Using Causality to Solve the Puzzle of Quantum Spacetime

by Jerzy Jurkiewicz, Renate Loll, and Jan Ambjorn
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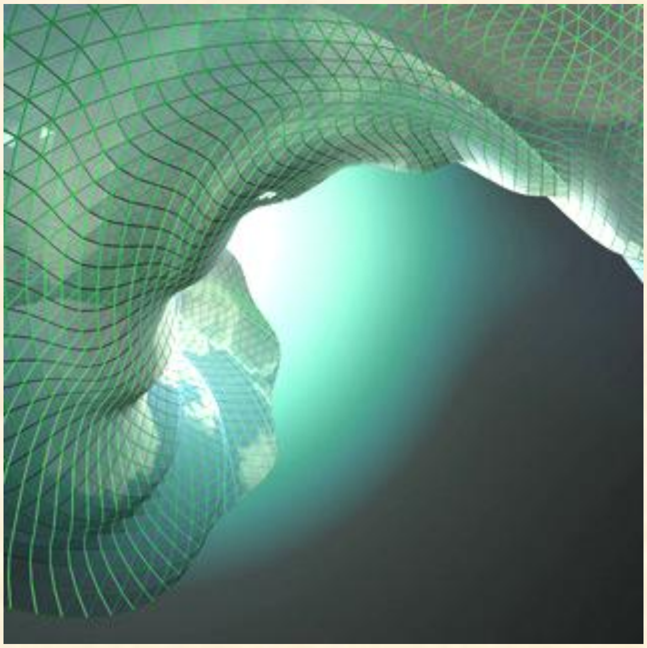
A new approach to the decades-old problem of Quantum Gravity goes back to basics and shows how the building blocks of space and time pull themselves together.



Key Concepts

- Quantum Theory and Einstein's general theory of Relativity are famously at loggerheads. Physicists have long tried to reconcile them in a theory of Quantum Gravity … with only limited success.
- A new approach introduces no exotic components but rather provides a novel way to apply existing laws to individual motes of spacetime. The motes fall into place of their own accord -- like molecules in a crystal.
- This approach shows how 4-dimensional spacetime as we know it can emerge dynamically from more basic ingredients. It also suggests that spacetime shades from a smooth arena to a funky fractal on small scales.

Editor's Note: Click ***here*** *for the web animations mentioned in the article*

How did Space and Time come about? How did they form the smooth 4-dimensional emptiness that serves as a backdrop for our physical world? What do they look like at the very tiniest distances?

Questions such as these lie at the outer boundary of modern Science and are driving the search for a theory of Quantum Gravity -- the long-sought unification of Einstein's general theory of Relativity with Quantum theory. Relativity describes how spacetime on large scales can take on countless different shapes, producing what we perceive as the force of gravity. In contrast, Quantum theory describes the laws of physics at atomic and subatomic scales, ignoring gravitational effects altogether.

A theory of Quantum Gravity aims to describe the nature of spacetime on the very smallest scales -- i.e., the voids in between the smallest known elementary particles -- by quantum laws and possibly explain it in terms of some fundamental constituents.

Superstring theory is often described as the leading candidate to fill this role. But it has not yet provided an answer to any of these pressing questions. Instead, following its own inner logic, it has uncovered ever more complex layers of new exotic ingredients and relations among them, leading to a bewildering variety of possible outcomes.

Over the past few years, our collaboration has developed a promising alternative to this much traveled superhighway of theoretical physics. It follows a recipe that is almost embarrassingly simple: take a few very basic ingredients, assemble them according to well-known quantum principles (nothing exotic), stir well, let settle … and you have created quantum spacetime. The process is straightforward enough to simulate on a laptop.

To put it differently, if we think of empty spacetime as some immaterial substance consisting of a very large number of minute, structure-less pieces -- and if we then let these microscopic building blocks interact with one another according to simple rules dictated by gravity and Quantum theory -- they will spontaneously arrange themselves into a whole that in many ways looks like the observed Universe. It is similar to the way that molecules assemble themselves into crystalline or amorphous solids.

