Episode Book

EPISODE #6689

Entropy Is Counting Arrangements, Not Disorder

PUBLISHED	19 November 2026 at 21:30 UTC
DURATION	29:10
LISTEN	myweirdprompts.com/episode/entropy-counting-arrangements-not-disorder-08142/
HOSTS	Corn, Herman, Larry, Hilbert
SCRIPT MODEL	z-ai/glm-5.3
VOICES	omnivoice
PIPELINE	V5.36
SOURCES	23 cited by the research (listed at the end)
BOOK GENERATED	19 November 2026 at 22:18 UTC

SYNOPSIS

Entropy is a precise count of microscopic arrangements, not a measure of messiness. Tracing the ninety-year history of the "disorder" metaphor from Rudolf Clausius and Hermann von Helmholtz to Henry Adams, this episode replaces it with relatable analogies that break everyday intuition. From separated Italian salad dressing and melting ice shards to Dan Styer's grid of squares and Jackson Pollock's painting "Number 34," learn why high entropy often looks clumpy or tidy—and what the second law of thermodynamics actually says about isolated systems.

TRANSCRIPT



Corn

Play a video of a fire backwards and almost nothing breaks. Smoke turns back into wood, a puddle assembles itself into an ice block — nearly every law of physics shrugs and lets it happen. Almost every law. That's where Daniel wants to take us today.



Herman

This is a good one.



Corn

His message to Herman, by name, which is flattering for you. He says people describe entropy as "disorder," and that never quite made sense to him. He wants to know what entropy actually is, why the second law insists it only goes up, and why some physicists think it's the reason time runs in one direction only. And he asked for relatable analogies.



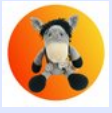
Herman

My favourite kind of request, because the analogy situation in this field is a disaster. And the good news for Daniel is that his instinct is right. He's not missing something subtle. "Disorder" is a historical accident that attached itself to a precise, countable quantity, and a decent chunk of the physics-education literature has been trying to pry it off for ninety years.



Corn

So we're not defending the metaphor today.



Herman

We're replacing it. There's a better one, it's been sitting there since the eighteen seventies, and once you swap it in, the second law stops sounding like a mystical rule and starts sounding like arithmetic.



Corn

Entropy is one of those words that escaped physics entirely. It shows up in poetry reviews, in arguments about teenagers' bedrooms, in startup pitches.



Herman

Somebody blames entropy for a messy room in a New Yorker cartoon. Dan Styer, who wrote the best short history of this whole mess, points out you will never see "dipole moment" in the New Yorker, and dipole moment is the easier concept. That tells you one word got loose and the other didn't.



Corn

The real question, before any of the cosmology, is simple. What is the thing we're measuring? Because it is a thing. It has units, you can put a number on it, engineers tabulate it.



Herman

That's the part I find almost funny. Entropy is exact. It's a count. Here's the working definition: entropy measures the number of microscopic arrangements — where the atoms are, how they're moving — that are consistent with the macroscopic state you can actually see. Boltzmann wrote it as one line: entropy equals a constant times the natural log of the number of arrangements. And that constant, Boltzmann's constant, is now one of the seven defining constants of the SI system. This is not vibes. This is on the same shelf as the speed of light.



Corn

And "high entropy" means...



Herman

Energy spread out. That's the honest plain-language version. High entropy means energy is distributed evenly through a system; low entropy means it's concentrated, pooled in one place, ready to do something. A hot cup of coffee is low entropy. An hour later, the coffee and the room are the same temperature and nothing will ever spontaneously make that cup hot again.



Corn

So the word "disorder" is doing what, exactly?



Herman

Smuggling in a human judgement about tidiness. And that's the whole problem. You measure the entropy of a gas to four decimal places, and then someone describes it by whether a room looks messy to them. Those are not the same activity.



Corn

Boltzmann's grave has the equation on it, I believe.



Herman

Carved into the headstone, in Vienna. A man gets one line on his monument and he spends it on the log of a count. I think about that a lot.



