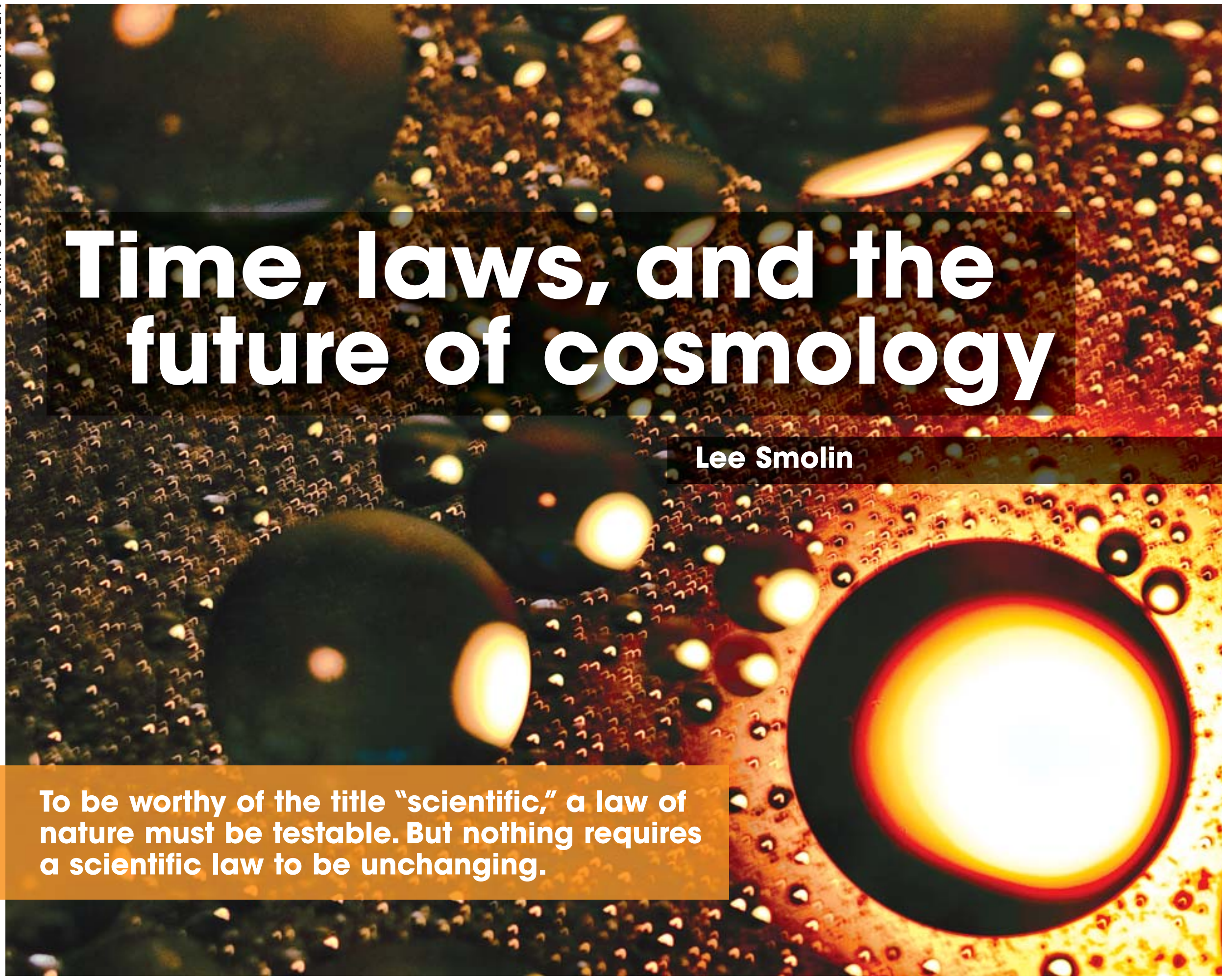

IT STARTS WITH ONE BY STEFAN KABEN

Time, laws, and the future of cosmology

Lee Smolin

To be worthy of the title "scientific," a law of nature must be testable. But nothing requires a scientific law to be unchanging.

