# Does String Theory Posit Extended Simples?

David John Baker
Department of Philosophy, University of Michigan
djbaker@umich.edu

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**Abstract**

It is sometimes claimed that string theory posits a fundamental ontology including extended mereological simples, either in the form of minimum-sized regions of space or of the strings themselves. But there is very little in the actual theory to support this claim, and much that suggests it is false. Extant string theories treat space as a continuum, and strings do not behave like simples.

## 1 Introduction

Although existing models are not there yet, the string theory program offers the ambition, and at least the potential, for a theory of everything. Should the program eventually succeed, we will have a theory whose interpretation provides the best possible guess at our world's fundamental ontology. Relatively little philosophical work has addressed string theory thus far, and not much of the extant work has focused on its ontology. This is understandable, since the theory has not yet reached a mature stage in either its mathematical form or its empirical confirmation.

But a few remarks have appeared in the philosophical literature addressing string theory's relevance to one debate in metaphysics: the possibility or existence of extended simples. Sometimes it is suggested that string theory posits an ontology of extended simples–either the strings themselves, or minimum-sized regions of "quantized" space. Both the popular literature on string theory and some technical presentations of the theory make this suggestion appear quite natural. Perhaps there is room for metaphysicians to wrangle over the metaphysical or conceptual possibility of dividing a string, but the fundamental entities of string theory are extended and physically indivisible; so the story goes.

String theory is a work in progress, and upon its completion we may indeed find that the final version posits extended simples. But string theory in its present form provides little to no evidence for the existence of extended simples. It is a quantum theory, and as in other quantum theories, its most obvious or literal physical interpretation is almost certainly unsatisfactory. The likeliest guesses at satisfactory interpretations do not involve extended simples. And even assuming the obvious interpretation, on which quantum string theory has the same ontology as the classical version of string theory, this ontology does not include extended simples.

To support these claims, I will of course need to present some details of the theory. In Section 2 I will do so, hopefully avoiding onerous technicalities in favor of conceptual clarity while doing justice to the facts. I will then consider in turn the claim that strings are extended simples (Section 3) and the claim that string theory posits minimum-sized regions of space (Section 4). The former rests on an untenably classical understanding of string theory, while the latter is supported only by the speculative or analogical remarks of some physicists. Neither the theory itself nor the likely direction of its future development bears out these remarks, which in some instances arise from a simple conflation of the detectable and the real. In actual string theories, spacetime (if it exists at all) is continuous.

# 2 String theory

Popular presentations of string theory can appear quite surprising to the physics-literate reader. One typically wonders, what happened to the quantum weirdness, the superpositions and the measurement problem? Can we do without those complications if we assume the world is made up of tiny strings? The answer is no. String theory is a quantum theory, just like its predecessor theories, quantum mechanics (QM) and quantum field theory (QFT).

Or more precisely, there are both quantum and classical versions of string theory. The classical version is typically used as a stepping stone to the quantum version, both pedagogically and in its construction. But it is the quantum version that claims to unify gravity with the other three forces, and that may eventually develop into a theory of everything. So as I begin by presenting the classical picture of string theory, bear in mind that it will have to be complicated by quantum effects–I'll get to that part shortly.[1]

In (special relativistic) classical string theory we can take the name quite literally–a classical string truly is a one-dimensional extended object that (at any given time) occupies a curve-segment in space. Compare this with the classical mechanics of a particle, which is easy to describe. In particle mechanics in a given reference frame, the configuration quantity is the vector variable $x_i(t)$ giving the position of the particle at time $t$, where $i$ ranges over the $n$ axes in $n$-dimensional space. In string theory a single string is described by the variable $X_i(\sigma, t)$, which gives the position in space of the point a distance $\sigma$ down the length of the string at time $t$. So for example, the position of one end of the string is written $X_i(0, t)$, and by convention we write $\sigma$ in units chosen so that the string is $\pi$ units long and the other end's position is $X_i(\pi, t)$.

