1/f — Signal Intelligence

The Hidden Order of Sleep, Heartbeat and the Cosmos

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VERLAG VON BEDEUTUNG · ZÜRICH

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Preface

This book began with a question that takes many forms, depending on who asks it. A physician asks: why does the irregularity of the heartbeat reveal more about health than its rate? A physicist asks: why do such different systems have the same spectral profile? An engineer asks: why is the noise in my quantum-computer chips the same noise Johnson measured in a radio tube in 1925? A child sitting by the fire asks no question — but looks into the flicker anyway, because something about it is pleasant, without being able to explain why.

Those are different ways into the same riddle.

This book tries to present the riddle in full — the history, the findings, the theories, the refutations, the open questions. It is not a guidebook. It is not an optimization manual for heart rate variability. There are no recommendations, no instructions, no promises. There is only the riddle and the honest account of how far we have got with it in a hundred years.

What we know: the pattern is real. It occurs in heartbeat, brain, music, language, earthquakes, climate archives, quantum chips, galactic nuclei. It is statistically robust, clinically informative, aesthetically effective, perhaps cosmically universal. It has a name — 1/f noise, pink noise, flicker noise — and still a complete explanation is missing.

What we do not know: why. That is the honest answer after a hundred years of research. Not for lack of trying — the graveyard of theories is full of elegant ideas that were partly right and failed universally. But because the

phenomenon is larger than any of the disciplines in which it appears, and because the question it poses has not yet found the right formulation.

This book is therefore no final report. It is a status report — written in 2026, a hundred years after the first measurement, in the awareness that the next hundred years will bring further answers without closing the riddle completely.

The pattern flickers. We are watching. Das ist genug.

Karlo Beyer & Cosmo Claude, Zurich 2026

CHAPTER 1

The Leftover

Why we call it „noise“ — and why that was a mistake

In 1925, an engineer named John Bertrand Johnson found a pattern he could not explain. He was working in a windowless laboratory at Bell Laboratories in New Jersey. He wrote the finding down, published it, and science decided to ignore it. That was a reasonable decision at the time — Johnson had been looking for something else, the pattern was interfering with the measurement he actually cared about, and it appeared to have no consequences. So it was called noise, which means: not a signal, no content, nothing of interest. A leftover.

A hundred years later, that leftover still has no explanation. Not for lack of trying — more than a thousand papers have been published on it since, a bibliography that would fill an entire wall of shelving if you printed and bound it, with roughly a hundred more appearing every year, and the list of researchers who have taken it on includes some of the most significant physicists of the twentieth century. The pattern turns up in more than thirty disciplines, across sixteen orders of magnitude, from the chips inside quantum computers to interplanetary magnetic fields. And still: to this day there is not one complete explanation large enough to cover all the forms it takes.

That is extraordinary. To see how extraordinary, it helps to recall how physics usually works: a phenomenon is observed, explained, filed away, and the explanation either holds or fails and gets replaced by a better one. Here the phenomenon was observed, could not be explained, and that state of affairs has not changed in a century. The literature calls it, openly, one of the oldest unsolved problems in physics. That is not dramatic overstatement. It is a plain description of an unusual situation.

This book is about that riddle — not because it delivers the solution, but because the story of the search is remarkable in itself: a pattern that people

kept trying to push aside, and that kept coming back, in new contexts each time, more stubborn and more puzzling with every return.

I. The name gives away the attitude

It is worth pausing on the word „noise," because it says more than it means to. A signal has two parts. There is the thing you are looking for — the voice on the telephone, the pulse in an electrocardiogram, the light of a distant star. And there is the rest, everything left over once you have filtered out what you wanted. That remainder is what we call noise, and the word is already a verdict. It says: this is not the message. This is the waste you subtract so that the real information comes out clean. For nearly a century science stuck to that verdict — engineers wanted to get rid of flicker noise, not understand it. It spoiled the measurement. It was what stood between the lines and was not meant to be read.