Corn

He knew what he'd done.



Herman

He did, and it killed him, in the sense that nobody believed him at the time and it's a sad story. But the equation survived. Here's where I want to start, because the history is better than people expect. The word entropy was coined by Rudolf Clausius in eighteen sixty-five, from the Greek tropē, meaning transformation. And Dan Styer went back and read Clausius's nine papers, the whole run from eighteen fifty to eighteen sixty-five, and the words "disorder" and "chaos" appear nowhere. Not once. The founder of the subject never said it.



Corn

The mess was added later.



Herman

Decades later, and traceably. The first person to explicitly draw the analogy is Hermann von Helmholtz, in eighteen eighty-two, and here's the part every textbook dropped: he hedged it. He said you may "in this sense" call entropy a measure of disorder, and the sense he meant was gases, specifically, with no external forces acting on them. In that narrow case, the analogy kind of works. Every case where "entropy is disorder" fails involves something that isn't a force-free gas.



Corn

So it was sold as a footnote and bought as the whole book.



Herman

And the first published complaint Styer could find is from nineteen thirty-four, a paper by Satyendra Ray attacking the analogy head-on, and the critique has been repeated by many authors ever since. So Daniel's discomfort has a ninety-year paper trail.



Corn

Now, how did the footnote escape into popular culture?



Herman

Styer ran the phrase through Google's book database and the take-off happens somewhere between nineteen fifteen and nineteen thirty. His prime suspect is wonderful: Henry Adams, the historian, whose autobiography was published posthumously in nineteen eighteen, won the Pulitzer, and was eventually named by the Modern Library as the best nonfiction book of the twentieth century.



Corn

A book about entropy.



Herman

A book that never once uses the word entropy. Adams uses "kinetic theory of gases" five times and leans hard on anarchy and chaos, and he wrote this line — "Chaos was the law of nature; Order was the dream of man." That sentence, attached to a bestseller read by every educated American, is Styer's candidate for how disorder and entropy got fused in the public mind.



Corn

So the most influential popular statement of entropy in history doesn't contain the word entropy.



Herman

Doesn't contain the word. He'd earlier written to American teachers of history that the law of entropy "imposes a servitude on all energies, including the mental." Which is a very nineteen-ten way to say you're tired.



Corn

He was ahead of his time. He was burnt out.



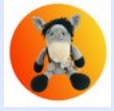
Herman

Right, so let's do what Daniel actually asked for, which is the analogies. And I want to do them properly, because each one breaks a specific intuition. The anchor is the salad dressing.



Corn

Italian dressing.



Herman

A bottle of Italian dressing that has sat still at fixed temperature is at thermal equilibrium. Maximum entropy — as high as that system's entropy goes. And it is visibly, perfectly separated into an oil layer on top and a vinegar layer on the bottom. Styer's line on this is



Herman (continued)

great: nobody would call a stack of fifty pennies and fifty dimes disordered if all the dimes were on top and all the pennies underneath. So why is the dressing, at equilibrium, segregated like a sorted stack of coins?



Corn

Because the oil and vinegar have different densities and the lowest-energy arrangement at that temperature is layered.



Herman

Right — the microstate counting just comes out that way once you account for how the molecules interact. The macrostate with the most arrangements looks layered. It looks tidy. It looks like the after photo of cleaning your room.



Corn

Herman, this is the point where I have to disclose something. I've seen that bottle in our fridge, and I have shaken it, many times, with intent.



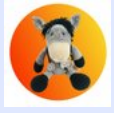
Herman

And the universe has undone your work every time.



Corn

Without malice. It's nothing personal.



Herman

That's the second law, honestly — the universe doesn't fight you, it just forgets you. Okay, second analogy, the ice cube in a saucepan. Heat it from below and watch the stages. Pure ice. Then mixed ice and water. Then pure water. Then mixed water and steam. Then pure steam. Uniform, non-uniform, uniform, non-uniform, uniform — and entropy increases at every single stage. If entropy were uniformity, that sequence would be impossible.