Spacetime then might be more like a simple stir fry than an elaborate wedding cake. Moreover, unlike other approaches to Quantum Gravity, our recipe is very robust. When we vary the details in our simulations, the result hardly changes. This robustness gives reason to believe we are on the right track. If the outcome were sensitive to where we put down each piece of this enormous ensemble, we could generate an enormous number of baroque shapes -- each a priori equally likely to occur -- so we would lose all explanatory power for why the Universe turned out as it did.

Similar mechanisms of self-assembly and self-organization occur across Physics, Biology, and other fields of science. A beautiful example is the behavior of large flocks of birds such as European starlings. Individual birds interact only with a small number of nearby birds. No leader tells them what to do. Yet the flock still forms and moves as a whole. The flock possesses collective -- or emergent -- properties that are not obvious in each bird's behavior.

a Brief History of Quantum Gravity

Past attempts to explain the quantum structure of spacetime as a process of emergence had only limited success. They were rooted in Euclidean quantum gravity -- a research program initiated at the end of the 1970s and popularized by physicist Stephen Hawking's best-selling book A Brief History of Time.

It is based on a fundamental principle from Quantum Mechanics: **superposition**. Any object -- whether a classical or quantum one -- is in a certain state. Characterizing its position and velocity, say. But whereas the state of a classical object can be described by a unique set of numbers, the state of a quantum object is far richer. It is the sum -- or superposition -- of all possible classical states.

For instance, a classical billiard ball moves along a single trajectory with a precise position and velocity at all times. That would not be a good description for how the much smaller electron moves. Its motion is described by Quantum laws which imply that it can exist simultaneously in a wide range of positions and velocities.

When an electron travels from point 'A' to point 'B' in the absence of any external forces, it does not just take the straight line between 'A' and 'B' but all available routes simultaneously. This qualitative picture of all possible electron paths conspiring together translates into the precise mathematical prescription of a quantum superposition formulated by Nobel laureate Richard Feynman which is a weighted average of all these distinct possibilities.

With this prescription, one can compute the probability of finding the electron in any particular range of positions and velocities away from the straight path that we would expect if the electrons followed the laws of Classical Mechanics. What makes the particles' behavior distinctly Quantum Mechanical are the deviations from a single sharp trajectory called **quantum fluctuations**. The smaller the size of a physical system one considers, the more important the quantum fluctuations become.

Euclidean Quantum Gravity applies the superposition principle to the entire Universe. In this case, the superposition consists not of different particle paths but of different ways the entire Universe could evolve in time. In particular, the various possible shapes of spacetime. To make the problem tractable, physicists typically consider only the general shape and size of spacetime rather than every single one of its conceivable contortions [see "Quantum Cosmology and the Creation of the Universe" by Jonathan J. Halliwell; *Scientific American*, December 1991].

Euclidean Quantum Gravity took a big technical leap during the 1980s and 1990s with the development of powerful computer simulations. These models represent curved spacetime geometries using tiny building blocks which, for convenience, are taken to be triangular. Triangle meshes can efficiently approximate curved surfaces which is why they are frequently used in computer animations.

For spacetime, the elementary building blocks are 4-dimensional generalizations of triangles called four-simplices. Just as gluing together triangles at their edges creates a 2-dimensional curved surface, gluing four-simplices along their "faces" (which are actually 3-dimensional tetrahedra) can produce a 4-dimensional spacetime.

The tiny building blocks themselves have no direct physical meaning. If one could examine real spacetime with an ultra-powerful microscope, one would not see small triangles. They are merely approximations. The only physically relevant information comes from the collective behavior of the building blocks imagining that each one is shrunk down to zero size. In this limit, nothing depends on whether the blocks were triangular, cubic, pentagonal, or any mixture thereof to start with.