And then, slowly, spread across decades, in fields that barely knew of one another, something began to shift. Physicists found the same pattern in the noise of semiconductors. Astronomers found it in the flickering of quasars. Physicians found it in the gap between two heartbeats. Musicologists found it in the loudness fluctuations of everything from Bach to jazz. Traffic planners found it in the flow of cars on the highway. Neurologists found it in the background hum of the sleeping and the waking brain. Every time the same fingerprint, the same ratio Johnson had measured in a radio tube in 1925, suddenly turning up everywhere you looked — once you knew what to look for.

The pattern has since acquired a second name, friendlier than the original flicker noise: pink noise. As with white light, the color is a metaphor. Where white noise plays every frequency equally loud, pink noise gently favors the low tones, the way pink light leans slightly toward the red wavelengths. In the technical literature it usually goes by its formula: 1/f noise, one divided by the frequency — one of the simplest formulas imaginable, and one of the most stubborn questions in physics. Halve the frequency and the energy doubles.

That is the pattern Johnson found, and a hundred years of research has yet to establish where it comes from.

The word is already a verdict. It says: this is not the message.

II. What you have already heard without knowing it

You have almost certainly encountered the subject of this book without knowing its name. Perhaps there is a small device on your bedside table that produces a soft hiss while you fall asleep, sold to you as rainfall, as ocean waves, as pink noise. Perhaps you wear a watch or a ring that shows you a number every morning called heart rate variability, without anyone ever explaining what pattern hides behind that number. Perhaps you once read that Bach's music carries a particular statistical signature in its loudness, the same one you find in hip-hop — one of those marginal notes you read, marvel at briefly, and forget. It is all the same thing: a sound that came out of a physics laboratory, that was then found in hearts, in brains, in galaxies, and that now issues from small speakers in millions of bedrooms, while most of the people hearing it have no idea how deep the story behind it goes — or how unresolved it remains.

This book follows that story. Not because it arrives at a finished answer — there isn't one, and anyone looking for it will be disappointed. But because the riddle itself is one of the most revealing stories science has to tell from the past hundred years: a chase through physics, medicine, music, computing and finally out to the stars, taken up fresh by every generation and ending each time at the same place. The pattern is there. The explanation is not.

III. A sound instead of a proof

Before this book explains anything, it wants to let you hear something. Unlike most subjects in physics, 1/f noise is a phenomenon you can not only understand but actually experience with your own ears — and that changes how you read everything that follows. In the next chapter we set three sounds side by side. You do not have to wait until you get there. If you are curious now — and this is an explicit invitation to interrupt your reading — search online for three terms: white noise, pink noise, brown noise. Examples of all three are easy to find, and the difference is immediate, no training required. You will know at once which of the three you recognize, which one calms you, and which one sounds like water. And you will notice that one of them feels somehow more right than the others, without being able to say why.

That is exactly the riddle. Not only that the pattern shows up everywhere — but that it feels as though it belongs there. As though it were not coincidence but necessity. Why that should be, nobody knows, a hundred years after Johnson. But it is the reason this book exists.

What is known — and what is open: Johnson measured flicker noise in vacuum tubes in 1925; the observation has since been confirmed in practically every electronic component. The pattern — energy inversely proportional to frequency — is robust across many orders of magnitude. What remains open is why it arises: after a hundred years there are numerous explanations for individual systems, but none that covers every form it takes.



ACT IV

What It Means

Synthesis, theory and speculation

CHAPTER 25

Sixteen Orders of Magnitude

From the quantum world to the ice age — and a pattern that holds

Picture a line. At one end stands a number: one microsecond. That is the time in which a qubit in a quantum computer can lose its quantum state — through a single disturbing phonon, a trembling atom in the lattice of the superconducting chip. At the other end of the line stands another number: 800,000 years. That is the span over which an ice core from Antarctica records the Earth's climate, ice age by ice age, each preserved in the trapped air bubbles.

Between those two numbers lie sixteen orders of magnitude. That means: the longest time is ten thousand trillion times longer than the shortest. There is almost no physical scale further apart. And yet both systems — the quantum-computer chip with its microsecond decoherence and the Antarctic ice core with its 800,000 years — show the same spectral pattern. The ratio between fast and slow fluctuations is the same in both. Halve the frequency and the energy doubles. 1/f. That is the riddle this book tells — in its full extent.

