The Principle of Locality
Module 1

A Historical and Conceptual Overview of Locality

Samuel Hagh Shenas

CONJECTURE UNIVERSITY

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A Toolkit for Locality

Before entering the historical and conceptual development of locality, it is useful to introduce a conceptual toolkit. This will help us build intuition and lay the groundwork for understanding what locality means in physics.

Newton's Law of Gravitation

Newton's law of gravitation provides a mathematical expression for the attractive force between two massive objects.

If we consider two bodies with masses m_1 and m_2, Newton's law tells us that the gravitational force between them is proportional to the product of their masses and is inversely proportional to the square of the distance between them. The proportionality constant, usually denoted by G, characterizes the strength of the gravitational interaction.

In this formulation, gravity is always attractive. Objects fall, planets orbit, and structures remain bound because this force never repels.

From a conceptual point of view, Newton's law raises a profound question. The force depends on distance, but there is no indication of how long it takes for the influence to travel. In Newtonian physics, gravity acts instantaneously. No matter how far apart two objects are, the force between them is felt immediately. In other words, Newtonian gravity seems to act nonlocally.

Coulomb's Law and the Structure of Forces

A very similar mathematical structure appears in Coulomb's law.

A core feature of electromagnetism, Coulomb's law describes the force between two electric charges. Here, the force is proportional to the product of the charges q_1 and q_2 and is inversely proportional to the square of the distance between them. Again, a constant appears, the so-called Coulomb constant, which reflects the nature of electric interactions.

Unlike gravity, this electric force can be either attractive or repulsive. Charges of the same sign repel one another; charges of opposite sign attract.

The similarity between Newton's law and Coulomb's law is striking. Both suggest forces that depend on distance. Both seem, at first glance, to imply action at a distance (nonlocality).

But are these forces truly acting nonlocally across arbitrary distances, or is there something else mediating the interaction along the space between them?

Fields: A Local Description of Interaction "At Distance"

To answer this question, physicists introduced the concept of a field—a quantity defined at every point in space.

Consider the electric field. At each point in space, the electric field has some numerical value, which can vary from point to point.

If a test charge q is placed in that region, it experiences a force proportional to the value of the field at its location. The force on the charge depends only on the field at that specific point.

Invoking the concept of the field saves the principle of locality: what happens to the charge is determined by the properties of the field only in the charge's immediate surroundings.

Different kinds of fields may have different geometries and properties, but the essential idea remains the same: interactions are described locally, point by point, rather than as instantaneous influences between distant objects.

Medium and the Propagation of Waves

Another important concept is that of a medium.

In everyday experience, waves require a medium to propagate.

Sound waves are mechanical perturbations of the air. When someone speaks, pressure variations travel through the air until they reach a listener. Throwing a pebble into a lake creates ripples that move across its surface as a water wave.

Historically, light was also understood as a wave. Light travels from the Sun to the Earth, and, if it is a wave, it seems natural to assume that it must propagate through some medium.

This reasoning led scientists to postulate the existence of a medium filling all of space called the ether. This was thought to be something subtle and elusive yet capable of carrying light waves across the universe.

The ether played a crucial conceptual role. It allowed physicists to preserve a local picture of propagation: waves move through something, step by step, rather than acting instantaneously across empty space.

Interference and the Interferometer

The idea of a medium becomes experimentally relevant in the study of interference. Interference occurs when two waves overlap and interfere with each other.

If two waves meet with their peaks aligned, their amplitudes add up, producing constructive interference. If a peak meets a trough, the amplitudes cancel, producing destructive interference. In general, a pattern emerges that contains information about how the waves have traveled and interfered with one another.

An interferometer is a device designed to exploit this phenomenon. A beam of light from a single source is split into two perpendicular paths. Each beam travels the same distance and reflects off a mirror so that they reconverge.

If the two beams experience different conditions along their paths, the interference pattern changes. By analyzing this pattern, one can detect extremely small differences in propagation.

This idea will become central when we later discuss the Michelson–Morley experiment.

Space-Time and Special Relativity

To understand locality at a deeper level, we must introduce space-time.

In everyday experience, we describe events using spatial coordinates that tell us where something happens.

In relativity, this is not enough. Every event must also be assigned a time coordinate. Space and time together form a four-dimensional structure called space-time.

One way to visualize this is to imagine a grid of points in space in which each point carries its own clock. Each clock measures time locally. There is no single, absolute time shared by all points in space.