The insensitivity to a variety of small-scale details also goes under the name of "universality". It is a well-known phenomenon in Statistical Mechanics (the study of molecular motion in gases and fluids). These substances behave much the same whatever their detailed composition is. Universality is associated with properties of systems of many interacting parts and shows up on a scale much larger than that of the individual constituents. The analogous statement for a flock of starlings is that the color, size, wingspan, and age of individual birds are completely irrelevant in determining the flying behavior of the flock as a whole. Only a few microscopic details filter through to Macroscopic scales.

Shriveling Up

With these computer simulations, Quantum Gravity theorists began to explore the effects of superposing spacetime shapes that classical Relativity cannot handle. Specifically, ones that are highly curved on very small distance scales. This so-called "nonperturbative" regime is precisely what physicists are most interested in but is largely inaccessible with the usual pen&paper calculations.

Unfortunately, these simulations revealed that Euclidean Quantum Gravity is clearly missing an important ingredient somewhere along the line. They found that nonperturbative superpositions of 4-dimensional universes are inherently unstable. The quantum fluctuations of curvature on short scales --

which characterize the different superposed universes contributing to the average -- do not cancel one another out to produce a smooth, classical universe on large scales.

Instead, they typically reinforce one another to make the entire space crumple up into a tiny ball with an infinite number of dimensions. In such a space, arbitrary pairs of points are never more than a tiny distance apart even if the space has an enormous volume. In some instances, space goes to the other extreme and becomes maximally thin and extended like a chemical polymer with many branches. Neither of these possibilities remotely resembles our own Universe.

Before we reexamine the assumptions that led physicists down this dead-end street, let us pause to consider an odd aspect of this result. The building blocks are 4-dimensional. Yet they collectively give rise to a space having an <u>infinite</u> <u>number</u> of dimensions (the crumpled universe) or 2 dimensions (the polymer universe). Once the genie is let out of the bottle by allowing large quantum fluctuations of empty space, even a very basic notion such as dimension becomes changeable. This outcome could not possibly have been anticipated from the classical theory of Gravity in which the number of dimensions is always taken as a given.

One implication may come as a bit of a disappointment to science-fiction aficionados. Science-fiction stories commonly make use of "wormholes" -- i.e., thin handles attached to the Universe that provide a shortcut between regions that would otherwise be far apart. What makes wormholes so exciting is their promise of time-travel and faster-than-light transmission of signals.

Although such phenomena have never been observed, physicists have speculated that wormholes might find a justification within the still unknown theory of Quantum Gravity. In view of the negative results from the computer simulations of Euclidean Quantum Gravity, the viability of wormholes now seems exceedingly unlikely. Wormholes come in such a huge variety that they tend to dominate the superposition and destabilize it. And so the quantum universe never gets to grow beyond a small but highly interconnected neighborhood.

What could the trouble be? In our search for loopholes and loose ends in the Euclidean approach, we finally hit on the crucial idea -- the one ingredient absolutely necessary to make the stir fry come out right. The Universe must encode what physicists call **causality**.

Causality means that empty spacetime has a structure that allows us to distinguish unambiguously between cause and effect. It is an integral part of the classical theories of Special and General Relativity.

Euclidean Quantum Gravity does not build in a notion of causality. The term "Euclidean" indicates that Space and Time are treated equally. The universes that enter the Euclidean superposition have 4 spatial directions instead of the usual one of Time and three of Space.

Because Euclidean universes have no distinct notion of Time, they have no structure to put events into a specific order. People living in these universes would not have the words "cause" or "effect" in their vocabulary. Hawking and others taking this approach have said that "time is imaginary" in both a mathematical sense and a colloquial one. Their hope was that causality would emerge as a large-scale property from microscopic quantum fluctuations that individually carry no imprint of a causal structure. But the computer simulations dashed that hope.

Instead of disregarding causality when assembling individual universes and hoping for it to reappear through the collective wisdom of the superposition, we decided to incorporate the causal structure at a much earlier stage. The technical term for our method is **causal dynamical triangulations**.

