- What is the basis for our belief in geometry?
- Does space exist?
- What is the relation between a theory and reality?

Views of Reality: a spectrum

The ontological spectrum

Idealism ⟷ **Realism**

Berkeley Mach Plato Planck Einstein xxx

postmodernists? Hume

- The common person
  There are definite events independent of observation. Our senses record these events. Theories can represent genuine causal patterns inherent in the events. Generally, the features we use to describe things, e.g. size, time…, are inherent in the events themselves. The world consists of collections of 'things'.
- Einstein
  There's a definite real world, of which we are observers, and also parts. But we can't count on even the deepest features to be as they seem. The world follows simple mathematical laws.
- Planck (Realism, not entirely naive):
  The goal of physics is a unified world picture. Laws must be independent of the observer. The picture must be consistent. Simplicity is a means to get to a true, general picture, not an end.

Is Euclidean geometry correct?

- Plato: The sensed world is an ephemeral approximation to the ‘true’ world of ideal essences. Reason tells us more about that true world than mere sensation can provide.
- Aristotle: the fundamental propositions are self-evident.
- Hume (1711-1776) (*Treatise on Human Nature*): Whatever we claim about reality, only senses are available. There are 2 types of statements:
  – *A priori*: they only unpack meanings of words “All bachelors are unmarried”
  – *A posteriori* can be rejected in light of experience.
  – One can only learn about reality through experience. Causation itself is a mental construct, not inherent in phenomena themselves. However, in pointing out that the idea of induction itself cannot be inductively confirmed (only disconfirmed), Hume implicitly indicated a way in which we seem to approach the world with "hard-wired" prior assumptions.
  – Note two problems with induction:
    - at the deepest level, the argument for it is circular
    - the categories to be used in extrapolating toward the future are not specified by any logical principle
  – Whatever we claim about reality, only senses are available. There is no logical basis for induction. Nevertheless we all must accept it in practice.

Kant (1724-1804)
Critique of Pure Reason

- Kant, agreed with most of Hume, but argued that there are two valid forms of *a priori* knowledge. One is the reasoning facility (logic) by which we analyze our experiences. The other is mathematics, such as geometry.
- It was known, however, that as a logical system, Euclidean geometry was not unique, but only one geometry of a larger family. Kant believed it to be the only conceivable actual geometry of the world.
  - There are non-trivial a priori propositions; meaningful statements that are irrefutable.
  - There exists a real world; sensations come from outside therefore there exists an outside.
  - Our perceptions are structured by our mind
  - Space and time are a priori.
  - We can't imagine a world without time or space.
  - We can imagine being blind or deaf but timeless?
  - Statements are irrefutable because that's how we think about it.

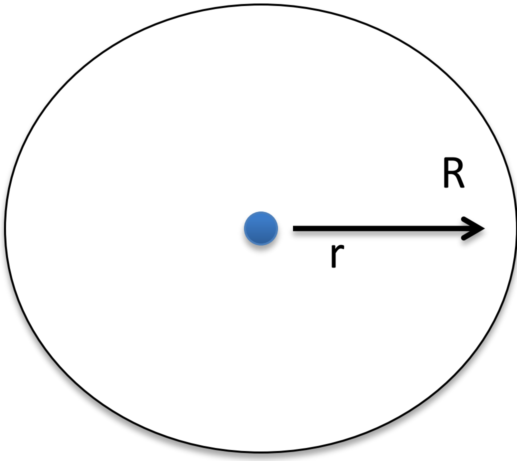
- Mach (a particularly subjective version of positivism): Sensory impression is primary. “Substances” are patterns of impressions. No eternal laws. (e.g., atoms aren’t real.)
- Both Planck and Mach recognize that we have nothing but sense impressions and the need to organize them simply. Planck implicitly assumes that the sense impressions come from somewhere, and have properties that make them fit into simple patterns. Mach assumes there's something arbitrary about the patterns we find, so that no pattern should be expected to be stable.

Empiricist position

- Anything meaningful can be refuted.
- Geometry is an experimental science.
- What is a line? We need an operational definition.
  - A straight edge (rulers can bend)
  - A beam of light (light diffracts)
- What is a point? Numbers describing where to put an infinitely small particle.
  - But particles have a definite size and we can’t measure their position to arbitrary accuracy. Quantum effects limit us.
  - Maybe the underling reality is discrete. Coordinates should not be continuous but integer like street addresses. Is there always a point between two other points?

Poincaré parable

- Consider a 2d world of a disk.
- Measuring sticks are sensitive to temperature but it gets colder the further out you are. Length = R^2-r^2.
- They think the disk is infinite since their sticks can never reach the edge in a finite number of steps. Space is Lobachevski with negative curvature.
- Suppose they have light rays with index of refraction $1/(R^2-r^2)$. Same conclusion.