As physicists, we have been educated to share a common conception of a law of nature. A law, such as one of Newton's laws of motion or the Schrödinger or Einstein equation, is a general statement that tells how large classes of systems change in time. Laws themselves don't change; they apply everywhere in space and for all time. According to the common conception, if a putative law changed, it wouldn't be a law. What changes is everything else—particles and fields—according to laws that never change.

The notion of unchanging natural laws is very old. It goes back to the atomism of the ancient Greeks, which says, in brief, that the world consists of atoms with unchanging properties that move in an unchanging space in a manner governed by unchanging laws. All that changes are the positions and motions of the atoms. Atomism is, more or less, physicists' modern picture of nature, but we have fields that satisfy unchanging laws and the space in which those fields move has a dynamical geometry whose evolution in time is also governed by a law. But the simple logic is unchanged. Now the space that doesn't change is more abstract; it is Hilbert space or phase space.

The above picture for understanding nature—I call it Newton's paradigm—can be formalized. Every system has available to it a space of possible states or configurations. A point in that space represents a possible state of the system. In the course of time, the system traces a curve in the state space as it passes from state to state. Some dynamical law governs those motions. That is, given an initial state, it returns a trajectory of states that determines the "final" state at any specified time. The space of states is fixed and so is the law; nothing changes except the point representing the current state of the system.

Whenever we actually use Newton's paradigm to compare experimental results to theoretical predictions, approximations necessarily creep in. That is because we always use the paradigm to model systems that are small parts of a larger universe. We always leave out a lot in our models. Indeed, we ignore almost all of the universe and thus neglect all the interactions between what we leave out and what we keep in. Experimentalists call those interactions background, and a large part of the experimental art is to minimize them. Perfect elimination, though, is impossible; for one thing, gravitational waves and forces can never be shielded.[1]

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Still, even though it renders our beautiful method for doing science inexact, making judicious approximations is exactly the right thing to do. All the successes of physics tell us so. And even the purest of theorists recognize the approximations involved when they are careful to speak of "effective" field theories—that is, models defined by truncations—that are actually tested by experiments.

Many physicists take solace in the thought that there remains one important case for which Newton's paradigm can be applied directly with no approximations: the universe as a whole. Since nothing is left out, no truncation is required. Thus cosmology must be the true domain in which timeless law is applied to a timeless space of states to reveal true motion.

I'm not buying it. After a lot of thought, I've come to the conclusion that extending Newton's paradigm to the universe as a whole is exactly the wrong thing to do. Even more, it is a crazy thing to do, for such an extension cannot yield further progress toward a scientific understanding of nature. Rather, it leads to the end of physics as a predictive science able to settle its disputes and decide among competing explanations and theories by appeal to experiments. I've argued the point in a popular book, *Time Reborn*, and more rigorously in an upcoming work coauthored with philosopher Roberto Mangabeira Unger.[2] This essay presents the main themes of those books.

Too much and not enough

Nature has presented physicists with three big questions about the universe that we will never be able to answer by extending Newton's paradigm to the universe as a whole. The first is how nature chose the specific laws that we deduce from observation. We theorists used to think we knew how to answer that question—namely, that there would be a unique way to unify the four known forces within the context of quantum theory. The development of string theory has shown us that nothing could be further from the truth: The unification of gravity, gauge fields, and fermions within quantum theory can be achieved an infinite number of ways. Simply put, the laws of physics—including the standard model with its many parameters—are all input to Newton's method.

The inability to deduce fundamental laws is exacerbated by a fact that physicists have appreciated for a long time, one that has been brought into sharp focus by recent results from CERN's Large Hadron Collider: The standard model's parameters are extremely fine-tuned. One aspect of that fine-tuning involves the hierarchy problems—the large ratios of fundamental scales in nature. Even more disturbing are the relations amongst the couplings—for example, that the electron mass is less than the mass difference between the neutron and proton—needed for a world with long-lived stars and chemical complexity.

Nor can Newton's method account for the extremely high degree of homogeneity required of our universe's initial state if the cosmos is to grow from the Big Bang to anything like what it is at present. Apparently, immediately after the Big Bang our universe contained neither black holes nor much gravitational or other radiation. Why is that? In Newton's paradigm, those extraordinary initial conditions are a given. They simply cannot emerge from application of the paradigm.