This framework allows us to make sense of the idea that time is not universal but rather depends on the state of motion of the observer. As we will see, space-time provides the geometric setting in which locality acquires a precise meaning.

Quantization of Light

At the beginning of the twentieth century, Max Planck discovered that energy is not exchanged continuously but rather in discrete packets called quanta.

Consider a beam of light emitted by a source, such as a flashlight. To our eyes, the beam appears continuous. But if we zoom in, we find that light consists of individual packets of energy.

Each packet has an energy proportional to the frequency of the light. The proportionality constant here is known as Planck's constant. Different frequencies correspond to different energies per packet.

If two beams have the same frequency but different intensities, the more intense beam merely contains a greater number of packets, not more energetic packets. That is, the packets in both beams all carry the same fixed amount of energy.

This idea forms the foundation of quantum mechanics. For the purposes of this toolkit, it is enough to recognize that even light, which propagates through space, does so in discrete units of energy.

Overview of Locality

Aristotle and Contact Action

In Aristotle's philosophical view of the world, every physical change requires direct contact. In his *Physics*, Aristotle wrote that nothing acts at a distance; every motion must occur through contact with something else. The world, in this view, is a continuous and connected fabric. A body cannot influence another unless something lies between them.

This idea dominated natural philosophy for centuries.

Newton, Gravity, and the Problem of Action at a Distance

Newton's law of gravitation was the first antagonist to Aristotle's picture.

Gravity appeared to act across empty space instantaneously, without any visible mediator.

Newton himself was deeply uncomfortable with this implication. In a letter to Richard Bentley in 1692, he wrote:

"That one body may act upon another at a distance through a vacuum without the mediation of anything else [...] is to me so great an absurdity that I believe no man [...] can ever fall into it."

Newton did not claim to understand the cause of gravity. His law was a powerful mathematical description, not a mechanical explanation.

Leibniz shared this discomfort. In his correspondence with Samuel Clarke, he argued that it is contradictory for a body to act where it is not.

Kant and the Epistemological Turn

Immanuel Kant accepted Newtonian gravity as an empirical fact but questioned its meaning.

In his *Metaphysical Foundations of Natural Science*, he argued that we can ascertain how forces behave, but not what ultimately causes them.

The question of locality was hence moved into the realm of knowledge itself: what we can know versus what exists.

Ether and the Return of Locality

To restore a local picture of nature, physicists in the eighteenth and nineteenth centuries proposed the ether.

Figures such as Huygens, Euler, Fresnel, and Poisson—among the most revered scientists of their time—imagined space filled with a subtle medium capable of transmitting forces and waves.

The ether was an attempt to preserve locality by reintroducing something tangible between interacting bodies.

Faraday, Maxwell, and the Field

In the nineteenth century, physics was transformed once again, this time by the theory of electromagnetism.

Michael Faraday introduced the idea that space itself might possess physical properties. His lines of force suggested that interactions propagate locally, from point to point.

Faraday wrote in 1832 that electrical induction is an action of contiguous particles, not an action at a distance.

James Clerk Maxwell translated Faraday's intuition into mathematics. His equations showed that electromagnetic disturbances—including the lines of the fields—propagate at a finite speed: the speed of light.

Light was no longer a mysterious entity; it was an electromagnetic wave.

Michelson–Morley and the End of the Ether

In 1887, Michelson and Morley attempted to detect the Earth's motion through the ether.

They found nothing. The speed of light was the same in all directions.

This result undermined the ether hypothesis and forced physicists to rethink the foundations of space, time, and locality.

Einstein and Relativistic Locality

In 1905, Einstein proposed special relativity.

From two simple postulates followed a radical conclusion: no influence can propagate faster than light.

Causal relationships became geometric. Events can influence one another only if they lie within very specific regions in space, relative to their positions (only events within the same lightcone can affect each other).

In general relativity, Einstein went further. Gravity became a manifestation of spacetime curvature. The field equations relate curvature and energy locally, point by point.

Locality was no longer a mechanical principle; it was built into the structure of spacetime itself.

Quantum Mechanics and the Challenge to Locality

Quantum mechanics introduced a new tension.

Entanglement suggests correlations between distant systems that appear instantaneous.Einstein famously called this “spooky action at a distance.” He believed quantum mechanics was incomplete; something essential was missing.

For the second time in history, locality faced a serious conceptual antagonist.