The motion of strings is often depicted pictorially using worldsheet diagrams (see Figure 1). Just as a point particle's trajectory through spacetime consists of a one-dimensional worldline recording its position at each point in time, the trajectory of a string forms a two-dimensional worldsheet. (When we move to quantum string theory, we must keep in mind that a quantum string's evolution in time will be given by a superposition of worldsheets rather than a single worldsheet.)

In classical particle mechanics, the only kinetic energy a particle has is the energy of its center of mass (which is all there is to the particle). A string, on the other hand, can also hold energy in the relative motion of the points along the string. It can oscillate like a guitar string, or stretch or compress like a spring. Strings may also join together at the ends, and the two ends of the same string can join, forming a loop-shaped *closed string*. These features account for the differences between point particles and the simplest strings. It really is not far wrong to think of a basic classical string as a rubber band moving in the Minkowski spacetime of special relativity.

But string theories of actual physical importance are quantum theories, and for them, the rubber band is no longer an especially useful analogy. The construction of quantum string theory from classical string theory parallels the construction of quantum particle mechanics.

[1]Throughout my presentation I will avoid details that clearly don't bear on the metaphysical question at hand. In particular, neither supersymmetry nor extra dimensions will be discussed in detail. If a bosonic string is not an extended simple, neither is a superstring; if a string in three-dimensional space is not an extended simple, neither is a string in nine dimensions. If some of the physics jargon I just used means nothing to you, that is not important for present purposes either.

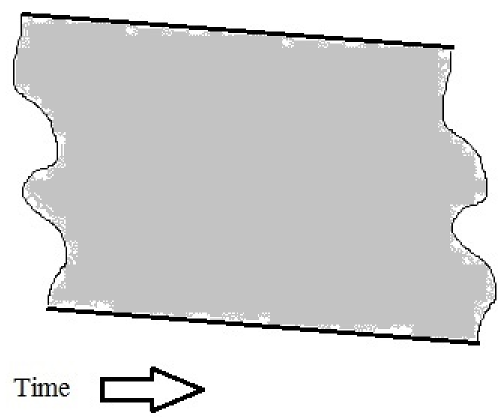


Figure 1: Example of a worldsheet for an open string.

In the case of particles, one promotes the classical quantities like $x_i$ to operators (written $\hat{x}_i$). This allows one to define uncertainty relations over the quantities by stipulating that some pairs of operators fail to commute–so for example, the position-momentum uncertainty principle arises because the operator for position does not commute with the operator for momentum. One then defines quantum states $|\psi\rangle$ as superpositions of classical particle states. The inner product $\langle\psi|\hat{x}_i(t)|\psi\rangle$ gives the expected value of $\hat{x}_i(t)$ in the state $|\psi\rangle$, and similarly for other quantities.

To quantize string theory, we do the same thing with the quantities associated with the string. $\hat{X}_i(\sigma, t)$ becomes the operator associated with the position of the $\sigma$ point on the string, and its expectation value in state $|\psi\rangle$ is $\langle\psi|\hat{X}_i(\sigma, t)|\psi\rangle$. Just as in particle mechanics, the quantum states are superpositions of classical states of the string. This is often colloquially described as the string or particle being in "many configurations at once." But really all we know, in the absence of an interpretation of the theory, is which expectation values are predicted by which quantum states. Many interpretations of quantum particle mechanics take $|\psi\rangle$ itself to represent the fundamental physical stuff. The *wavefunction* realism of Albert (1996) is the most straightforward example of this approach, but Wallace and Timpson (2010) also base their fundamental ontology for quantum theory on one mathematical representation of the state (in terms of density operators). Neither of these is a complete interpretation in the sense of solving the quantum measurement problem, but both aim to provide metaphysical underpinnings for many potential solutions.

No interpretation of quantum mechanics has been formally extended to quantum string theory. But there may be some grounds for informed speculation. We will return to this question in the next section.