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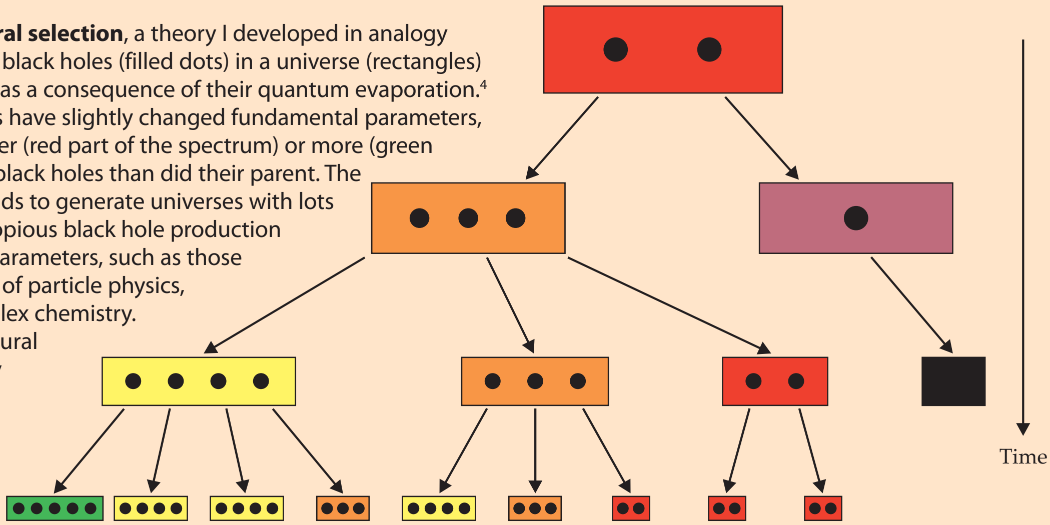
A third special feature of our universe is that it remains far from thermal equilibrium 13.8 billion years after its initiation. That out-of-equilibrium state is evidenced by the dominance of irreversible processes on a vast range of scales. Physicists speak of several arrows of time: the thermodynamic arrow (in an isolated system, entropy is most likely to increase), the electromagnetic arrow (information carried by light comes to us from the past and not



In cosmological natural selection, a theory I developed in analogy to population biology, black holes (filled dots) in a universe (rectangles) spawn baby universes as a consequence of their quantum evaporation.[4] If those baby universes have slightly changed fundamental parameters, they may produce fewer (red part of the spectrum) or more (green part of the spectrum) black holes than did their parent. The resulting evolution tends to generate universes with lots of black holes—and copious black hole production implies fundamental parameters, such as those of the standard model of particle physics, compatible with complex chemistry. Thus cosmological natural selection explains why the standard-model parameters have the values they do.

the future), the biological arrow (we age rather than grow young), the informational arrow (we remember the past and not the future), and so forth. Each of those asymmetries requires explanation in a world governed by laws that are symmetric under time reversal (as is typically assumed in applications of Newton's paradigm) and so in no way distinguish the past from the future.

The conventional "explanation," originally proposed by Ludwig Boltzmann, is called the past hypothesis. It postulates that the world began in an incredibly low-entropy and thus highly improbable state. Evidently, the universe began so far from equilibrium that 13.8 billion years later it is still dominated by irreversible processes seeking to bring it to equilibrium.

But, clearly, the past hypothesis is not an explanation at all; it simply replaces one mystery with another. Doesn't it seem absurd to explain a dominant feature of our universe by the hypothesis that it started out in an extremely improbable state? And what does probability even mean when the object of study is a single universe?

The mysteries just described stem partly from a mismatch between Newton's paradigm and the mission of answering cosmological questions. The nature of the paradigm is that any theory has an infinite number of solutions, determined by the infinite number of possible initial conditions. That flexibility perfectly fits the laboratory experimentalist who, by varying a system's initial conditions, tests hypotheses as to the nature of general laws. But there exists only one universe, notwithstanding the infinite number of solutions to Einstein's equations that describe possible universes. Thus general relativity or any other theory formulated according to Newton's paradigm explains at once too little and vastly too much. It explains too little because it fails to account for how one out of an infinite number of universes allowed by its laws is realized. And it explains far too much by describing an infinite number of features of other solutions that are never realized in nature. The root cause of the problem is the attempt to take a general law, whose connection with experiments is deduced from its validity in a vast number of cases, and apply it to a single case—the one universe as a whole.