In it, we first assign each simplex an arrow of Time pointing from the Past to the Future. Then we enforce causal gluing rules. Two simplices must be glued together to keep their arrows pointing in the same direction. The simplices must share a notion of Time which unfolds steadily in the direction of these arrows and never stands still or runs backward. Space keeps its overall form as Time advances. It cannot break up into disconnected pieces or create wormholes.

After we formulated this strategy in 1998, we demonstrated in highly simplified models that causal gluing rules lead to a large-scale shape different from that of Euclidean Quantum Gravity. That was encouraging but not yet the same as showing that these rules are enough to stabilize a full 4-dimensional universe. Thus we held our breath in 2004 when our computer was about to give us the first calculations of a large causal superposition of four-simplices. Did this spacetime really behave on large distances like a 4-dimensional, extended object and not like a crumpled ball or polymer?

Imagine our elation when the number of dimensions came out as <u>four</u> (more precisely, as 4.02 ± 0.1). It was the first time anyone had ever derived the observed number of dimensions from <u>first principles</u>. To this day, putting causality back into quantum-gravitational models is the only known cure for the instabilities of superposed spacetime geometries.

Spacetime at Large

This simulation was the first in an ongoing series of computational experiments whereby we have attempted to extract the physical and geometric properties of quantum spacetime from the computer simulations.

Our next step was to study the shape of spacetime over large distances and to verify that it agrees with **reality** -- that is, with the predictions of General Relativity. This test is very challenging in nonperturbative models of Quantum Gravity which do not presume a particular default shape for spacetime. In fact, it is so difficult that most approaches to Quantum Gravity (including string theory except for special cases) are not sufficiently advanced to accomplish it.

It turned out that for our model to work, we needed to include from the outset a so-called **Cosmological Constant** -- an invisible and immaterial substance that space contains even in the complete absence of other forms of matter and energy. This requirement is good news because cosmologists have found observational evidence for such energy.

What is more, the emergent spacetime has what physicists call a **de Sitter geometry** which is exactly the solution to Einstein's equations for a universe that contains nothing but the cosmological constant. It is truly remarkable that by assembling microscopic building blocks in an essentially random manner without regard to any symmetry or preferred geometric structure, we end up with a spacetime that on large scales has the highly symmetric shape of the de Sitter universe.

This dynamical emergence of a 4-dimensional universe of essentially the correct physical shape from <u>first</u> <u>principles</u> is the central achievement of our approach. Whether this remarkable outcome can be understood in terms of the interactions of some yet-to-be identified fundamental "atoms" of spacetime is the subject of ongoing research.

Having convinced ourselves that our quantum-gravity model passed a number of classical tests, it was time to turn to another kind of experiment -- one that probes the distinctively quantum structure of spacetime that Einstein's classical theory fails to capture.

One of the simulations we have performed is a diffusion process. That is, we let a suitable analogue of an ink drop fall into the superposition of universes and watch how it spreads and is tossed around by the quantum fluctuations. Measuring the size of the ink cloud after a certain time allows us to determine the number of dimensions in space.

The outcome is pretty mind-boggling. **The number of dimensions depends on the <u>scale</u>.** In other words, if we let the diffusion go on for just a short while, spacetime appears to have a different number of dimensions than when we let it run for a long time. Even those of us who specialize in Quantum Gravity can scarcely imagine how spacetime could smoothly change its dimension depending on the resolution of one's microscope.

Evidently, a small object experiences spacetime in a profoundly different way than a large object does. To that object, the universe has something akin to a fractal structure. A **fractal** is a bizarre kind of space where the concept of size simply does not exist. It is self-similar -- which means that it looks the <u>same</u> on all scales. This implies there are no rulers and no other objects of a characteristic size that can serve as a yardstick.

How small is "small"? Down to a size of about 10 meter, the Quantum Universe at large is well described by the classical, 4-dimensional de Sitter geometry although quantum fluctuations become increasingly significant. That one can trust the classical approximation to such short distances is rather astonishing. It has important implications for the Universe both very early in its history and very far into its future.