A final complication of the emerging string-theoretic picture of reality is M-theory. In ten-dimensional spacetime there are five consistent superstring theories which were initially considered as candidate theories of everything. But in the present day the received view holds that all five of these theories are limiting cases (approximations within certain domains) to a more fundamental theory called M-theory, which takes place in eleven dimensions.

Although most of its properties are not yet known, M-theory is thought to behave a lot like string theory. In place of one-dimensional strings, though, it introduces higher-dimensional objects called *branes.* A brane behaves like a string, except that it is a higher-dimensional surface (so a string is effectively a one-dimensional brane or one-brane). Although alternatives exist, the ordinary picture of M-theory involves two- and five-dimensional branes (Becker *et al.*, 2007, 329-332). The two-branes, for example, move and interact like strings but are shaped like infinitely thin sheets of paper. Like string theory, M-theory is a quantum theory which can be expected to face the measurement problem and the attendant interpretive challenges.

# 3 Simple strings?

It has sometimes been suggested that string theory posits extended objects with no proper spatial parts: the strings. We have here an unusual example of a prominent physicist putting forward a clear and unequivocal metaphysical thesis. In his popular book *The Elegant Universe*, Brian Greene asks what strings are made of:

> There are two possible answers to this question. First, strings are truly fundamental - they are "atoms," uncuttable constituents, in the truest sense of the ancient Greeks... From this perspective, even though strings have spatial extent, the question of their composition is without any content. Were strings to be made of something smaller they would not be fundamental... [A] string is simply a string - as there is nothing more fundamental, it can't be described as being

> composed of any other substance. That's the first answer. The second answer is based on the simple fact that as yet we do not know if string theory is a correct or final theory of nature. If string theory is truly off the mark, then, well, we can forget strings and the irrelevant question of their composition. Although this is a possibility, research since the mid-1980s overwhelmingly points toward its being extremely unlikely. (Greene, 1999, 141-142)

So unless the theory is wrong, says Greene, strings have no proper parts. In the course of criticizing metaphysical arguments against the possibility of extended simples, Craig Callender similarly claims that "on its most natural interpretation, superstring theory–one of the more promising attempts at a theory of quantum gravity–posits extended simples." (Callender, 2011, 38) McDaniel (2007) cites the passage from Greene to motivate studying the metaphysical possibility of extended simples (which I will not dispute). So the idea that strings are extended simples has been aired in at least a few places.

How do Greene and Callender justify their contention that strings are naturally understood as simples? Neither discusses the issue at length, but both emphasize that strings are physically fundamental and, as Greene says, "uncuttable." The point about fundamentality is a delicate one, since there are ways for an object to be fundamental that do not necessarily require it to be simple. Indeed, on some interpretations of quantum mechanics this distinction between physically fundamental things and simples is an important one. On the spacetime state realism of Wallace and Timpson (2010), the quantum state of each region in spacetime is a fundamental physical property of that region, and these form the fundamental building blocks of a world. But a region (or the state of a region) has many sub-regions as parts, and the states of these sub-regions are also fundamental quantities according to Wallace and Timpson. There is also, perhaps arguably, a notion of fundamentality involving metaphysical grounding: the fundamental things are the ungrounded things that ground everything else. There is no contradiction in supposing that composite objects are fundamental in this sense; for example, Schaffer (2010) has argued that the universe as a whole grounds its parts.

Suppose we stipulate that everything is made up of strings, and there is nothing deeper to say about how matter is constituted. Could strings be the smallest constituents of matter, and yet fail to be simples? In a sense, they could, if every string were made up of smaller strings and they lacked point-sized parts–if strings were, in the metaphysician's parlance,

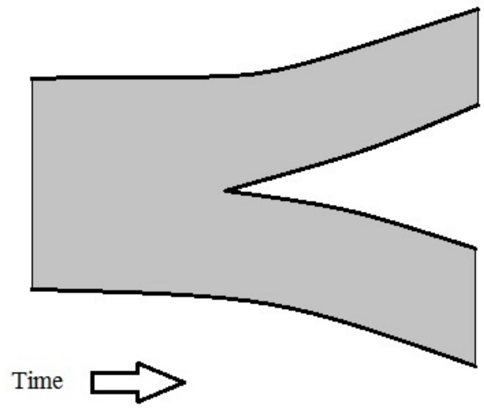


Figure 2: Splitting interaction for an open string.