How do we convince them that the world is really Euclidean?

- Poincaré (1854-1912): Any geometry is possible. Decide on the basis of convention or convenience. Since Euclidean geometry is simpler, use it.
- Einstein: Beams of light define geodesics. Equivalence principle implies space-time is curved.

Empiricist reply to Poincaré

(Eddington, Reichenbach)

Alternative geometries can always explain any new data. We can save Euclid by convention.

- This is just a reworking of the meanings of length and time.
- If predictions are the same, the theories are the same.
- In physics we define what we mean by length. Then there is a real distinction between Euclidean and non-Euclidean geometries.
- If we say rods shrink and expand that is a new definition.
- Poincaré must introduce universal forces, something that shrinks all lengths.
- There is an interconnection between geometrical laws and physical laws.

- How about the topology of space? Is that convention?

TAXONOMY OF BELIEF IN GEOMETRY (Sklar)

- Disbelievers: everything is theory, even definitions of length
- Believers in observational basis
  - Reductionists: theory=observation, alternatives are rewordings.
  - Antireductionists: theory is more than observations
    - Skeptics: no rational choice is possible between alternative theories. We may never know what lies beyond our measurements
    - Conventionalists: simply choose a theory. There is no true reality only convention.
    - A priorists: choose a theory on the basis of simplicity, elegance, initial plausibility

Is space real?

- If GR forces us into non-Euclidean geometry, does this require that space is “real”?
  - A <u>relationist</u> would say that this only implies that the geometrical relations between objects is not what we thought. No *substantive* spacetime is required.
- However, there are two new <u>substantivalist</u> arguments.
  - In GR the gravitational interaction between objects is mediated by the geometry. That is, geometry plays the same role as, *e.g.*, the electric field. An object distorts the geometry in its vicinity. This distortion affects the motion of other objects, because the geodesics are modified. Thus, *spacetime plays a more direct role in the dynamics than in Newton’s physics.*
  - Finite propagation speeds give fields more of a reality in SR (and GR) than they had before. We already saw quite dramatically in electromagnetism, in which wave motion of the fields was predicted and then observed. GR makes a similar prediction for the gravitational field. If the Sun were to move we would feel the changed gravity at the Earth 500 seconds later. As the Sun shakes back and forth, say as the planets orbit, GR says it would emit gravitational radiation (waves) with many of the same properties of EM waves.
  - Gravitational waves are as real as any other object. They carry energy and momentum. They have recently been directly observed.

Relationist vs. substantivalist

- Space-time seems to have observable properties in itself, like electromagnetic fields, etc.
- These properties are far from resembling those expected for Newton's space.
- Einstein's original motivation was to develop physics that followed Mach's principle, but GR does *not* follow that principle. (And Mach was unable to follow SR, much less GR.) It may be possible to add Mach's principle as a separate requirement, i.e. to rule out those GR spacetimes which do not obey Mach's principle, but nothing about the structure of GR itself tells you to do so.
- Newton said (in effect) that two masses tied together and spun would stretch a string taut, because they would need a force to keep them both accelerating toward the middle, regardless of the condition or existence of anything else. They have "absolute acceleration". Mach said the string could not go taut because "absolute acceleration" is meaningless- you need the other stuff in the universe to create the forces. Einstein abandons the phrase "absolute acceleration", but GR allows solutions in which the string is taut. Such a solution can either be described as two masses rotating in nearly flat space-time *or* as a strange twisty space-time exerting peculiar gravitational forces. But operationally, Newton and Einstein agree on what the possibilities are, and they *include* the possibilities excluded by Mach.

GR outgrew its philosophical ancestry.

Some conceptual implications

- Spacetime is beginning to become more substantial than it was (contrary to Einstein’s original motivation). The geometry of spacetime varies from place to place in a way that is observable. We’ll see next time that it’s even more real than this.
- Elevating unexplained “coincidences” (the equivalence principle) into general postulates succeeded again.
  - Will it work in general?
- Geometry is empirical. Kant was wrong that it was only possible to conceive of the world in Euclidean terms. The world violates Euclid's axioms.

Global vs. Local

- They are equivalent locally (if no singularities), but not globally. Only special configurations of gravity (uniform gravity, for example) can be completely eliminated by going to an accelerated reference frame. In particular, nonuniform gravity gives tidal forces which can't be transformed away. One can maintain flat geometry if one attributes effects such as the slowing of clocks to dynamics (similar to the pre-SR Lorentz contraction, etc.), but that gains one nothing and is vulnerable to the same criticism (it's *ad hoc*) that Einstein made of the pre-SR theories.
- Imagine the universe really had the topology of a sphere, that has global consequences (*e.g.*, one might be able to go around) which can't happen in flat space. The large scale geometry of the universe is still not known. However, it has been shown mathematically that the geometry must have at least one singularity- an infinite deviation from the simple flat-space picture- which would be extremely hard to mimic in a flat-space model.
- Furthermore, GR makes many detailed predictions which have been beautifully confirmed, and which beat the predictions of a whole slew of rivals- most of which also have curved space, anyway. There is no competing theory with the same simplicity and predictive power, except theories whose predictions are already known to be wrong.

