

What Is a Signal?

IDE-024 · Fundamental Ideas

Concept essays for *The Universe and Its Observers*

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Scale / context: From a voltage above the thermal floor to a pulse that crossed the galaxy

Boundary: A signal as a physically distinguishable variation carrying information against a background: what makes one detectable, what limits it, and what cannot be signalled at all. The metrology of a measurement result belongs to IDE-014 and the epistemics of observing to IDE-023

Related works: IDE-023, IDE-019, IDE-018

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Article Abstract

A signal is not the same thing as a sound, a light or a voltage. It is a variation that could have been otherwise, selected from a set of possibilities the receiver already treats as possible, and carried across a channel that adds noise of its own.[1] Shannon's formulation makes that precise and, in the same paper, sets the semantic question aside as irrelevant to the engineering problem, which is a boundary that popular accounts routinely erase. Physics adds two constraints that are not matters of technique: a noise floor fixed by temperature rather than by workmanship,[2,3] and a causal structure that forbids some signals outright, including the ones people expect entanglement to allow.[4,5] This article asks what has to be true of the world for anything to count as a signal at all.

In 60 Seconds

A signal is a physically distinguishable variation drawn from a set of alternatives, and it carries information only in proportion to how much it narrows what the receiver did not already know.[1] A constant tone, however loud, tells you nothing after the first instant. Every channel adds noise, and part of that noise is not a defect of the equipment: the thermal agitation of charge in a conductor produces a fluctuation whose power depends on temperature and bandwidth alone, measured by Johnson and derived from thermodynamics by Nyquist in the same year.[2,3] Below that floor no engineering helps, though longer integration and a filter matched to the expected waveform can still pull a weak signal out. [7] Relativity forbids controllable influence outside the light cone, and quantum theory turns out to respect that even for entangled systems: the statistics on one side do not depend on what setting is chosen at the other, so correlations that no local model can reproduce still transmit nothing.[4,5] Finally, detecting a signal and knowing what produced it are separate problems, and the second is not solved by the first.[6]

Why This Question Matters

Almost every dispute about extraordinary claims turns on the difference between a signal and a fluctuation. Was that a detection or a coincidence? Could the effect have been produced by the apparatus itself? Would a message from elsewhere be recognisable as one? These questions have technical answers, and the answers are not intuitive: the threshold that separates signal from noise is a choice with consequences on both sides, the noise floor is set by physics rather than by budget, and some transmissions that sound merely difficult are prohibited outright. Knowing which is which is what keeps enthusiasm and dismissal both in check.

1. A Difference That Could Have Been Otherwise

Ask what a signal is and the natural answer points at a medium: a sound, a flash, a voltage on a wire. That answer misses what does the work. A steady tone at constant volume is a sound and carries nothing after the first moment, because the information is in the departure from what was expected rather than in the physical quantity itself.

Shannon made this exact and in doing so defined the field. Information is measured over a set of alternatives with probabilities attached: the amount conveyed by a particular outcome depends on how unlikely it was and on how many alternatives it excluded.[1] A source that can only do one thing has nothing to say, and a source whose output is completely unpredictable to the receiver conveys the maximum per symbol.

Shannon specifies a destination and a set of possible messages and requires a communication system to operate for every possible selection, not only the message actually sent. Inference: in the engineering reading adopted here, whether a fluctuation functions as message or noise depends on the receiving system and its alternatives.

Where That Leaves Us

A signal is a variation drawn from a set of alternatives the receiver already treats as possible, and it carries information in proportion to what it excludes rather than in proportion to its energy. That makes signal a relational notion rather than a property of the medium. What is not relational is how much of the variation the world itself supplies.

2. The Floor Is Physical, and the Threshold Is a Choice

Noise is usually imagined as a fault to be engineered away. Some of it is: interference, pickup, a badly grounded instrument. But a resistor sitting at room temperature, connected to nothing, produces a fluctuating voltage across its terminals, and that fluctuation cannot be removed without cooling it.

Johnson measured the effect in 1928 and showed that it depends on temperature and on the resistance and bandwidth of the circuit rather than on the material or the details of construction.[3] Nyquist derived the same result from thermodynamics in a companion paper, which is why the effect is not a curiosity of one laboratory's wiring but a consequence of equilibrium between a conductor and its surroundings.[2] Every amplifier built since inherits that floor.

Detection below the obvious level is still possible, because the floor limits power per unit bandwidth rather than what can be recovered from a long enough record. Coherently combining aligned observations of a known timed waveform improves signal-to-noise ratio when the added

noise is zero-mean and uncorrelated between observations.[7] A matched filter for a known signal maximizes signal-to-noise ratio at the sampling instant.[7] A separate result, Shannon's, gives a noisy channel a capacity: below it, coding can make the error rate as small as desired.[1] What no method supplies is certainty. A threshold set low enough to catch weak events accepts false alarms, and one set high enough to exclude them misses real ones, which is a trade rather than a problem to be solved.

Where That Leaves Us

Part of the noise in any measurement is set by temperature and bandwidth rather than by workmanship, which Johnson measured and Nyquist derived in the same year. Coherently combining aligned observations of a known timed waveform improves signal-to-noise ratio when the added noise is zero-mean and uncorrelated between observations. Physics also rules out some transmissions altogether, whatever the equipment.