*gunky* (see e.g. Sider, 1993). As we'll see, this may be the right way to understand strings.

Greene's insistence that strings are uncuttable is echoed by Callender's complaint that metaphysicians who think strings must be made of point-sized simples "*must posit strange new laws to ensure that the simples stay together in stringy configurations.*" (Callender, 2011, 39) Callender seems to be praising by contrast a picture on which strings stay together because they have no parts, and there is nothing more to say. But this is curious, because strings do not always stay together, and the process by which they separate into parts is an important aspect of interacting string theory.

As noted above, strings can sometimes join together at the ends (or also in the middle). The reverse process is also possible–it has to be, since the theory is time-reversal invariant. Figure 2 shows a worldsheet diagram for the simplest sort of splitting interaction, in which an open string divides into two strings.[2] This process has all the hallmarks of a composite object breaking in two; for example, the lengths of the two outgoing strings sum to equal the length of the original string (West, 2012, 657). Isn't this exactly the sort of behavior that leads us to believe everyday objects have parts?

A view like Callender's could perhaps be motivated if there were "basic" strings which could not split, but could only interact by joining. Then we could say that the basic strings are simples, and other strings are composed of them. But in fact there are no basic strings

[2]There are other relevantly similar interactions with more useful physical applications; for example, when an open string crosses itself at some point and "pinches off" into a closed string and an open string.

in this sense. Every string is capable of splitting. So contrary to Callender's accusation, *everyone* will need to posit laws to determine when strings stay together–and when they break apart. String theory itself describes these laws.

One interaction that *is* impossible is a point-sized bit splitting off from a string. The products of a splitting interaction must all themselves be strings. This may suggest that strings lack point-sized parts, but are made up of smaller and smaller strings–in effect, that strings are gunky. But there is a deeper problem with all of this literal discussion of strings and their parts, namely that it ignores the problem of interpreting quantum string theory to overcome the measurement problem. Most likely the ontological picture of classical string theory will need to be replaced with something quite different, just as the ontological picture of classical particle mechanics is arguably untenable when we move to quantum mechanics.

In quantum string theory, remember, the states are not strings but superpositions of strings in different configurations. The measurement problem for string theory will be much the same as it was for quantum mechanics. When an observable quantity in string theory is measured in a state where different values of that quantity are superposed, the measuring device, observer, etc. will end up in a superposition of registering different measurement results. The need thus arises for an interpretation to explain why we don't see these macroscopic superpositions. What sort of interpretation might succeed is anybody's guess, but if the state of play in quantum mechanics is any indication, successful interpretations are unlikely to preserve the ontology of classical string theory.

Think of what happens when we set out to solve the measurement problem in quantum mechanics. Starting with the quantum version of a classical theory of particles, we end up mostly with interpretations (like many-worlds and collapse interpretations) that count the quantum state $|\psi\rangle$ as the fundamental stuff. The main exception is Bohmian mechanics, which does include particles, but for this theory to succeed a preferred frame must exist, in contradiction with the most straightforward understanding of relativity theory. Perhaps a future Bohmian string theory will similarly include strings as fundamental objects; but it will likely have similar disadvantages, which may become even worse in the context of quantum gravity. At a guess, the state realism of Wallace and Timpson (2010) is most likely to remain nearly unchanged in the transition to string theory, since it will probably still be possible to assign string-theoretic states to spacetime regions, which is all that state realism requires to get off the ground. But then the ontology of string theory will remain much the same as the ontology of quantum field theory on this picture: a highly structured field of local but non-separable quantities. No strings involved, at the fundamental level.

