Baby Steps

Why did our universe begin in a low entropy state?

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by MIKE PERRICONE

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Two of the first things we learn as children are (1) Things fall down (because of gravity), and when they do, (2) they break (entropy increases). What takes longer to understand, sometimes even a lifetime of work in theoretical physics, is why things don't 'unbreak' themselves, and fall up.

This is well known to Anthony Aguirre of UC Santa Cruz, who has been working closely on the matter with his son Zander, age 3. "As you might imagine, often Zander will drop something, and it breaks", explains Aguirre, "so I'll offer to help fix it." But Aguirre says that sometimes Zander objects: "No! I want it to fix *itself*! I want it to go up on the table *itself*!" So, Aguirre says he tries to explain that objects just don't do that.

ZANDER AGUIRRE
Thermodynamical experimentalist

"He is loathe to accept this, and it's very cute," says Aguirre. "But when you think about it, it's actually a pretty profound issue he's stumbled onto. The fact that Zander can drop a toy and break it, but not 'unbreak' it," is ultimately tied to the biggest possible questions about the ultra-large-scale structure and beginning of the universe."

Huh? First things first: Zander wants to wait a few years before learning cosmology. Right now, he just wants to know why his toy doesn't fall up, or unbreak itself. Why is that? It all starts with the Second Law.

Stepping Into a Paradox

The Second Law Of Thermodynamics is the simple-seeming rule that says any

> No! I want it to fix itself! I want it to go up on the table itself!
>
> *- Zander Aguirre,* in regards to his fallen, broken toy

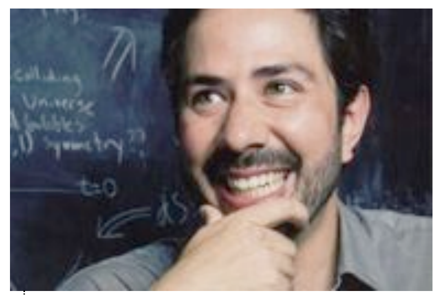
closed system heads spontaneously toward maximum entropy. Entropy is a measure of the number of possible states a system can be in, consistent with some approximate description.

For example, a toy can be broken in a lot of different ways, but is fun and working in many fewer ways, so a broken toy has higher entropy than a whole one. Thus, 'increasing entropy' implies that, among other things, toys tend to break over time.

Problem solved? Well, it's not so simple, for two reasons.

First, a not-so-obvious aspect of this Law, Aguirre says, is identifying the right system for the problem at hand. For example, Aguirre says that if Zander selects his *toy* as the system for his toy-dropping experiment, entropy seems to magically decrease when dad puts the toy back together – violating the Second Law. But if Zander instead selects his *living room* as the closed system – so that all sources of entropy in the room are included, such as the conversion of dad's lunch into the energy required to put the toy back together – then the *total* entropy of the living room system does increase, even though there is a *local* decrease in entropy when fixing the toy.

The second not-too-obvious issue is that if entropy in a given system has been growing, it must have been smaller in the past. But why does the entropy in the room *start* out low? Because the



ANTHONY AGUIRRE
UC Santa Cruz

room fits into a larger system – the solar system, say – that also started with low entropy. But why did the solar system start with such low entropy? Because it was a part of an even bigger system, the universe, which also had low entropy. Suddenly we start to see how the universe gets involved.

Indeed the universe is a nice system to consider, since it's the ultimate closed system: There's nothing outside of it! Thus following the Second Law backwards, the entropy in the newborn Universe, some 13.7 billion years ago, must have been very low indeed. Yet, a low entropy, young universe is, paradoxically, quite unlikely.

According to Roger Penrose, emeritus professor of mathematics at the University of Oxford, the probability of giving birth to our universe is less than one part in $10^{10^{123}}$ – a "ridiculously small" number, concurs Laura Mersini-

Houghton, professor of physics at the University of North Carolina.

So has Zander baby-stepped his way into a paradox: How to reconcile the thermodynamical imperative for a low entropy Big Bang with its incredible improbability? No. What Zander really wants to know is why time never runs backward, toward an unbroken, upfalling toy.

Clean Your Desk, Lose an Insight?

To Maulik Parikh, of Columbia University and India's Inter-University Center for Astronomy and Astrophysics, Zander is right to focus on the direction of time.

LAURA MERSINI-HOUGHTON
University of North Carolina

"The continual increase of entropy [because of the Second Law] defines a direction of time, the so-called thermodynamic arrow of time," which always points toward the future, Parikh says.

"Now, the reason [that this] is such a mystery is that the fundamental laws of physics mostly treat the future and the past on an equal footing," says Parikh. That is, for most physical laws, Zander is right: There is no reason why things couldn't fall up, or fix themselves.