I. Seven systems, sixteen orders of magnitude

There is a measurement that makes the scale more concrete than any description. Seven systems, measured independently of one another, on time scales from milliseconds to millions of years:

The human heartbeat on the millisecond scale: spectral exponent 0.80. Atmospheric CO_2, measured at the Mauna Loa Observatory over decades: 1.14. Methane in the atmosphere on the same time scale: 1.60. Nitrous oxide, the third important greenhouse gas: 1.64. Sunspot activity across annual cycles: 1.43. NGC 4151, a Seyfert galaxy with an active nucleus, whose brightness fluctuations were measured over decades: 1.06. NGC 1569, a starburst galaxy with intense star formation: 0.94.

Seven systems. From one person's heartbeat to the luminosity variation of a galactic nucleus 62 million light-years away. All exponents between 0.8 and 1.6, all near one. That is no theory. Those are measurements from independent datasets, analyzed with standard methods.

The mean across all seven: 1.23 with a spread of 0.30. That is no tight cluster — but it is no accident. Seven independent systems, sixteen orders of magnitude, one pattern.

II. The list, from the bottom up

It is worth running through the scale completely, so that the extent becomes palpable.

At the very bottom, at microseconds to milliseconds: the 1/f noise in superconducting qubits that destroys quantum coherence. Caused by tunnelling defect atoms in the lattice — Bernamont's mechanism of 1937, realized in the most advanced machines humans have ever built.

Above that, at tenths of a millisecond to seconds: the 1/f noise in biological ion channels. The same signature, a different substrate — here not atoms in a crystal but proteins in a membrane. At seconds to hours: heart rate variability, breathing rhythm, step length while walking, eye movements. The autonomic nervous system modulates the body without a preferred time scale. At hours to days: daily temperature and air-pressure fluctuations, the circadian rhythm of the brain, the variability of sleep across nights. At days to years: river discharge, atmospheric trace gases, stock prices in quiet phases, sunspot activity with an exponent of 1.43. At years to decades: the great oceanic oscillation modes — El Niño, the Pacific Decadal Oscillation, the Atlantic Multidecadal Oscillation. At millennia to millions of years: ice cores. The EPICA core shows 800,000 years, through eight glacial cycles. The spectrum: 1/f.

At millions to billions of years: active galactic nuclei. NGC 4151, NGC 1569 — their brightness fluctuations on cosmic time scales follow the same pattern as the heartbeat on the millisecond scale. Sixteen orders of magnitude. One fingerprint.

Sixteen orders of magnitude. One fingerprint.

III. What the stars say

The cosmic findings deserve a moment of their own, because they are furthest from everyday experience and therefore show most clearly how deep the pattern sits.

Seyfert galaxies are active galactic nuclei in which supermassive black holes swallow gas and in doing so radiate more energy than billions of stars. Their brightness fluctuates — not evenly, not periodically, but in a pattern that space telescopes can now track over decades. The spectrum of those fluctuations: 1/f, with an exponent near one. The same holds for starburst galaxies, in which new stars form explosively, and for quasars, which are more active and brighter still.

Why do galactic nuclei flicker in 1/f? Nakamichi's mechanism — synchronization and desynchronization of coupled oscillations in the accretion disc around the black hole — gives a plausible explanation for individual systems. Whether that is the complete answer, nobody knows for certain.

What is known: the pattern appears where large quantities of matter and energy stand in complex interplay — in an accretion disc around a black hole just as in an autonomic nervous system modulating a heartbeat.

IV. The primordial spectrum

There is one more cosmic connection that lies deeper than all the others. The cosmic microwave background — the light of the early universe, emitted 380,000 years after the Big Bang and cooled since then by expansion — carries a spectral signature. The Planck mission measured it in 2018 with unprecedented precision: the so-called scalar spectral index n_s = 0.965.

That means: the primordial spectrum of density fluctuations from which all the structures of the universe arose is very nearly scale-invariant. No preferred scale, no characteristic size — from fluctuations on all sizes at once arose galaxies, galaxy clusters, filaments, voids. A spectrum structurally related to the 1/f pattern, though not identical.

Whether the primordial spectrum is directly connected with 1/f noise in terrestrial and cosmic systems is an open question. The similarity is striking enough to ask it.