At both these extremes, the Universe is effectively empty. Early on, gravitational quantum fluctuations may have been so enormous that matter barely registered. It was a tiny raft tossed on a roiling ocean. Billions of years from now, because of the Universe's rapid expansion, matter will be so diluted that it likewise will play little or no role. Our technique may explain the shape of space in both cases.

On still shorter scales, quantum fluctuations of spacetime become so strong that classical, intuitive notions of geometry break down altogether. The number of dimensions drops from the classical 4 to a value of about 2.

Nevertheless, as far as we can tell, spacetime is still continuous and does not have any wormholes. It is <u>not</u> as wild as a burbling spacetime "foam" as the late physicist John Wheeler and many others imagined. The geometry of spacetime obeys nonstandard and nonclassical rules. But the concept of distance still applies.

We are now in the process of probing even finer scales. One possibility is that the Universe becomes self-similar and looks the same on all scales below a certain threshold. If so, spacetime does not consist of strings or atoms of spacetime but a region of infinite boredom. The structure found just below the threshold will simply repeat itself on every smaller scale *ad infinitum*.

It is difficult to imagine how physicists could get away with fewer ingredients and technical tools than we have used to create a Quantum Universe with realistic properties. We still need to perform many tests and experiments. For example, to understand how matter behaves in the Universe and how matter in turn influences the Universe's overall shape.

The "holy grail" -- as with any candidate theory for Quantum Gravity -- is the <u>prediction</u> of observable consequences derived from the microscopic quantum structure. That will be the ultimate criterion for deciding whether our model really is the correct theory of Quantum Gravity.

About the Authors

Jan Ambjorn, Jerzy Jurkiewicz, and Renate Loll developed their approach to Quantum Gravity in 1998.

Ambjorn is a member of the Royal Danish Academy and a professor at the Niels Bohr Institute in Copenhagen and at Utrecht University in the Netherlands. He has a reputation as an accomplished Thai cook *(a claim that the editors look forward to evaluating firsthand).*

Jurkiewicz is head of the department of the theory of complex systems at the Institute of Physics at the Jagiellonian University in Krakow. His many past positions include one at the Niels Bohr Institute in Copenhagen along whose shores he was introduced to the beauty of sailing.

Loll is a professor at Utrecht University where she heads one of the largest groups for Quantum Gravity research in Europe. Previously she worked at the Max Planck Institute for Gravitational Physics in Golm, Germany where she held a Heisenberg Fellowship. In her rare spare time, Loll enjoys playing chamber music.

Further Reading

Deriving Dimensions

Planckian Birth of a Quantum de Sitter Universe

The Emergence of Spacetime (or Quantum Gravity on Your Desktop)

Renate Loll's website

http://www.sciam.com/article.cfm?id=letters-sciammag-nov-08

Readers Respond

Universal Units?

In “The Self-Organizing Quantum Universe”, Jan Ambjørn, Jerzy Jurkiewicz, and Renate Loll describe how in looking to reconcile Quantum Theory with Einstein’s General Theory of Relativity, they developed a new approach to quantum gravity called "causal dynamical triangulations".

In this approach, on the smallest scales space-time has only 2 dimensions (approximated as a series of triangles). But on larger scales, it smoothly transforms to 3, then 4 dimensions (approximated as the triangles constructing curved shapes).

Could this fact mean that Quantum Mechanics would apply only to particles that experience less than 4 dimensions and that Relativity would apply only to the 4-dimensional universe?

If so, there would seem to be no point in looking for a mathematical framework that can join these 2 pillars of Physics.

-- Howard Wolowitz via e-mail

Ambjørn, Jurkiewicz, and Loll state that “space keeps its overall form as time advances; it cannot break up into disconnected pieces.” How, then, is the expansion of the universe explained by the geometric space-time structures they describe? Perhaps new pieces keep getting created in between and push away the others?