3. What Cannot Be Signalled

The constraint imposed by relativity is often stated as a speed limit, which understates it. The structure of spacetime divides events into those that can influence a given event and those that cannot, and the prohibition applies to controllable influence: if any procedure allowed an experimenter here to make a difference to what an experimenter there records outside the light cone, the causal ordering of events would depend on the observer's frame.[5]

Entanglement looks like a way around this and is not. Measurements on separated entangled systems are correlated more strongly than any model assigning pre-existing local values allows, and the temptation to read this as influence is understandable. What the formalism gives, though, is that the probabilities of outcomes on one side are unchanged by the choice of setting on the other, so the correlation becomes visible only when the two records are brought together, which requires an ordinary channel.[5]

This is a theorem rather than an accident of the particular experiments. Ghirardi, Rimini and Weber showed generally that no local operation on one wing, meaning any measurement or transformation confined to that side, changes the statistics available on the other, whatever the shared state; so the quantum measurement formalism cannot be used to transmit a controllable signal faster than light.[4] The result is worth stating carefully because it is the point at which a large popular literature goes wrong: the correlations are real, and they are useless for sending anything.

Where That Leaves Us

Relativity forbids controllable influence outside the light cone, and quantum theory complies: outcome probabilities on one side of an entangled pair do not depend on the distant setting, so correlations become visible only when records are compared through an ordinary channel. That is a theorem, not a limitation of current technique. Detecting something real, though, is still not the same as knowing what sent it.

4. A Regular Signal Is Not a Message

In 1967 a Cambridge survey recorded a radio source emitting pulses about 1.34 seconds apart, repeating with a regularity unlike anything then known from an astronomical object.[6] The possibility that the source was artificial was taken seriously enough to be weighed in the discovery paper rather than dismissed.

The reasoning that settled it was not about the regularity but about everything else, and its strands did different work. The absence of measurable parallax placed the source well beyond the solar system, while the frequency-dependent drift in arrival time was consistent with dispersion in interstellar plasma and, under the model used at the time, implied a path length of order 65 parsecs. The pulse timing also showed no additional orbital motion comparable with the Earth's, which argued against a transmitter on an orbiting planet.[6] A message hypothesis survives none of the three.

The general lesson is that detection and identification are different problems resting on different evidence. A pattern that could have been otherwise is a signal by the engineering definition whatever produced it, and narrowing the source means finding independent constraints, which is what the parallax, the dispersion and the arrival times provided. Regularity by itself is weak evidence about origin, because the universe contains excellent clocks.

Where That Leaves Us

The first pulsar was a signal by every engineering criterion and its origin was still open, settled not by its regularity but by a parallax bound, by dispersion in the interstellar plasma and by the absence of any orbital motion beyond the Earth's. Detection and identification take different evidence. What neither of them supplies is what the signal means.

5. Where Signal Ends and Meaning Begins

Shannon opened his paper by setting meaning aside: the semantic aspects of communication, he wrote, are irrelevant to the engineering problem, which is to reproduce at one point, either exactly or approximately, a message selected at another.[1] The restriction was deliberate and it is the reason the theory works. Bits do not care what they are about.

The restriction is also routinely forgotten. Claims that a system transmits information, or that a genome or a neuron carries a message, are often making the engineering claim, which is measurable, while sounding like the semantic one, which is a different claim needing its own argument. Keeping the two apart costs nothing and prevents a great deal of confusion.

What remains after the restriction is a clean physical picture. Something varies in a way that could have been otherwise; the variation crosses a channel that adds noise with a floor set by temperature; a receiver holding a set of hypotheses registers it and decides, under a threshold that trades errors of two kinds; and the question of what produced it, and of what it is about, is answered by other evidence entirely.

Where That Leaves Us

Shannon's theory works because it excludes meaning, and confusing the engineering claim with the semantic one is the most common error made in its name. A signal is a variation that could have been

otherwise, surviving noise, registered against a hypothesis. What it is evidence of is the question the observer brings, and answering that is what the rest of this series has been about.

What We Know, and How

- A signal is a variation drawn from a set of alternatives, and the information it carries depends on what it excludes rather than on its energy.[1]
- Part of the noise in any electrical measurement is thermal, depending on temperature, resistance and bandwidth rather than on construction; it was measured and independently derived in 1928.[2,3]
- No procedure using entangled systems transmits a controllable signal, because the outcome probabilities on one side are independent of the setting chosen on the other.[4,5]
- Detecting a signal and identifying what produced it are separate problems resting on different evidence, as the first pulsar showed.[6]

What We Still Don't Know

- Whether the no-signalling constraint would survive in a theory superseding quantum mechanics, since the available proofs establish it within the present formalism rather than as an independent principle.[4,5]
- How to state, without smuggling in a receiver's purposes, when a physical variation counts as carrying information about something rather than merely correlating with it, which is the question Shannon set aside.[1]
- What threshold is appropriate for announcing a detection in fields where the prior probability of the effect is genuinely unknown, which the mathematics of decision under noise does not itself supply.[1]

What Could Change Our Minds

- A reproducible protocol using entangled systems that changed the outcome statistics on one side according to a setting chosen at the other would contradict the no-signalling result and, with it, the compatibility of quantum theory with relativistic causal order.[4,5]
- A measurement of electrical noise power in thermal equilibrium departing systematically from its dependence on temperature, resistance and bandwidth would contradict the thermodynamic derivation of the noise floor.[2,3]
- A source of astronomical pulses whose dispersion and arrival times matched a transmitter on an orbiting body rather than a natural object would reopen the identification question that the pulsar case is taken to have settled.[6]

If You Remember Only One Thing

A signal is a difference that could have been otherwise, surviving a noisy channel, recognised by a receiver that already knew what to look for.

Related Articles

- IDE-023 — What Is Observation?

- IDE-019 — What Is Light? Wave, Quantum and Observer
- IDE-018 — Connection: What an Edge Claims

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