

2.4: Regions of Spacetime

special relativity is limited to free-float frames

"Region of spacetime." What is the precise meaning of this term? The long narrow railway coach in Figure 2.3.1 probes spacetime for a limited stretch of time and in one or another single direction in space. It can be oriented north-south or east-west or up-down. Whatever its orientation, relative acceleration of the tiny ball bearings released at the two ends can be measured. For all three directions - and for all intermediate directions - let it be found by calculation that the relative drift of two test particles equals half the minimum detectable amount or less. Then throughout a cube of space 20 meters on an edge and for a lapse of time of 8 seconds (2400 million meters of light-travel time), test particles moving every which way depart from straight-line motion by undetectable amounts. In other words, the reference frame is free-float in a local region of spacetime with dimensions

$$(20 \text{ meters} \times 20 \text{ meters} \times 20 \text{ meters of space}) \times 2400 \text{ million meters of time}$$

“Region of spacetime” is four-dimensional

Notice that this "region of spacetime" is four-dimensional: three dimensions of space and one of time.¹

✓ Question and Answer

Why pay so much attention to the small relative accelerations described above? Why not from the beginning consider as reference frames only spaceships very far from Earth, far from our Sun, and far from any other gravitating body? At these distances we need not worry at all about any relative acceleration due to a nonuniform gravitational field, and a free-float frame can be huge without worrying about relative accelerations of particles at the extremities of the frame. Why not study special relativity in these remote regions of space?

Answer

Most of our experiments are carried out near Earth and almost all in our part of the solar system. Near Earth or Sun we cannot eliminate relative accelerations of test particles due to nonuniformity of gravitational fields. So we need to know how large a region of spacetime our experiment can occupy and still follow the simple laws that apply in free-float frames.

When is general relativity required?

For some experiments local free-float frames are not adequate. For example, a comet sweeps in from remote distances, swings close to Sun, and returns to deep space. (Consider only the head of the comet, not its 100 -million-kilometer-long tail.) Particles traveling near the comet during all those years move closer together or farther apart due to tidal forces from Sun (assuming we can neglect effects of the gravitational field of the comet itself).² These relative forces are called **tidal**, because similar differential forces from Sun and Moon act on the ocean on opposite sides of Earth to cause tides (Box 2-1). A frame large enough to include these particles is not free-float. So reduce spatial size until relative motion of encompassed particles is undetectable during that time. The resulting frame is very much smaller than the head of the comet! You cannot analyze the motion of a comet in a frame smaller than the comet. So instead think of a larger free-float frame that surrounds the comet for a limited time during its orbit, so that the comet passes through a series of such frames. Or think of a whole collection of free-float frames plunging radially toward Sun, through which the comet passes in sequence. In either case, motion of the comet over a small portion of its trajectory can be analyzed rigorously with respect to one of these local free-float frames using special relativity. However, questions about the entire trajectory cannot be answered using only one free-float frame; for this we require a series of frames. General relativity - the theory of gravitation - tells how to describe and predict orbits that traverse a string of adjacent free-float frames. Only general relativity can describe motion in unlimited regions of spacetime.

✓ Question and Answer

Please stop beating around the bush! In defining a free-float frame, you say that every test particle at rest in such a frame remains at rest "within some specified accuracy." What accuracy? Can't you be more specific? Why do these definitions depend on whether or not we are able to perceive the tiny motion of some test particle? My eyesight gets worse. Or I take my glasses off. Does the world suddenly change, along with the standards for "inertial frame"? Surely science is more exact, more objective than that!

Answer

Science can be “exact” only when we agree on acceptable accuracy. A 1000-ton rocket streaks 1 kilometer in 3 seconds; do you want to measure the sequence of its positions during that time with an accuracy of 10 centimeters? An astronaut in an orbiting space station releases a pencil that floats at rest in front of her; do you want to track its position to 1-millimeter accuracy for 2 hours? Each case places different demands on the inertial frame from which the observations are made. Specific figures imply specific requirements for inertial frames, requirements that must be verified by test particles. The astronaut takes off her glasses; then she can determine the position of the pencil with only 3-millimeter accuracy. Suddenly—yes! — requirements on the inertial frame have become less stringent—unless she is willing to observe the pencil over a longer period of time.

1 “Region of spacetime” is four-dimensional

2 When is general relativity required?

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