-- Fuat Bahadir , Omaha, Neb

The Authors Reply

As to the first question, all known elementary particles (i.e., those that are in an energy range that allows us to observe them directly in particle accelerators) behave according to the rules of both Quantum Mechanics and 4-dimensional space. So there is no contradiction here.

The phenomenon of the change in the spectral dimension observed in the theory of causal dynamical triangulations happens on much shorter scales and crucially needs the input of both General Relativity and Quantum Theory in a unified way. This unusual behavior will affect particles (matter) as well as the dynamical behavior of space-time itself at these scales.

Regarding the second question, when we wrote about the “overall form” of space, we were referring to the way it “hangs together” as a whole (what a mathematician would call its topology). This approach still leaves the freedom for space to grow or shrink, to bend, deform, or develop bumps in places and so on, which indeed will depend on how the microscopic pieces fit together, appear and disappear.

The important point is that 3-dimensional space cannot break up into several pieces or develop additional handles to change its overall connectedness.

http://www.sciam.com/article.cfm?id=what-is-a-dimension-anyway&print=true

What is a "Dimension", anyway?

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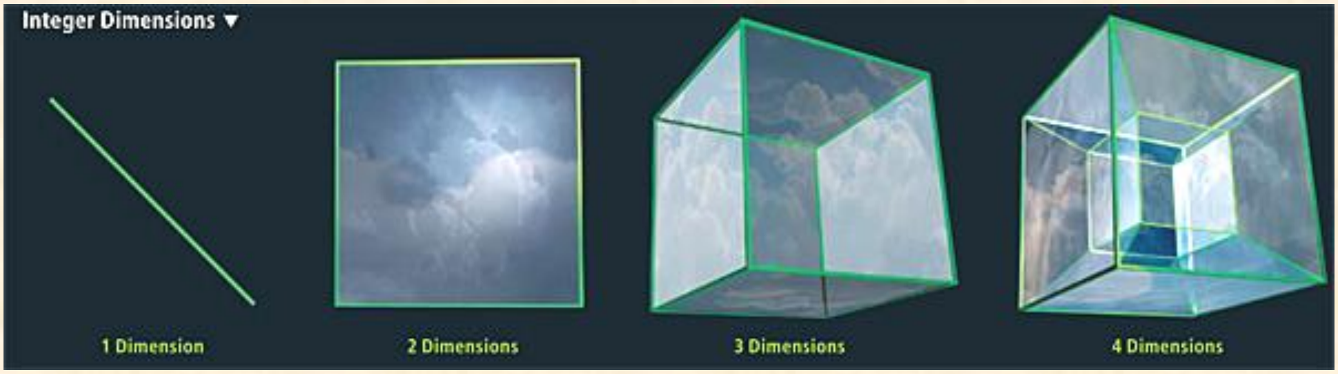
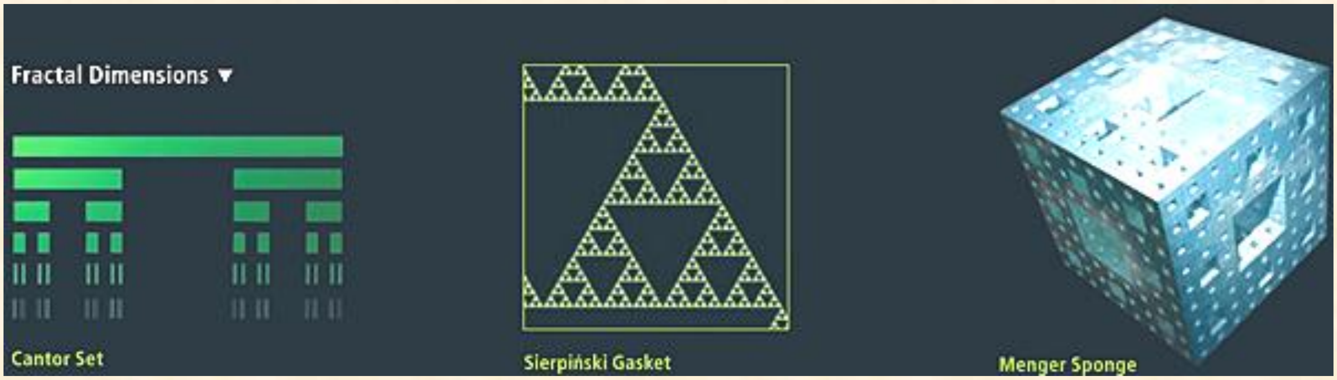
A Whole New Dimension to Space