Speaking of the fundamental level, it is worth keeping in mind that string theory is generally agreed to be a non-fundamental theory these days. The real candidate for a fundamental theory is M-theory. M-theory is thought to describe two- and five-dimensional branes. Since these can split like strings, they are not good candidates for extended simples either. It is not even entirely settled that M-theory will be a theory of branes. On one proposal, M-theory is an ordinary quantum field theory on 11-dimensional spacetime (Hořava, 1999). In that case the fundamental entities will be fields on spacetime, which are clearly not extended simples. Moreover, M-theory will face the measurement problem in the same way as string theory, so the fundamental entities in a successful interpretation of M-theory may not be branes at all.

# 4 Quantized space?

So perhaps strings are not good candidates for the coveted title of Extended Simple. The string-theoretic concept of space may provide a better candidate. At least it is sometimes suggested that space is quantized, in the sense that the concept of space (and time?) breaks down below some very tiny scale of distance (Gross and Mende, 1988, 407). That sounds an awful lot like the claim that there are smallest-sized extended regions of space. If those had parts, the parts would presumably be even smaller-sized regions, which is impossible. So the minimum-sized regions must be simples. And they are, of course, extended.

Braddon-Mitchell and Miller (2006) have offered this sort of argument for extended simples:

> Here, then, is the physical hypothesis about our world that we will consider. Our world contains objects–little two-dimensional squares–that are Planck length by Planck length...
>
> We agree that you can... divide the square, in the sense of being able, conceptually, to divide it using the relevant metric. But does this mean that there is any robust sense in which it has spatial parts? Now, there are disagreements as to exactly what it takes for something to count as a proper mereological spatial part of something else. But, plausibly, it is at least *necessary* that a proper spatial

> part is an object that occupies a region of space that is a sub-region occupied by the whole...
>
> But if proper parts occupy sub-regions of space occupied by the whole, then we have good reason to suppose that given the actual physics of space-time, our Planck square has no such parts. For physicists tell us that we cannot divide space into any finer-grained regions than those constituted by Planck squares. (Braddon-Mitchell and Miller, 2006, 223-224)

They go on to cite several string theory publications (Gross and Mende, 1988; Amati *et al.*, 1989; Greene, 1999) along with Rovelli and Smolin (1995). (Rovelli and Smolin are concerned with space in loop quantum gravity, a competitor to string theory, so their results don't bear on our question about string theory.[3]) I'll begin this section by showing that none of the string theory publications Braddon-Mitchell and Miller cite support their contention about minimum-sized spatial regions. Afterward I'll explain why string theory, from what we can tell at present, requires that there are no minimum-sized regions.

Gross and Mende do begin their paper with a sort of money quote: "It is widely believed that when string theory, or any other consistent theory of quantum gravity, is explored at the scale of the Planck length fundamentally new physics will emerge. Perhaps spacetime itself will lose its meaning at very short distances, to be replaced by something else." (Gross and Mende, 1988, 407) But from that point on they leave the question hanging, and go on to discuss the scattering theory of strings at high energies, in effect exploring the short-distance behavior of interactions between strings. None of their actual conclusions have anything to do with the possible breakdown of space or spacetime below the Planck scale.

Amati *et al.* (1989) investigate a question more closely related to the quantization of space: whether distances shorter than the characteristic length of a string can be measured. They argue that this is impossible, and the smallest measurable distance is of the same order of magnitude as the string length. But this provides an argument that smaller spatial regions are physically meaningless only if we commit ourselves to an empiricism austere enough to

[3] There does seem to be a much stronger case for quantized space in loop quantum gravity. Since the minimum-sized regions of that theory are formed from configurations of non-spatiotemporal objects called spin networks, it may be inaccurate to describe the regions as mereological simples, however. See Huggett and Wütrich (2013, 279-280). It is also worth noting that loop quantum gravity is widely regarded as a less successful research program than string theory.

verge on positivism. If we allow for the existence of undetectable things, there is nothing in the work of Amati *et al.* that entails a minimum size for spatial regions.