Does the Earth go around the Sun?

- Let's revisit this question, maybe for the last time. We concluded that the Earth orbits the Sun (approximately) because otherwise we would have to throw out the whole Newtonian framework that described not only planetary motion, but pendulums, etc. Now *we have thrown out that framework anyway*, and replaced it with a different (and more generally accurate) one.
- What happens in our new framework?
- The GR laws are the same for an "accelerated" reference frame (such as the Earth) as for any other. However, there are still reasons for preferring reference frames that are near to the old "non-accelerated" ones.
- In an "accelerated" reference frame (e.g., rotating or moving in a circle), the gravitational field does not vanish at large distances, and distant space is not flat. We do not actually know the very-large scale geometry of space-time, but with a more conventional frame, at least a large patch of our universe can be described as very nearly flat.
- If we want to convert easily between a correct GR description and a very good Newtonian approximation, the conversion is much simpler if the GR description uses a conventional reference frame.

An Answer?

- So we have a nice argument for using frames in which the Earth spins and orbits the Sun, but it doesn’t carry the same weight as the old Newtonian one, in which non-inertial observers get the wrong laws of physics. We're stuck with GR whichever reference frame we use.

- We know that GR or quantum mechanics is wrong, if pushed to extremely small length scales.

- Does the Sun go around the Earth or does the Earth go around the Sun?

- Why is it dark at night?

Where do we stand, after relativity?

- Newton's hunch about action at a distance was correct. With fields and finite propagation speed, it is gone.
- The ether is also gone. Has it been replaced by spacetime?
- Not in a local sense, although there is the possibility that the global topology of the universe gives us a preferred reference frame. There is no evidence for this. (but there is a microwave average frame)
- Geometry is empirical. (Kant was wrong.) We will question some of our other basic beliefs when we study quantum mechanics.
- Mach's hope that the large scale motion of the matter in the universe can explain inertia is not fulfilled by GR. (See Sklar, p. 79) The geometry of spacetime is not determined solely by the objects within it, an argument against relationism.
- The expansion of the universe solves Olber's paradox. Distant galaxies are dimmer than previously expected as a result of the cosmological red shift.
  So now we know why it's dark at night!
  - There actually is a glow from all directions- it's just been lowered to 2.7K (rather than the original effective T, near that of a star surface) by the stretching of space.
- The existence of horizons implies a loss of knowledge and, possibly, of determinism.

The nature and status of scientific theories

- What does it mean to say that Copernicus was right and Ptolemy wrong, or that relativity is correct and the ether theory wrong?
- Clearly, agreement with direct observation is important.
- However, new theories sometimes change the meaning of statements in such a way as to make direct comparison difficult. Even the notion of what is "directly observable" can change (*e.g.*, time comparisons). Does the Earth go around the Sun?
  - Some of these changes are (or appear to be) just a matter of convention.
- Suppose two competing theories predict exactly the same experimental consequences. Are they really different theories?
  - They might incorporate completely different metaphysical frameworks.

Criteria for Judging Theories

If full "correctness" may not be applicable, what about makes a theory preferable? Here are some possible criteria:

Intrinsic plausibility? Conservatism? Simplicity?

- Intrinsic plausibility: Ptolemy was more plausible than Copernicus until we learned to think differently. Essentially, "plausibility" in this context is another word for preferability, so we still need to find what makes a theory more preferable.
- Conservatism (make the fewest changes): This is very powerful when the old theory has worked well. We would be very reluctant to abandon conservation of energy. It can't be the whole story, because sometimes we have to change theories.
- Simplicity: Simplicity is somewhat in the eye of the beholder. Is the non-Euclidean geometry of GR simpler than an alternative theory which keeps the geometry and complicates the dynamics? But there can be a more-or-less objective count of how many parameters are adjustable in a theory. The more adjustable parameters (Ptolemy) the less impressive is the fit to observation.

Theory and the external world

This central issue for the philosophy of science is dormant as long as everyone works within the same conceptual framework (Kuhn’s "paradigm"). When there are changes, then people begin to worry about the meaning of the new theory. More big changes are coming up. The shifts brought about by SR and GR are small compared to what quantum mechanics will do.

The theories of Special and General Relativity are forceful reminders that the foundations of our mental models of the world are not secure.