In everyday life, the number of "dimensions" refers to the minimum number of measurements required to specify the position of an object such as latitude, longitude, and altitude. Implicit in this definition is that space is smooth and obeys the laws of Classical Physics.

But what if space is not so well behaved? What if its shape is determined by quantum processes in which everyday notions cannot be taken for granted?

For these cases, physicists and mathematicians must develop more sophisticated notions of dimensionality. The number of dimensions need not even be an integer as in the case of "**fractals**" -- i.e., patterns that look the same on all scales.





Cantor Set: Take a line, chop out the middle third, and repeat ad infinitum. The resulting fractal is larger than a solitary point but smaller than a continuous line. Its Hausdorff dimension [see below] is 0.6309.

Sierpinski Gasket: A triangle from which ever smaller subtriangles have been cut, this figure is intermediate between a 1-dimensional line and a 2-D surface. Its Hausdorff dimension is 1.5850.

Menger Sponge: A cube from which subcubes have been cut, this fractal is a surface that partially spans a volume. Its Hausdorff dimension is 2.7268 (similar to that of the human brain).

Generalized Definitions of Dimensions

Hausdorff Dimension

Formulated by the early 20th Century German mathematician Felix Hausdorff, this definition is based on how the volume **V** of a region depends on its linear size **r**. For ordinary 3-dimensional space, **V** is proportional to $\mathbf{r}^{3}$. The exponent gives the number of dimensions.

"Volume" can also refer to other measures of total size such as Area. For the Sierpinski gasket, **V** is proportional to **r1.5850**, reflecting the fact that this figure does not even fully cover an area.

Spectral Dimension

This definition describes how things spread through a medium over time be it an ink drop in a tank of water or a disease in a population. Each molecule of water or individual in the population has a certain number of closest neighbors which determines the rate at which the ink or disease diffuses.

In a 3-dimensional medium, a cloud of ink grows in size as time to the 3/2 power. In the Sierpinski gasket, ink must ooze through a twisty shape. So it spreads more slowly as time to the 0.6826 power, corresponding to a spectral dimension of 1.3652.

[more info => "List of fractals by Hausdorff dimension" (Wikipedia) http://en.wikipedia.org/wiki/List_of_fractals_by_Hausdorff_dimension]

Applying the Definitions

In general, different ways to calculate the number of dimensions give different numbers because they probe different aspects of the geometry. For some geometric figures, the number of dimensions is not fixed. For instance, diffusion may be a more complicated function than time to a certain power.

Quantum-gravity simulations focus on the spectral dimension. They imagine dropping a tiny being into one building block in the quantum spacetime. From there, the being walks around at random. The total number of space-time building blocks that it touches over a given period reveals the spectral dimension.

if on the Internet, Press <BACK> on your browser to return to the previous page (or go to www.stealthskater.com)

else if accessing these files from the CD in a MS-Word session, simply <CLOSE> this file's window-session; the previous window-session should still remain 'active'