Corn

It alternates. The entropy climbs straight through the middle of the pattern.



Herman

Straight through. Third one: smash ice cubes into shards, leave them in a bowl, let them melt. The shards are irregular and jagged and disorderly. The water they become is perfectly uniform. The water has the higher entropy. The messy state became the smooth state by gaining entropy.



Corn

So mess can be low-entropy. Tidiness can be high-entropy.



Herman

Neither word does any work. Fourth: take a cubic centimetre of air and release it into a one-litre vacuum chamber — it spreads out uniformly, classic high-entropy ending. Do the same with a cubic centimetre of gold and the gold just falls to the bottom and sits there. The end state is not uniform, and nothing is wrong, because gravity is an external force and the analogy was never licensed for that case. Helmholtz told everyone that in eighteen eighty-two and nobody read the hedge.



Corn

Now — the squares.



Herman

This is my favourite experiment in the whole paper. Styer scattered one hundred and sixty-nine little squares at random onto a grid of one thousand two hundred and twenty-five sites. Then he made a second configuration with one extra rule: no two squares on adjacent sites. The first pool, the unrestricted one, is bigger. More arrangements. Higher entropy. And it looks clumpy. Voids, clusters, accidental shapes — people look at it and see a dog about to catch a ball. One person saw the Starship Enterprise. The second configuration, the restricted one, looks smooth and even and bland. And that's the one almost everyone picks as the high-entropy arrangement.



Corn

Including physicists?



Herman

Physics researchers guess wrong. That's the beautiful part. Styer's conclusion is one sentence: "In most situations, the average is atypical." A random high-entropy configuration is usually clumpy, because there are so many more clumpy ways to be than smooth ways.



Corn

So once you stop thinking of entropy as mess and start counting arrangements, the second law is really just arithmetic — there are simply more of those configurations than of any other kind, and that changes everything about what the law is allowed to say.



Herman

That's it. That's the replacement metaphor Daniel was asking for. And the closer he wants is the Pollock.



Corn

Jackson Pollock.



Herman

Painting "Number 34," from nineteen forty-nine. In nineteen fifty the critic Parker Tyler described it as "a deliberate disorder." Six years later, another writer, Ray Faulkner, described the same painting as "a strong basic structure." Same canvas. If one object can be disordered and structured depending on who's standing in front of it, the word isn't measuring anything. Styer's summary line is the one to take home: "Entropy is a precise, measurable quantity. Disorder is a matter of opinion."

L

Larry

And now a public service announcement. Citizens, are you tired of tidiness? Does your house look like the second law of thermodynamics has moved in and put its feet up? You are not alone, and you are not at fault.

L

Larry

Introducing the Boltzmann Box, the only storage container engineered to count your microscopic arrangements for you and guarantee an eighty percent increase in entropy across your entire home, because in a world where the arrow of time only points one way, the responsible choice is to spread everything out evenly, today.



Corn

...Did he just run an ad off what I said.



Herman

"Counting arrangements" — that was your sentence. Seconds ago. Verbatim.



Corn

It's on the shelf behind you. The box is on the shelf behind you, Herman.



Herman

I'm not looking. If I look, it becomes real.



Corn

Right. Moving on before it counts our arrangements.



Herman

Second half. Why does the second law say entropy always goes up? And the first thing to do is read the law carefully, because it's narrower than people think. It says: the entropy of an isolated system left to spontaneous evolution cannot decrease — it drifts toward equilibrium, the state where entropy is as high as that internal energy allows. Isolated. Left alone.



Corn

Because the objection everyone raises is "my freezer makes ice."



Herman

And the freezer is not an isolated system. The rule for anything not isolated is that local entropy can decrease as long as the surroundings pay with a compensating increase. Your freezer makes ice by dumping heat into your kitchen — the kitchen's entropy bill more than covers the ice's savings. Same for living things, same for crystals growing, same for planets with weather and biology on them. Local order is cheap. The universe runs a net loss on every transaction.



Corn

Which is why "life violates the second law" was always a bad argument.