Greene (2004, 477-481) presents a more interesting argument, and also provides the most direct inspiration for Braddon-Mitchell and Miller's proposal. Greene's argument rests on a demand for an explanation of the Bekenstein-Hawking formula which tells us that a black hole's entropy is proportional to the surface area of its event horizon. Greene illustrates this visually by saying that a "black hole's entropy equals the number of [Planck-length-by-Planck-length] squares that can fit on its surface. It's hard to miss the conclusion to which this result strongly hints: each Planck length is a minimal, fundamental unit of space, and each carries a minimal, fundamental unit of entropy."(Greene, 2004, 480) This goes a bit beyond what the Bekenstein-Hawking formula entails, though, in implying that there must be a minimum unit of area or entropy. The formula itself says only that the entropy is proportional to the area. It does not itself rule out, for example, the possibility of a black hole whose horizon has an area of half a square Planck length, or a third, etc.

So where does Greene get the idea that there must be minimum units of area? He seems to be gesturing at a form of argument surveyed by Wald (1994, 175). The idea is that the relationship between a black hole's entropy and its area is mysterious: why should the entropy be proportional to the area? Ordinarily we think of an object's entropy as the logarithm of the number of physical states available to the object. Thus the mystery disappears if we assume that there are a finite number of physical states possible for the black hole for each unit of its horizon's area. As Wald explains, this would make sense if the black hole's degrees of freedom (the physical quantities specifying its state) were distributed over the surface of its horizon, and if there were finitely many of them for each square Planck length of the horizon's area. As Greene puts it, "The theory should be so tightly in tune with nature that its maximum capacity of keep track of disorder (entropy) *exactly* equals the maximum disorder a region can possibly contain," and black holes have the maximum possible entropy for their volume (Greene, 2004, 481).

Suppose for the moment that this black hole entropy argument succeeds. Does it show, as Braddon-Mitchell and Miller suggest, that reality is built up out of Planck-sized squares? No; in fact it would seem not to fit with that conclusion at all. Greene uses the device of Planck squares somewhat imprecisely to illustrate the relationship between a black hole's entropy and its area. But in fact, an event horizon is spherical, and no spherical surface can literally be divided into square-shaped pieces. Indeed, the argument implies that the smallest possible region is the same size as the smallest possible black hole, which (if Greene is right) means a spherical region whose surface area is one square Planck length. In general there is no single shape for a Planck-sized surface that could be combined to cover the event horizon of every possible black hole. So it seems clear that Greene's talk of Planck squares was not meant literally.

That said, the black hole entropy argument deserves a bit of scrutiny. There is something to the argument, but to call it decisive would certainly be an overstatement. There may be other possible explanations for the relationship between a black hole's horizon area and its entropy. And a different explanation would be preferable for physical reasons, since the proposed one seems to treat the event horizon as a special sort of physical object, which does not fit with our ordinary understanding of horizons (Wald, 1994, 175). In general relativity a horizon is just a region of space surrounding the black hole which cannot be crossed by outgoing light rays, due to gravitational curvature. The mass of the black hole does not itself exist at the horizon, but rather lives at its center.

As Greene notes, the proposal that the black hole's degrees of freedom live in its horizon can potentially be made sense of if we take seriously the notion of holographic duality. A *duality* is a sort of transformation that can relate two theories; theories which are dual to each other are usually taken to be physically equivalent. To explain holographic duality, think first of a sphere in three dimensions and the two-dimensional surface of that sphere. In string theorists' terms, the interior part of the sphere is called the *bulk* and the surface is called the *boundary.* According to a widely-accepted conjecture, many string theories are dual to field theories that take place on the boundary of the string theory's bulk spacetime. If this conjecture is true, the string-theoretic description of the physics within a given spherical region may be physically equivalent to some other theory describing a physics that takes place only on the region's surface. So this may provide a way of understanding how the behavior of a black hole could be understood purely in terms of degrees of freedom that exist on the surface of its event horizon (Greene, 2004, 482-485).