Survival of the fittest universe

One approach to addressing the origin of laws, initial conditions, and irreversibility is to posit that the universe is not unique but one of an infinite ensemble of causally disconnected universes—the multiverse.[3] In such scenarios, Newton's paradigm goes unchallenged. And given that the paradigm makes sense only when applied to a subsystem of a larger entity, accepting the Newtonian view almost forces one to conclude that our universe is part of a larger ensemble. However, despite several decades of concerted efforts by very good people, the multiverse hypothesis has failed to produce a single falsifiable prediction for a doable experiment. And I believe it unlikely that the hypothesis ever will suggest a viable observational test, in part because of various ambiguities arising from, for example, the need to define probabilities on infinite sets of unobservable entities.

Instead, it seems clear to me that a new paradigm of explanation is needed to address the cosmological questions I have been emphasizing. Theories within the new paradigm must be scientific, which means they must overcome the difficulty the multiverse hypothesis has faced and make novel and unique predictions by which they could be falsified or verified. After a great deal of thought during the late 1980s, I came to the conclusion that a successful paradigm will include a dynamical process by which the laws of physics change in time.

The idea that the laws of nature have evolved over time is not new. It has been advocated by great physicists, including Paul Dirac, Richard Feynman, and John Wheeler, and argued for by influential philosophers such as Unger and Charles Peirce. My own path to the idea came as I was wondering how the vacuum of string theory might have been chosen by nature from a vast number of possibilities. I especially wanted to understand how the choice resulted in a standard model so finely tuned as to produce a wealth of complex phenomena at energy scales much below the quantum gravity or string scale. Where in science, I asked myself, do we have an explanation for such fine-tuning for complexity? The answer: Only in biology. I then decided to copy the formal structure of population biology by which populations of genes or phenotypes evolve on so-called fitness landscapes. The analogy was obvious. The possible vacua of string theory live on a "theory fitness landscape," analogous to the fitness landscape of phenotypes. And the parameters of the standard model evolve, as do genes in biology.

To complete the analogy, I needed to postulate a mechanism for universes to reproduce; a "fitter" universe is simply one that produces more offspring. Already by the late 1980s, physicists had suggested that quantum effects remove black hole singularities and lead to the creation of baby universes. All I had to add to that idea was the notion that due to some unknown microscopic dynamics, whenever a new universe is created, the standard-model parameters change by small random increments. Thus was born the theory of cosmological natural selection.[4] Roughly speaking, cosmic evolution tends to favor standard-model parameters leading to universes that produce lots of black holes, hence lots of baby universes. The figure at left sketches the idea; for additional detail and precision, see the box at right.

The theory of cosmological natural selection relies on singularities of general relativity being removed by quantum effects. Good evidence now suggests that such eradication is a robust outcome of quantum gravity theories applied to cosmological models.[5] It follows that the Big Bang was not the first moment of time but only a transition from a previous era of the universe. And that conclusion opens up the possibility that dynamical processes may lead to evolving physical laws. It also suggests that the initial conditions just after the Big Bang could be explained in terms of dynamical processes in the prior era.

Those processes, which occurred in our past, might imply testable predictions. Two examples in which that possibility is realized are the cyclic cosmology of Paul Steinhardt and Neil Turok and a different version by Roger Penrose.[6] Their cosmologies explain the homogeneity of cosmological initial conditions as a consequence of the processes that initiate a new Big Bang from a previous era. The Steinhardt–Turok version predicts observable levels of non-Gaussian temperature fluctuations visible in the cosmic microwave background and an absence of so-called tensor modes; the Penrose cosmology predicts concentric rings of elevated temperatures in the cosmic microwave background. The Steinhardt–Turok model is being tested in data obtained by the *Planck* satellite; meanwhile, contentious debate rages in the physics literature as to whether Penrose's predictions have been confirmed or refuted.

Cosmological natural selection may or may not describe nature, but it is a scientific theory that made genuinely falsifiable predictions. The two main predictions,[4] first published in 1992, have survived despite several chances to falsify them since.[7] One of those is actually easy to state: The upper mass limit of neutron stars is at most two solar masses.