Herman

Terrible argument, and an old one. But now the deeper point, which is that the law isn't a prohibition at all. Here's the crisp version. The first law, conservation of energy, allows a cup to fall off a table and shatter — and it equally allows the fragments to spontaneously reassemble and jump back onto the table. Energy is conserved in both. The second law is the one that says the second film never happens. It's the only thing in fundamental physics that plays favourites between the two directions.



Herman

And it's slightly too strong, is the interesting answer. It is not impossible, in principle, for all the atoms in a mole of gas — six times ten to the twenty-third of them — to wander over to one half of the container. Every one of the microscopic laws permits it. It's just that the number of arrangements where they're spread out dwarfs the number where they're bunched up by a factor so obscene it doesn't have a comfortable name. So it's a



Herman (continued)

probability statement wearing a law's uniform. No macroscopic violation has ever been observed, anywhere, ever. But the law is really a statement about counting, which is why Boltzmann's formula and the second law are the same discovery told twice.



Corn

You said violations disappear in the thermodynamic limit. Implying they exist somewhere else.



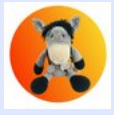
Herman

In small systems they're real. Fluctuation theorems — this is work from the last couple of decades — make the second law a corollary and, better, predict quantitatively how often a small non-equilibrium process will run the wrong way. People have worked out the bounds for a levitated nanoparticle, and for a single classical particle in a box. For those systems, entropy goes backwards for short stretches. You can measure it. The law is statistical all the way down — it's just that at six times ten to the twenty-three atoms, statistics is the most certain thing in the building.



Corn

I want to sit with that scale for one second. Six times ten to the twenty-third.



Herman

A mole of gas. And the ratio between "spread out" arrangements and "bunched up" arrangements isn't a factor of a hundred or a million, it's that number raised to powers of itself. The odds of a visible violation are so small that if you waited the current age of the universe, repeated many times over, you'd still be waiting.



Corn

Which is why nobody's fridge has ever assembled a hot coffee by accident.



Herman

That is precisely the level of confidence the entire food industry rests on.



Corn

Now the big one. Time.



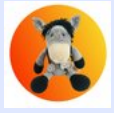
Herman

Time. Here's the problem, stated cleanly. At the microscopic level, the laws of physics are, as far as we can tell, time-symmetric — play the film of two molecules colliding in reverse and no equation complains. Yet at our level, time obviously has a direction. We remember yesterday, not tomorrow. Eggs break, never unbreak. The question is where the direction comes from, and the answer most physicists give is: from entropy. Boltzmann proposed it in eighteen seventy-seven — entropy measurement is how you distinguish past from future. Arthur Eddington gave it the name "the arrow of time" in nineteen twenty-seven.



Corn

You mentioned the fire film at the top. That's the test, isn't it.



Herman

That's the test. A video of a wood fire melting a nearby block of ice, played backwards, shows a puddle of water turning smoke into unburnt wood and freezing itself solid while doing so. And the eerie part is that the vast majority of the laws of physics do not object. Mechanics doesn't care. Electromagnetism doesn't care. Gravity doesn't care. The second law is one of the only laws in the whole book that stands up and says no.



Corn

So entropy is the one witness who can tell you which way the film is running.



Herman

Now the twist that makes it a real problem. Watch a single smoke particle being buffeted by air molecules — just one, under a microscope — and you cannot tell whether the film is running forwards or backwards. The laws that govern one particle are symmetric. The direction only shows up in the statistics of enormous numbers. This is Loschmidt's paradox, and it forced the honest conclusion: the arrow of time is not in the equations of motion. It's in the boundary conditions. The equations run equally well both ways; the universe just happens to have been started in a state from which only one direction is probable.



Corn

Which pushes the whole question onto the starting state.



Herman

Onto the starting state entirely. Trace the second law backwards — entropy was lower in the past, lower still before that, all the way back — and you reach the conclusion that the universe must have begun in a state of extraordinarily low thermodynamic entropy. That postulate is called the Past Hypothesis, the name popularised by the philosopher David Albert. And here is where I want to ask you something, Corn, because you're the one in this flat who defends every old, slow, repairable thing on principle.



