local frames. We can completely tile spacetime with adjoining frames, so the stone knows how to move everywhere in a global spacetime region, such as that near a black hole or near Earth.

CONSTANT OF MOTION

A quantity that describes the motion of a free stone or massless particle and whose value does not change with time in the given global coordinate system. Constants of motion arise when all coefficients in the metric are independent of one or more global coordinates. Map energy and map angular momentum are each a constant of motion for a free stone near a black hole.

METRIC ON A CURVED SURFACE *VS.* METRIC IN CURVED SPACETIME

ON A STATIC CURVED SURFACE IN SPACE:

First, measure directly the DISTANCE between nearby points using a ruler or tape measure—or timed round trip of laser or radar pulse. This direct measurement requires no coordinates. Second, set up a SURFACE MAP, which is just a rule that assigns unique coordinates to each point on the surface. Aside from requirements of uniqueness and smoothness, map coordinates are totally arbitrary. Third, ask for the relation between the directly-measured distance between two given nearby points and their coordinate differences. The result is a local MAP SCALE between the two points. Finally, generalize, seeking a GLOBAL METRIC: a function whose inputs are coordinates and coordinate differences between a pair of adjacent points anywhere on the surface and whose output is the squared distance between them.

The output of the metric is an INVARIANT: the directly-measured distance between two nearby points has the same value no matter what map coordinates we choose.

Almost everywhere on our surface we can treat as FLAT a sufficiently small surface patch. Choose local coordinates to turn this patch into a FRAME. The resulting LOCAL METRIC tells us the invariant distance between any pair of points in that frame. Demand that *every* measurement on the entire curved surface be made in such a local frame.

The frame metric derives from the global metric. The reverse is not true; the frame metric tells us *nothing* about the global metric from which it is derived.

IN A REGION OF CURVED SPACETIME:

First, measure directly the SPACETIME SEPARATION (*timelike*, *lightlike*, or *spacelike* interval) between nearby events. This direct measurement requires no coordinates. Second, set up a SPACETIME MAP, which is just a rule that assigns unique coordinates to each event in the spacetime region. Aside from some simple requirements of uniqueness and smoothness, map coordinates are totally arbitrary. Third, ask for the relation between the directly-measured spacetime separation between two given nearby events and their coordinate differences. The result is a local MAP SCALE between the two events. Finally generalize, seeking a GLOBAL METRIC: a function that satisfies Einstein's field equations whose inputs are coordinates and coordinate differences between a pair of adjacent events and whose output is the squared spacetime separation between them.

The output of the metric is an INVARIANT: the directly-measured spacetime interval between two nearby events has the same value no matter what map coordinates we choose.

Almost everywhere in our spacetime region we treat as FLAT a sufficiently small spacetime patch. Choose local coordinates to turn this patch into a FRAME. The resulting LOCAL METRIC tells us the invariant interval between any pair of events in that frame. Demand that *every* measurement in the global spacetime region be made in such a local frame.

The frame metric derives from the global metric. The reverse is not true; the frame metric tells us *nothing* about the global metric from which it is derived.