In current quantum field theory, causality is typically defined by the vanishing of field commutators for spacelike separations. Two researchers at the University of Massachusetts and Universidade Federal Rural in Rio de Janeiro have recently carried out a study discussing and synthesizing some of the key aspects of causality in quantum field theory.Â New research synthesizes different aspects of causality in quantum field theory. by Ingrid Fadelli , Phys.org. The simple Feynman diagram on the left is decomposed into two time-ordered diagrams. In one of the time orderings, the final particles emerge before the initial particles have been annihilated. Credit: Donoghue & Menezes. This places causality in a higher role than that of time. We naturally conceive reality as what happens on a stage we call space as it evolves in time, and daily intuition has taught us that the passage of time gives rise to causal relations. But in actuality, it must be the other way around: the existence of causal relations gives rise to our experience of time. Let us go back to the geometric form of the spacetime interval.Â Si esta frase te sorprende tienes que leer a Daniel FernÃ¡ndez en The road to quantum gravity (1): Spacetime as [â€¦] Cartografiando la ignorancia #249 | La manzana podrida. December 22, 2018. [â€¦] La realidad no es una espacio tridimensional que evoluciona en el tiempo, sino un espaciotiempo cuatridimensional sin evoluciÃ³n temporal. In non-relativistic quantum mechanics, causality is violated by saying that the amplitude of propagation of a particle $$A=\langle \textbf{x}|\exp{\Big(\frac{-i\textbf{p}^2t}{2m\hslash}}\Big)|\textbf{x}_0\rangle$$ between any two points $\textbf{x},\textbf{x}_0$ is non-zero for any time t, however small. But this is also true in quantum field theory. The amplitude of propagation of a particle from a spacetime point x to another spacetime point y, given by $$A(x,y)=\langle 0|\phi(x)\phi(y)|0\rangle\neq 0$$ even for space-like separations. Therefore, isn't by the previous argument, he...Â Use the same letter if you want, but you are dealing with two different objects. In mathematical physics, the concept of quantum spacetime is a generalization of the usual concept of spacetime in which some variables that ordinarily commute are assumed not to commute and form a different Lie algebra. The choice of that algebra still varies from theory to theory. As a result of this change some variables that are usually continuous may become discrete. Often only such discrete variables are called "quantized"; usage varies.

Traditionally, quantum theory assumes the existence of a fixed background causal structure. But if the laws of quantum mechanics are applied to the causal relations, then one could imagine situations in which the causal order of events is not always fixed, but is subject to quantum uncertainty. Such indefinite causal structures could make new quantum information processing tasks possible and provide methodological tools in quantum theories of gravity. Here, I review recent theoretical progress in this emerging area. Revisiting the notion of causality in quantum mechanics may lead to new direct Abstract In an exact quantum-mechanical framework we show that space-time expectation values of the second-quantized electromagnetic elds in the Coulomb gauge, in the presence of a classical source, automatically lead to causal and properly retarded elec-tromagnetic eld strengths. The classical -independent and gauge invariant Maxwellâ€™s equations then naturally emerge and are therefore also consistent with the classical spe-cial theory of relativity.Â In general, it is notoriously dicult to solve the SchroÂ¨dinger equation with an explicitly. time-dependent Hamiltonian. Due to the at most quadratic dependence of a and aâˆ— in. Eq.(3.6) it is, however, easy to solve exactly for the unitary quantum dynamics. Indeed, if. Causality, Measurement Theory and the Differentiable Structure of Space-Time - February 2010.Â It is to provide a glimpse into the generalizations of the formalism of quantum mechanics on Hilbert space that are required to describe the symmetries and dynamics of systems with infinitely many degrees of freedom, owing to the qualitative differences that arise when the number of degrees of freedom tends to infinity. The burden of the preceding chapters was that the notion of a geometrical point is as meaningful in quantum physics as it is in classical physics. The argument involved a lengthy excursion into quantum-mechanical measurement theory. During this excursion, we found that the noti A new approach to the decades-old problem of quantum gravity goes back to basics and shows how the building blocks of space and time pull themselves together. Share on Facebook. Share on Twitter. Share on Reddit. Share on LinkedIn. Share via. Print.Â Scientific American Space & Physics is a roundup of the most important stories about the universe and beyond. Subscribe Now! Follow us. instagram. soundcloud. youtube. twitter.