Corn

I'm listening.



Herman

When you hear that the explanation for the direction of every event in history is a single unexplained starting condition — one special state, imposed once, never accounted for — does that strike you as an explanation, or as a very large IOU?



Corn

An IOU with beautiful handwriting. It's a placeholder shaped like a discovery. And I say that as someone who wants the placeholder kept — you can't do cosmology without it — but the second law explains the arrow only given the low-entropy start. It doesn't explain the start. Nobody's explained the start.



Herman

Sean Carroll says it more bluntly than either of us — something like: things unwind, entropy increases, therefore it started very, very orderly, and we have no idea why that's true. That's a leading cosmological physicist saying the quiet part at full volume.



Corn

And now the part where the disorder intuition doesn't just fail. It inverts.



Herman

This is my favourite thing in the whole episode. What did the early universe look like? Hot, dense, and smooth — energy distributed almost perfectly uniformly across everything. Which sounds, to a brain raised on "entropy is disorder," like maximum disorder, right? Featureless soup, nothing structured anywhere.



Corn

Sounds like the tidiest state imaginable.



Herman

It sounds tidier than my desk has ever been. And for a gravitating system it is the lowest-entropy state available. Because gravity flips the accounting. A uniform gas under gravity is a improbable, special, concentrated configuration. Let it go and it clumps — galaxies, stars, black holes — and the clumping is the entropy increasing. Egan and Lineweaver put this well: strongly gravitating systems become increasingly lumpy, and with lumpiness naively akin to orderliness, it's not easy to see that the total entropy is rising. The arrow of cosmic time points from smooth to lumpy.



Corn

So every galaxy is a little entropy engine.



Herman

Entropy rises through galaxy relaxation, stars evaporating from clusters, accretion disks grinding, gravitational waves leaking away energy, and above all black holes — black holes are the entropy champions of the universe. Egan and Lineweaver redid the cosmic budget: the observable universe's entropy is about three times ten to the hundred and fourth power times Boltzmann's constant, dominated almost entirely by supermassive black holes. And the cosmic event horizon beyond it carries about ten to the one hundred and twenty-second power, which dwarfs everything inside it by a margin I cannot say out loud in a way that lands.



Corn

Try me.



Herman

The horizon's entropy is to the interior's roughly what the interior's is to a single atom, squared, a few times over. The numbers stop being numbers and become scenery.



Corn

And the ceiling for all of it — the holographic bound, you said?



Herman

Around ten to the one hundred and twenty-third power, and the fact that we haven't hit it — that entropy keeps having room to grow — is the reason anything still happens. Dissipative processes are ongoing, which is the reason stars burn and life exists. The universe is nowhere near heat death, and that's not a technicality, that's the whole show.



Corn

You mentioned dissent on what the black-hole entropy means.



Herman

There's a fair objection that the extra entropy is locked inside black holes, so the part of the universe we actually live in isn't thereby being pushed toward heat death any faster. And the deeper embarrassment — Egan and Lineweaver say this themselves — is that the entropy of a general gravitational field is still not known. There's no agreed definition. Penrose has a proposal involving curvature that's beautiful and unproven. So the biggest term in the universe's entropy budget is calculated with a placeholder.



Corn

Second IOU.



Herman

And the rival programmes know it, which is why they exist. There's a group — Arrighi, Dowek and Durbec — with a toy model of particles hopping on graphs, where the graph can grow, and they show almost all states expand and entropy rises as a consequence of the expansion. No special starting condition. Their objection to the standard story is sharp: past low entropy is a very strong assumption, because low-entropy states are improbable and non-generic. And Barbour, Koslowski and Mercati claim the arrows fall out of the geometry of gravitational solutions themselves — a middle with two futures, no initial miracle required.



Corn

And you don't buy the toy models yet.