Even if cosmological natural selection does not describe nature, it does demonstrate the possibility of inventing testable, falsifiable hypotheses for how the laws of physics might have been chosen by dynamical processes acting in the past. And I don't think it's putting it too strongly to insist that the

Cosmological natural selection

To illustrate a theory of changing laws that can generate falsifiable predictions for real experiments, I present in detail one particular example, cosmological natural selection. The theory proceeds from several hypotheses. Before stating them, I need to define a multidimensional space $\mathcal{P}$, the landscape of standard-model parameters. Each point in the landscape represents a set of possible standard-model parameters p_i. Including neutrino masses and mixing angles, there exist 27 in all. Now for the hypotheses:

1. Spacetime singularities are removed by quantum effects. As a result, a black hole evaporates, leaving behind a new expanding region of spacetime to the future of where the singularity would have been.
2. Our own universe has a very long chain of ancestors that went through the black-hole-to-new-universe creation process.
3. Each time a new universe is created, the parameters p_i change by a small random amount.
4. Define the fitness function on $\mathcal{P}$, $f(p_i)$, to be the average number of black holes formed in a universe with parameters p_i. Assume that $f(p_i)$ is strongly varying so that its local maxima are much higher than a typical value.
5. Pick an arbitrary universe far back in our chain of ancestors and call it μ^0; it has parameters p_i^0. After M generations, the population of descendants of μ^0 makes a distribution on $\mathcal{P}$ called ρ_M. Our own universe is a member of the Nth ensemble with distribution ρ_N; assume it is typical.

Assumption 1 is justified by now-established results concerning the elimination of cosmological and black hole singularities. To defend assumption 4, I note that in our universe $f \approx 10^{18}$ and that the bulk of black holes arise as supernova remnants. In universes with more generic parameters, such remnants would not form, because generic universes lack nuclear bound states, hence chemistry, hence stars. Assumptions 2 and 5 are standard typicality assumptions, common in many forms of statistical reasoning.

The only novel postulate is 3. When I proposed cosmological natural selection in 1992, I admitted the ad hoc nature of that postulate,[4] but since then, work on the so-called landscape of string theory has provided a possible microscopic justification for it.

A standard result in population biology says that if N is large enough, ρ_N is peaked at local maxima of $f(p_i)$. Since our universe is typical (per hypothesis 5), it follows that most small changes in p_i from their present values will lead to a lower $f(p_i)$ and hence to a universe that produces fewer black holes.

Much evidence supports the above conclusion.[4,7] At least 12 changes of the present p_i would plausibly lead to a world with many fewer black holes. Thus cosmological natural selection explains the finely tuned relations among many of the standard-model parameters. Moreover, cosmological natural selection makes a few genuine, falsifiable predictions. One is that neutron stars can be no heavier than twice the solar mass—a prediction that has so far been confirmed in all accurate determinations of neutron-star masses.

theory is the only explanation for the standard-model parameters that makes falsifiable predictions for real observations. Moreover, cosmological natural selection genuinely explains the fine-tuning of the standard-model parameters, because long-lived stars and carbon chemistry are essential for the processes that copiously produce massive stars and hence black holes.

The reality of time

The idea that laws evolve in time raises some tough questions. If laws evolve, it is natural to ask if some metalaw governs their evolution. But the introduction of metalaws raises an obvious question—why one metalaw rather than another—that is rather like the question that evolving laws were designed to answer. The example of cosmological natural selection shows that a metalaw may be stochastic and weak; perhaps those conditions lessen the mystery. Another possible response to the metalaw question is that there is a principle of universality mandating

> Our sense of time and its passage may be a direct perception of the true nature of reality.

that all metalaws give the same predictions for how laws evolve.[8] One common feature of any approach that involves evolving laws seems to be a breakdown of the distinction between the state of a system and the law that evolves it—a distinction that is absolute in Newton's paradigm. Roughly speaking, everything evolves, but on different time scales; a feature that appears unchanging and law-like on one time scale is merely an aspect of a state that is changing on much longer time scales.

