

Why does lightning take a branching path?

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A lightning photograph can look like a map of decisions: a bright trunk, sharp turns and several abandoned routes. But the flash has not surveyed the space between cloud and ground and chosen a crooked shortcut. Its conducting path develops progressively. Electrical breakdown changes the air, and the growing discharge changes the electric field that guides further growth. The branches are part of making the path, not obstacles encountered by a current following a finished wire.

1. A photograph compresses a sequence

Consider a common negative cloud-to-ground flash. Before its conspicuous bright stage, a conducting channel called a stepped leader advances intermittently and can divide. High-speed imaging resolves light from successive steps that an ordinary photograph combines. The National Weather Service describes branches becoming more or less prominent according to the surrounding electric field. [1] This account concerns that kind of flash; not every lightning discharge travels downward to the ground or follows the same sequence.

Near the ground, upward discharges can develop from objects below. A connection completes a conducting route. [2] The completed channel and the earlier process of extending it are different physical situations. Asking why the eventual current follows the channel does not yet explain why the channel acquired its geometry.

Nor does brightness measure how much charge passed along every visible twig. A camera records emitted light over an exposure interval, with limited sensitivity and a particular viewing direction. A faint branch can disappear from an image without having been absent from the discharge. A two-dimensional photograph also hides the three-dimensional distances between apparent crossings.

2. Air becomes part of the circuit

Ordinary air has relatively few mobile charges compared with a metal conductor. An electric field can accelerate free electrons. Collisions energetic enough to ionize molecules release additional electrons, allowing multiplication. A discharge therefore changes the electrical properties of the medium through which it develops.

At smaller scales, streamer discharges are advancing ionization fronts. Their own separated charge enhances the electric field near their tips, so the field driving them is partly made by the discharge itself. Streamers help precede and extend larger discharges, including lightning; a streamer is not simply another name for the entire hot lightning leader. Nijdam, Teunissen and Ebert's review makes these distinctions central to its description. [3]

That distinction prevents a misleading picture of a bolt as one object pushing through resistant air. There are coupled processes: charges move, collisions change the population of charged particles, local fields change, and the conducting region grows. A useful explanation must keep all four in view. Merely saying that electricity takes the easiest route treats the route as if it already existed.

3. Why one advancing tip can become several

A growing discharge need not preserve a smooth, symmetrical front. Different parts of the front experience different fields and ionization conditions. Small differences can grow; neighbouring channels also alter one another's electrical surroundings. Branching and competition are therefore compatible with a single overall potential difference between separated charge regions. [3]

Importantly, a branching pattern does not prove that a large obstacle sat at every fork. Wang and colleagues compared three-dimensional simulations of positive streamers with dedicated laboratory experiments. Their model treated photoionization, the production of new charged particles by emitted light, as discrete and stochastic. It reproduced branching probabilities and shapes reasonably well under the studied conditions. [4] That is evidence about a specified streamer system, not a complete experimental reconstruction of every branch of a thunderstorm leader.

The distinction between fluctuations and environmental structure matters. A discharge can be influenced by pre-existing differences in its surroundings, while some differences emerge through its own growth. The visible tree alone does not tell us how much each contributed. Reconstructing a particular flash requires measurements beyond its final outline.

4. A small electrostatic model, and its limit

A simple calculation explains why geometry can matter without pretending to calculate a lightning bolt. For an isolated conducting sphere in electrostatic equilibrium, the potential relative to infinity is $V = kQ/r$, and the surface field is $E = kQ/r^2$. Here Q is charge, r is radius and k is the electrostatic constant. Dividing gives $E = V/r$.

Within this idealization, two spheres maintained at the same potential have different surface fields: halving the radius doubles the field. The comparison is at fixed potential, not fixed charge. At fixed charge, halving the radius would instead multiply the field by four. Specifying what remains fixed is part of the explanation.

Neither result makes a leader a collection of isolated spheres. Its charge is changing, other channels are nearby, and ionization changes the surrounding medium. The calculation supplies only a physical reason why a voltage difference alone cannot determine a discharge's local behaviour. Geometry and local charge distribution matter too. A cloud-to-ground average field cannot substitute for the conditions at every advancing tip.

5. What observations can distinguish

High-speed optical records can establish the order in which luminous structures appear. Electrical and radio measurements constrain other aspects of the evolving discharge. Laboratory experiments allow controlled comparisons that a thunderstorm does not. Their value is complementary: a laboratory result can identify a mechanism, while observations determine whether its assumed regime is relevant outside the laboratory. [3,4]

The laboratory comparison in [4], for example, goes beyond matching one attractive tree shape. Comparing branching statistics across many realizations asks whether a model reproduces variability. A model can draw something that resembles lightning and still get the distribution of branch lengths, timing or branching frequency wrong.

For the same reason, agreement in streamer experiments should not silently become agreement for an entire lightning flash. A larger leader involves heating and channel

development on additional scales. The scope of a successful test must travel with the result.

6. A mechanism is not a finished forecast

The broad answer is secure: lightning creates an evolving conducting network, and its growth responds to local electrical conditions rather than to a precomputed shortest path. The review identifies open questions about discharge inception and streamer evolution; a complete description of a particular natural flash requires evidence beyond a successful small-scale model. Knowing how an ionization front can branch is not equivalent to knowing exactly where the first sustained leader will form in a particular cloud. [3]

A forecast of the exact forks would additionally require the relevant state of the cloud and the discharge with sufficient spatial and temporal detail. The photograph at the end cannot supply all those missing initial conditions. Uncertainty about the detailed route does not negate the electrical mechanism, but the mechanism does not remove that uncertainty.

The quick answer, “it follows the path of least resistance,” reverses the important part of the story. Much of the conducting path is being created while the flash develops. Its shape is an outcome of breakdown, field redistribution and growth, not a route that lightning inspected in advance.

Related reading

Article 023, “Why can a flame go out while fuel remains?”, examines a different process that must continually sustain the conditions for its own continuation. The association is optional; combustion and electrical breakdown are not the same mechanism.

References

- [1] National Weather Service. Understanding Lightning: Initiation of a Stepped Leader. <https://www.weather.gov/safety/lightning-science-initiation-stepped-leader>
- [2] National Weather Service. Understanding Lightning: Connection with the Ground. <https://www.weather.gov/safety/lightning-science-connection-ground>
- [3] S. Nijdam, J. Teunissen and U. Ebert. The physics of streamer discharge phenomena. Plasma Sources Science and Technology 29, 103001 (2020). <https://doi.org/10.1088/1361-6595/abaa05>
- [4] Z. Wang, S. Dijcks, Y. Guo, M. van der Leegte, A. Sun, U. Ebert, S. Nijdam and J. Teunissen. Quantitative modeling of streamer discharge branching in air. Plasma Sources Science and Technology 32, 085007 (2023). <https://doi.org/10.1088/1361-6595/ace9fa> Open author manuscript: <https://arxiv.org/abs/2208.07279>