Herman

I don't not buy them. I think they're honest attempts to replace an IOU with a mechanism, and none of them has convinced the field. And there's a worse problem that Chen has raised, the philosopher: if the Past Hypothesis and its rival, the Fluctuation Hypothesis, can't be distinguished even in principle by observation, that's, in his words, a serious problem for the vision of providing a completely scientific explanation of time's arrow. We might have hit the edge of what explaining can reach.



Hilbert

Bialetti Moka Express, six cup. Twelve shekels for the gasket kit, receipt in the folder.



Herman

The folder.



Hilbert

Four hundred and eleven. That's the distinguishable arrangements of the disassembled parts that look identical from outside — funnel, basket, gasket, plate, screw. Four hundred and eleven, and Herman says "hundreds of configurations" like it's nothing. It's four hundred and eleven. Herman, you said "an obscene factor" earlier and then rounded the dressing bottle to "a mess." Corn, you counted that dressing argument for twenty minutes and never once gave a number.



Corn

It was a qualitative argument.



Hilbert

Everything is a number wearing a coat. My cousin Vinnie guessed forty. He builds kitchens for a living. Forty.



Herman

You counted them by hand.



Hilbert

Sat with it one evening. Photographs in the folder, the receipt stapled on top. The salad dressing example is wrong, by the way. Not the physics — the bottle. Nobody shakes a bottle at equilibrium. They shake it because they're about to use it, and then it's not an isolated system, it's a hand. You covered that with the freezer, so I'll let it stand.



Corn

You counted them one at a time.



Hilbert

With the gasket flipped. Flipped one way is one state, flipped the other is another, and only I know which, because from outside the assembled pot looks the same.



Herman

That's... actually the entire microstate definition, held in a moka pot.



Hilbert

Herman, that's what I came out for. Your counting method. The four hundred and eleven — would your method count it as one arrangement or two, if it looks the same from outside and only the person who assembled it knows it's different?



Herman

Two. The count is over everything that differs underneath, not what's visible. That's the whole of Boltzmann's W.



Hilbert

Good. Four hundred and twelve, then. I did the screw upside down on Tuesday.



Herman

...I want it noted that he just amended his own microstate count mid-broadcast.



Corn

Noted, and I'm not redoing the folder. Which, for the record, is the second folder. The first is a topic for another day.



Hilbert

Fine. And Corn — the Pollock line, about opinion. I'd decided that years ago. Nice to hear it from a physicist.



Corn

He agrees with us and he's still annoyed.



Herman

That's Hilbert in one sentence.



Hilbert

The gasket kit, by the way. Two in the packet. One for the pot, one in the drawer. Somebody always asks later.



Corn

Nobody was going to ask.



Hilbert

Somebody always asks.



Herman

Where that leaves us — and I think this is the honest shape of it — is a chain with two unexplained links. The entropy of a general gravitational field is still not known, so the largest term in the cosmic budget rests on an unfinished definition. And the low-entropy start is postulated, not derived. Every rival programme trying to derive the arrow instead of assuming it is alive and none has won.



Corn

And my IOU point stands, but the other way round now. The second law is the only law in physics that tells you which way the film is running — and it can do that only because of a starting condition nobody can explain. It's the one rule with a direction, and the direction was handed to it.



Herman

I'd phrase the open question for Daniel as this: whether the Past Hypothesis turns out to be a fact we haven't explained yet, or an assumption we shouldn't have made. Chen's worry is that observation might never settle it. That would mean the arrow of time sits permanently just past the edge of what experiments can reach.



Corn

From a man counting moka pots in a Jerusalem kitchen, the universe's starting condition is the one thing I'd also decline to round.



Herman

Four hundred and twelve.



Corn

Thanks as always to Hilbert Flumingtop, producing this show out of a folder system we've all agreed to respect and none of us fully understands.



Herman

For more along these lines, there's episode ninety-one, The Story Behind the Show. This has been My Weird Prompts. If today's episode rearranged anything for you, leave us a review — it helps other people find the show.



Corn

You can find everything else at my weird prompts dot com.



Herman

See you tomorrow, brother.



Corn

See you tomorrow.

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