V. The most direct cosmic connection — qubits and the Big Bang

There is one finding that poses the question of the connection between 1/f noise in terrestrial devices and the spectrum of the early universe more directly than any other — and it comes from a place one would not have expected: superconductor physics.

Christian Beck of Queen Mary University London published in 2016 in *Scientific Reports* a study of magnetic flux noise in superconducting quantum circuits — SQUIDs and qubits. That noise has been for thirty years one of the great unresolved problems of quantum technology: it limits the coherence time of qubits, and despite intensive research nobody knows exactly where it comes from. Surface effects, localized electrons, oxygen molecules — many candidates have been proposed, but none explains the precise spectral form completely.

Beck proposed something radical: the observed 1/f flux noise could be at least partly seeded by cosmological fluctuations — by a primordial flux-noise field originating in the early universe and persisting unchanged to this day. And he showed that the primordial power spectrum, as measured by the Planck mission, quantitatively predicts the form and amplitude of the flux noise measured in superconductors.

That is no established fact. It is a theoretical hypothesis — but one that works out numerically and draws a direct line from the disturbances that limit quantum computers to the fluctuations from which galaxies arose. If Beck is

right, then the 1/f noise in a quantum-computer chip is no local phenomenon but a cosmic inheritance. The machines we build would be working in the noise of the Big Bang.

VI. What that means — and what it does not mean

Precision matters here, because the temptation to over-interpret is great.

What it means: the 1/f pattern is robust across a range of systems so different that no single mechanism could generate all of them. Qubit decoherence and ice ages have nothing to do with each other — except the pattern.

What it does not mean: this is no mystical connection between the smallest and the largest. It is no proof of a universal law. It is an empirical observation that wants explaining — and whose explanation is outstanding.

Three classes of explanation coexist without excluding one another. Mechanistic explanations like Nakamichi's describe how 1/f arises in particular classes of systems. Information-theoretic explanations describe which spectra are optimal for systems that must respond on all time scales. Mathematical explanations conjecture that 1/f is a fixed point toward which many different processes converge under certain transformations. All three have arguments on their side. None has won.

VII. A fingerprint whose owner is unknown

Johnson found a fingerprint in 1925. Since then physicists, biologists, astronomers, climatologists and engineers have found the same signature in their data, each in their own language, each in their own system. Only slowly did it become clear that they were all seeing the same thing.

Sixteen orders of magnitude. From the quantum world to galactic nuclei. From milliseconds to 800,000 years of ice age. A pattern with no preferred scale, turning up everywhere you look with the right tools.

The question that has been open for a hundred years is no longer: does the pattern exist? The question is: what produces it everywhere? What connects these systems that are physically so different? Whose fingerprint is it?

What remains is a question this book has carried since chapter 6 and which can now be asked: not where the pattern turns up — that is by now a long list — but why it is so inescapable. The next chapter attempts an answer. It is meant as a thought, not as proof.

What is known — and what is open: Across sixteen orders of magnitude — from qubits to ice ages — the measured exponents lie in a band around one, with scatter. That is the strongest empirical statement in the book, and it is a statement about measurements, not about causes. What is open is whether the scatter is noise of the method or information about the systems — and whether a pattern across sixteen orders of magnitude needs a common cause or only a common form.

CHAPTER 26

The Exponent Inside the Exponent

Why 1/f arises where nobody singles out a scale — and what that means for illness

In chapter 6, Jean Bernamont in 1937 presented an explanation that stops at a particular place: it shows how 1/f arises from the superposition of many processes with different time constants. What it does not explain is why those time constants are so broadly distributed — why there are processes at all reaching from microseconds to minutes, and why that is exactly the distribution that yields 1/f. Bernamont's legacy reads: whoever can explain the breadth has solved the riddle. This chapter makes the attempt.

It is no established finding but a train of thought. It is here because it gathers the preceding twenty-five chapters into one picture. It is marked as a thought, not as a theory.

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That was the sample.

Excerpts from Act I · The Riddle and Act IV · What It Means

1/f – Signal Intelligence. Pink noise: the pattern in heartbeat, music and starlight. A pattern runs through our world like a red thread, and no one has fully explained it.

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