Another tough question concerns the nature of time. The time variable does not appear in what many theorists regard to be the fundamental equation of quantum cosmology—the Wheeler–DeWitt equation, which constrains the wavefunction of the universe.[9] Theorists have come to expect that at a fundamental level, the quantum universe is timeless and time is an illusion, a quality that emerges in a semiclassical approximation from timeless laws. Indeed, many aspects of everyday perception are illusory. Those include the solidness of matter and the smoothness of fluids. And if modern theories of quantum gravity are correct, even space is an illusion that emerges from a more fundamental network of relationships. But if laws evolve, then time must be prior to law. That makes time a core aspect of reality, perhaps the only aspect of our everyday experience that does not emerge from something more fundamental. Our sense of time and its passage may be a direct perception of the true nature of reality.

The reality of time represents a fundamental challenge to quantum gravity. For one thing, it means the Wheeler–DeWitt equation cannot be the basis of quantum cosmology. One way out is to base quantum spacetime on something called a fundamental causal structure. In that picture, time marks the creation of new events from past events and laws arise only at the level of statistical regularities.[10,11]

If time is real, the past can be distinguished from the future. What, then, is one to make of the relativity of simultaneity in special and general relativity? Doesn't the experimental success of relativity imply that time's passage is a chimera, so that all that is real is the whole history of the universe laid out at once? That point of view,[12] the block-universe perspective, led Albert Einstein to declare in a letter to the family of his friend Michele Besso that the "distinction between past, present, and future is only a stubbornly persistent illusion."

A reformulation of general relativity called shape dynamics[13] resolves the quandary posed in the previous paragraph. The theory trades in the relativity of time for a relativity of size but does not give up any of the experimental successes of special and general relativity. In shape dynamics, there is no conflict between observation and the notion that the past, present, and future are distinct—a requirement if laws of nature evolve.

Shape dynamics has had other successes as well. For example, it gives an independent explanation for the AdS/CFT (anti–de Sitter/conformal field theory) correspondence between a conformal field theory and a gravitational theory in a world with one more spatial dimension. (See reference 14 and the article by Igor Klebanov and Juan Maldacena, PHYSICS TODAY, January 2009, page 28.) According to shape dynamics, the famous correspondence is general, not tied to string theory or supersymmetry. Another success of shape dynamics has been to illuminate the origin of irreversibility,[15] the third of my key cosmological questions.

Fletching an arrow of time

It has long been clear that gravity is important for keeping the universe out of thermal equilibrium. Gravitationally bound systems have negative specific heat—that is, the velocities of their components increase when energy is removed. Consider a system, such as a globular cluster, containing many objects bound by gravity. Such a system does not evolve toward a homogeneous equilibrium state. Instead, it becomes increasingly structured and heterogeneous as it fragments into subsystems.

The laws that gravitationally bound systems obey, whether expressed in the language of Newton or Einstein, are invariant under time reversal. The laws of shape dynamics, too, are time-reversal invariant. But shape dynamics gives great insight into why a gravitationally bound system will most likely evolve to become more structured and heterogeneous.[15] Roughly speaking, when gravity dominates, time-reversal invariance is spontaneously broken so that most solutions have an arrow of time; the universe does not evolve to a homogeneous equilibrium state, which would look the same with a clock run forward or backward.

Shape dynamics explains why our universe has not evolved to a structureless, homogeneous equilibrium. But it does not explain why the universe starts off so drastically homogeneous and feature-less, a condition so unlike its complex and messy present.

To address the improbability of the initial conditions requires something more, something radical. As Penrose advocated as early as 1978, only a law that is irreversible in time could explain why the future of the universe is so unlike its beginning.[16] That said, many physical systems seem well described by time-invariant laws. We physicists have a good grasp of how time-irreversible effective laws can emerge from time-reversible fundamental laws; that is the legacy of Boltzmann and Josiah Willard Gibbs. But might the reverse also be possible? Could time-reversible effective laws emerge from irreversible fundamental laws? That is a new question, which I am beginning to investigate with Marina Cortês.[11]

The ideas I have discussed here may seem adventurous. I put them forward, though, because I believe that the only way to give testable explanations for the three big cosmological questions—laws, initial conditions, and irreversibility—is to give up Newton's paradigm of fixed laws acting on fixed state spaces when attempting to model the universe as a whole. Testable is the key word: In my arguments I have always insisted that scientific theories must make predictions for doable experiments that are both verifiable and falsifiable. And in adhering to that ethic, I'm as conservative as can be.

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