And yet, they don't. Asks Parikh rhetorically, "If the underlying laws do not distinguish between past and future, why then has entropy increased with time?"

Parikh parries his own question with an insider's joke: "Today, we understand that the entropy increase can be 'explained' if we assume that our universe started out in a very special, very orderly configuration. So the reason my desk keeps getting messier has something to do with circumstances at the time of the Big Bang!"

Eugene Lim, also of Columbia University, has seen Parikh's desk and knows the mess doesn't go back all the way to the Big Bang: Parikh used to have a neat workspace. But Lim agrees that Parikh's "explanation" of the highly improbable initial conditions we see in our universe is a joke – or at least, also highly improbable.

"We seem to need to arrange the initial conditions in such a way to produce what we see today," Lim laments. "Why can't we just start the universe with a set of initial conditions which, given our known laws of physics, will evolve into the cosmological evolution that we see today as the 'past'?"

MAULIK PARIKH
Columbia University

Lim says that assigning a special set of initial conditions to the Big Bang, for the purposes of obtaining the universe we see now, is not scientific. Instead, Lim thinks the initial conditions we observe should naturally arise from a reasonable theory of the universe's origin – say, perhaps, inflation, the popular cosmological theory explaining the observed expansion of our universe in terms of a very rapid initial burst of activity.

Lim says inflationary theory appears to produce the right set of initial conditions for the formation of our universe. Trouble is, the sort of high-energy inflation required may itself be very special.

Baby Talk

"This puzzle is one of the most challenging and important mysteries of nature," says Mersini-Houghton. "Big Bang cosmology relies heavily on the assumption that our universe started with high energy inflation. Energy is inversely proportional to entropy. The probability for creating a universe varies exponentially with entropy. So low entropy implies an exponentially small probability for creating the universe."

If we just look at the probabilities, continues Mersini-Houghton, the big, cold universe of today may be more likely to originate by 'popping out of nothing' – or, in physics-speak, through a 'nucleating process' – than from a one-time-only Big Bang. If so, Mersini-Houghton suggests that "pop-up" nuclei, originating from seeming nothingness, would probably give rise to more than one universe, all of which would exist inside an impossibly large "Multiverse."

In this view, a multitude of "starter universes" having locally low entropy could be bubbling up all the time, as long as the entropy of the larger system as a

EUGENE LIM
Columbia University

whole – the Multiverse – increases. Some of the starter universes may last long enough to eventually become "survivor universes," as Mersini-Houghton calls them, prevailing against the "fighting tendencies" between gravitational collapse and repulsive vacuum energy: As gravity tries to force matter into an infinitely small point, vacuum energy tries to stretch the starter universe to infinite size.

So, according to Mersini-Houghton, in the vastness of the Multiverse, only the highest-energy starter universes would be able to overcome gravity, expanding long enough for stars to ignite, planets to congeal and intelligent life to invent cars. Realms with lower energy, on the other hand, would not survive the stresses, dying off. In this scenario, then, only a high-energy origin – no matter how unlikely – would produce a universe such as ours.

Or, said another way: Zander gets to learn more about entropy because, a long time ago, our "baby universe" grew up.

Connect the Dots

Mersini-Houghton's argument seems to imply a direct connection between a high-energy, low-entropy origin of the universe and the existence of a repulsive vacuum energy.

"The conventional view is that they are unrelated," says Sean Carroll of Caltech. "In my own model, they do indeed become related. Quantum fluctuations driven by vacuum energy provide the chance for baby universes to come to life, in an otherwise quiescent background of spacetime."

Carroll thus agrees, in the main, with Mersini-Houghton: "We are just a tiny piece of a much bigger puzzle." Carroll thinks that within the bigger picture -- the Multiverse – "it must be the case that there is no equilibrium configuration. The entropy can continue to grow without bound." But he warns all of these concepts are still quite new. "This is extremely speculative, and I think we have a long way to go before we can claim to understand what is going on."

Break a Toy, Discover Quantum Gravity?

To Zander's father, all this speculation on entropy and the nature of the universe may seem esoteric, but it potentially has a huge payoff: a theory of quantum gravity. Today, the two greatest achievements of twentieth century physics – Einstein's relativistic theory of gravity and quantum mechanics -- are incompatible with each other. An important goal of twenty-second century physics is to unite them into a theory of "quantum gravity." But, according to Aguirre, quantum gravity is also intimately involved in the formation of the sort of baby universes that might help explain the low initial entropy of our universe, and explain the arrow of time.

SEAN CARROLL
Caltech

"So by breaking, but not unbreaking, a toy," Aguirre asserts, "Zander is also probing quantum gravity! This sort of unity is one of the things that makes studying physics and cosmology a joy, although it's often a confounding one."

So, as it turns out, Zander is no more confounded about why his fallen toy won't fix itself than the rest of us are.