

THE RESISTANCE OF LIGHT



AN EXPLORATORY ESSAY

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From Optical Fibers to the Memory of the Universe

It begins with a simple question: does light experience resistance? Following that question through glass, optical fibers, empty space, and the Big Bang reveals how radiation exchanges momentum, shapes matter, and leaves its signature on cosmic history.

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Uncompressed Thinking

The question that opened the door

The journey began with a deceptively simple question: does light experience friction while moving through a material, in something like the way electric current experiences resistance in a wire? It sounds at first like a question of terminology. It is actually a question about what light is, what matter does to it, and whether the empty universe is really capable of remaining untouched by whatever passes through it.

The electrical analogy is irresistible. Current enters a conductor, charges interact with the atomic lattice, useful electrical energy is converted into heat, and we call the result resistance. Light entering glass also changes its behavior. It slows down, bends at the boundary, and may gradually become weaker. Why not call that light resistance?

Because three different physical events are hiding inside the same everyday impression: delay, redirection, and loss. Once we separate them, the fog clears. Then, almost immediately, a much stranger landscape appears.

The central lesson is simple: slowing is not the same as losing energy, and changing momentum is not the same as friction.

Slowing without rubbing

When light enters glass or water, its electromagnetic field interacts with the charged particles in the material, especially electrons. Those charges respond by oscillating, and their response becomes part of the propagating wave. The disturbance advances through the coupled system of field and matter more slowly than light travels through vacuum.

$$v = c/n$$

Here, n is the refractive index. In ordinary glass, it is roughly 1.5, so the optical disturbance propagates at about two thirds of the vacuum speed of light. Yet this is not a photon scraping its way through molecular sandpaper. In an ideal transparent material, the frequency remains unchanged, the photon energy associated with that frequency remains unchanged, and the light returns to propagation at c after it leaves the material.

A better mental picture is a message passing through a responsive crowd. Each part of the crowd reacts, and that collective response delays the advance of the message. Nothing needs to be grinding against anything. The slowing belongs to the combined electromagnetic and material excitation, often described in more technical language as a polariton.

Real materials, of course, are not ideal. Light can be absorbed and converted into heat or electronic excitation. It can be scattered into other directions, reflected from a boundary, or transformed into radiation of another wavelength. A beam may therefore weaken approximately according to

$$I(x) = I_0 \exp(-\alpha x)$$

That attenuation is the closest optical relative of electrical resistance. It represents organized electromagnetic energy being removed from the original beam. Reduced propagation speed by itself does not.

If light slows or turns, who feels the push?

The next question followed naturally. If a material changes the motion of light, must the material itself respond? Yes, because light carries momentum even though photons have no rest mass. In vacuum, the momentum associated with energy E is

$$p = E / c$$

Imagine a pulse entering a perfectly transparent, reflection-free glass block. While the pulse is inside, momentum is shared between the electromagnetic field and the polarization response of the glass. The block receives a minute forward impulse. When the pulse exits, a compensating impulse removes the temporary velocity. In the idealized Balazs thought experiment, the block ends at rest but has shifted forward by an unimaginably small distance.

Absorption changes the ending. If the material keeps the light's energy and momentum, it receives a net impulse. Reflection can produce an even larger impulse because the light reverses direction. Radiation pressure, optical tweezers, and laser-driven microscopic devices are practical descendants of this same fact: a flow of light is also a flow of momentum.

Light is not a stream of massive pellets, but turning a flow of electromagnetic momentum still requires force, and the object doing the turning feels the reaction.

A glass road narrow enough for light

Optical fiber gave us a wonderfully concrete laboratory for these ideas. Most fibers are not hollow tubes. The usual telecommunications fiber contains a solid glass core surrounded by solid glass cladding with a slightly lower refractive index. Protective coatings, strength members, and the visible cable jacket are armor. The real optical roadway is the microscopic core.

In the simplified ray picture, light repeatedly undergoes total internal reflection at the core-cladding boundary. The fuller picture is more elegant: the fiber supports stable electromagnetic field patterns called guided modes. Most of the field occupies the core, while a small evanescent part reaches into the cladding. Specialized hollow-core fibers do exist, using intricate surrounding structures to confine light in air or gas, but they are the exception rather than the ordinary Internet cable.

Now bend the fiber. The guided momentum must continuously change direction. The glass supplies the inward force that curves the optical path, and the light supplies an equal reaction toward the outside of the bend. The force is normally tiny, on the scale of nanonewtons per watt for common geometries, but it is real.

A bend also tests the quality of confinement. As curvature increases, the optical field shifts toward the outside of the bend. Some of it may escape, first into the cladding and then into the surroundings. Stress can change phase and polarization. If the bend becomes too sharp, optical loss rises rapidly. This is why every practical fiber cable has a minimum bend radius. The warning is not merely about breaking glass. It is also about keeping the light on its road.

Diameter, modes, and the multiplication of channels

The word diameter hides two very different dimensions. The outer cable may be millimeters thick because it needs strength and protection. The light-carrying core may be only a few micrometers across. Changing the jacket diameter mainly changes mechanical behavior. Changing the core diameter can change the nature of propagation itself.

The useful guide is the normalized frequency, or V-number:

$$V = (2\pi a / \lambda) NA$$

The core radius a , the wavelength λ , and the numerical aperture NA together determine how many spatial modes the fiber can support. Below the familiar step-index threshold of about $V = 2.405$, only the fundamental mode propagates. A typical single-mode core is roughly 8 to 10 micrometers wide. A multimode core is often 50 or 62.5 micrometers wide.

A wider multimode core is easier to illuminate, but its many field patterns do not all make the journey in exactly the same way. A short pulse spreads because different modes arrive at different times. Single-mode fiber provides a narrower entrance and a far more orderly long-distance trip. Importantly, single-mode does not mean single signal. It describes the spatial field pattern, not the number of conversations the fiber can carry.

One armored cable may contain hundreds or thousands of separate fibers, with negligible interference between properly confined cores. Within each fiber, many wavelengths can travel simultaneously, each carrying an independent data stream. Thus capacity is multiplied twice: many glass roads inside one cable, and many colors of light on each road. Modern communication turns a hair-thin waveguide into something closer to a many-lane, many-level highway.

Leaving glass behind

At this point the original question escaped from matter altogether. If glass interacts with light, what about a true vacuum? Does light encounter space itself as a medium? Does empty space slow, absorb, recoil, or remember?

Ordinary vacuum is not an invisible ether. Light does not push through it as a bullet pushes through air. It is a traveling excitation of the electromagnetic field, and that field exists throughout spacetime. In empty, flat spacetime, light propagates locally at c without friction, heating, or gradual loss of energy. Space does not receive a mechanical shove in the way a glass block can.

Spacetime is nevertheless not irrelevant. General relativity says that gravity is geometry. Light follows the straightest possible path in curved spacetime, a null geodesic. Near a star, galaxy, or black hole, the route bends. Light may be gravitationally redshifted or blueshifted, and its travel time may differ from what distant observers expect. Locally it still moves at c . Geometry has guided the path without behaving like a resistive substance.

The relationship also runs in the opposite direction. Light carries energy and momentum, and energy-momentum contributes to gravity. A box containing trapped radiation weighs slightly more than the same box without it, by E/c^2 . An intense beam therefore curves spacetime, though for ordinary light the effect is absurdly small.

Can space remember light?

This became the most provocative question of the conversation. After a pulse has passed through a region of empty space, is anything left behind?

Classically, the electromagnetic answer is no. Once the trailing edge passes, the electric and magnetic fields at that location return to their previous values. There is no luminous tunnel, no heated vacuum, and no optically worn corridor. Empty space does not keep a photograph of the beam.

Matter can keep one. Gas may be ionized, dust heated, and atoms excited. Radiation pressure can rearrange particles. A powerful laser leaves a glowing channel because it has changed the air, not scarred space. Both peak intensity and total delivered energy matter.

At extraordinary energies, quantum electrodynamics adds a subtler possibility. Vacuum is permeated by quantum fields and is not perfectly linear. Photons can interact indirectly through virtual charged particles; sufficiently energetic photons in the presence of other photons, fields, or matter can create real particle-antiparticle pairs. Yet a solitary ideal plane wave does not simply exhaust itself against emptiness. Energy and momentum still have to balance.

Gravity offers the closest thing to a trace in spacetime. A powerful, asymmetric burst of radiation can contribute to gravitational memory, a permanent relative displacement of freely floating test masses after the radiation is gone. The effect depends especially on total radiated energy and its directional distribution. For everyday beams it is hopelessly small, but conceptually it changes the answer. Space does not retain light as a stain, yet spacetime geometry can retain a minute historical aftereffect of radiated energy.

The Big Bang was not a flash inside a room

Once intensity entered the question, the Big Bang seemed like the ultimate test. If an intense beam can alter matter, quantum fields, and even geometry, what trace should have been left by the greatest light event imaginable?

The first correction is decisive. The Big Bang was not a brilliant point exploding into an already existing dark emptiness. The early universe was hot and dense everywhere, and space itself was expanding. At the mathematical limit we call $t = 0$, our established theories cease to be reliable, so it may not even be meaningful to speak of familiar photons at that exact moment.

In the early periods we can describe, radiation filled the universe in nearly every direction. There was enormous energy density and pressure, but not one outward beam passing a stationary observer. In an exactly isotropic radiation field, directional flows cancel even while the pressure remains immense.

$$p_{rad} = u_{rad} / 3$$

Nor was this light freely crossing empty space. The universe was a plasma. Photons constantly scattered from charged particles and could not travel far before being redirected or absorbed and re-emitted. The scene was closer to the interior of an unimaginably hot star than to a flashbulb illuminating a room.

Radiation's deepest trace was not a trail behind a passing beam. Its energy and pressure were major ingredients in cosmic evolution and helped determine the expansion rate. As the universe expanded,

radiation energy density fell as the fourth power of the scale factor: three powers from dilution and one from the stretching and redshifting of every photon.

$$u_{\text{rad}} \propto a^{-4}$$

The radiation-filled plasma also shaped matter. It influenced particle creation and annihilation, the proton-neutron balance, the primordial production of light nuclei, and the pressure waves whose patterns later appeared both in the cosmic microwave background and in the large-scale distribution of galaxies. These are not scratches in empty space. They are structural memories written into the composition and architecture of the universe.

Then, about 380,000 years after the beginning, the universe cooled enough for electrons and nuclei to combine into neutral atoms. Photons stopped scattering continuously and began traveling freely. We still receive that ancient radiation today as the cosmic microwave background, cooled by expansion to about 2.7 kelvin.

The cosmic microwave background is not merely a trace left by ancient light. It is ancient light itself, still arriving after nearly 13.8 billion years of cosmic expansion.

What the original analogy revealed

The conversation began by asking whether light has something like electrical resistance. The final answer is more interesting than either yes or no. In matter, light can be delayed without losing energy, attenuated by absorption or scattering, and redirected through momentum exchange. In a fiber, geometry and refractive index turn those effects into a technology capable of carrying civilization's information. In vacuum, light meets no ordinary friction, but it follows the geometry of spacetime and contributes, however faintly, to that geometry.

When we ask whether light leaves a trace, the answer depends on where we look. Matter may remember through heat, ionization, motion, and structure. Quantum fields may respond under extreme conditions. Spacetime may preserve gravitational memory. The early universe went further: radiation helped make the cosmos evolve as it did.

That is what made the original question so fertile. The analogy to electrical resistance was not quite correct, but it was exactly the right door to open. It forced us to distinguish speed from energy, matter from momentum, a waveguide from an empty pipe, vacuum from ether, and a passing flash from a universe born hot everywhere. We started by wondering whether light rubs against the world. We ended with a more beautiful idea: light does not merely travel through the history of the universe. Under the right conditions, it helps write that history.