This may indeed be right. But if it *is* right, as Greene himself points out, it would seem to give us good reason to suppose that spacetime is really a sort of illusion, or at least an emergent but non-fundamental feature of reality. For if the holographic duality conjecture is true, this means that the physics of a three-dimensional space (the bulk) is completely equivalent to a different theory taking place in a two-dimensional space (the boundary).[4] According to the duality conjecture, these two "theories" are really just the same theory written in different mathematical notation. So it would seem that the dimension of space is an artifact of notation, and hence that space is unreal or non-fundamental. But this does not fit with Braddon-Mitchell and Miller's conclusion. On the contrary, I see no clear way to make sense of the notion of an extended simple if reality is not fundamentally spatiotemporal and there is no matter of physical fact that determines even the dimensionality of space. We will return to this problem in Section 4.2. For now, suffice it to say that the reasons Braddon-Mitchell and Miller cite for believing in Planck-sized squares are actually reasons to think that our spatial concepts fail to describe string-theoretic reality.

That said, Greene's assumption that duality entails physical equivalence is controversial. For example, the existence of a duality between theories does not entail that they are isomorphic (Teh, 2013, 301-304). In light of this, it may be that a different explanation for the entropy-area connection is needed. And indeed, despite this suggestive puzzle about black hole entropy, working string theorists have not generally taken steps toward representing spacetime as divided into minimum-sized parts.

So how does string theory actually represent spacetime? Although many confusing claims are made in the literature, the answer is pretty simple: all known physically realistic string theories are set on continuous spacetime. In particular, there are five consistent superstring theories which are considered physically realistic; each exists on a ten-dimensional manifold (Becker *et al.*, 2007, 8-9).[5] These are all thought to be low-energy limits of M-theory. Although many of its features are not yet well-understood, M-theory is thought to exist on an eleven-dimensional continuous spacetime (Becker *et al.*, 2007, 332).

There are complications with the string-theoretic picture of spacetime, but I don't think they do much to undermine the basic fact that realistic string theories live in continuous space. Still, it is worth seeing why the complications don't get in the way of continuity.

[4]Of course in realistic string theories (or M-theory), the actual dimension of the bulk would be ten (or eleven) and the boundary would be nine- or ten-dimensional.

[5]A manifold is a set of points with the same local structure as $\mathbb{R}^n$, which of course entails continuity.

## 4.1 Non-commutative geometry

The main complication is non-commutative geometry. There are many ways for spacetime to look unusual, in a quantum sort of way, at small length scales. One way is for Braddon-Mitchell and Miller's description to be accurate, and spacetime to break down into minimum-sized squares (or cubes, or something similar). None of the promising candidates for a fundamental theory that have come out of the string theory program so far have this feature. But another way for the classical picture of spacetime to break down has been explored extensively in the string theory program. This is the suggestion that different spatial dimensions might fail to commute–hence the name non-commutative geometry.

Non-commutative geometry is a difficult notion to describe precisely without a long technical digression; Huggett and Wütrich (2013, 281-282) strike a good balance of accessability and fidelity to the details. I will try to explain in a less detailed way. When two quantities in a quantum theory fail to commute, the main physical consequence of this is the existence of an uncertainty principle relating the two quantities. So for example, the failure of position and momentum to commute in quantum mechanics entails that no state can take on sharp values of both quantities. The sharper its predictions about position (that is, the lower the standard deviation of those predictions), the less sharp its predictions about momentum are allowed to be.

Non-commutative geometry rests on the idea that the different dimensions of space may fail to commute in this way. So for example, if distance along the $x$ axis and distance along the $y$ axis don't commute, there will be an uncertainty principle preventing sharp states of $x$-distance and $y$-distance. The spatial metric will become an unsharp quantity in such a theory, just as position and momentum are unsharp in quantum mechanics. Although in some cases non-commutative geometry can be represented on a manifold, this arguably does not provide the right physical interpretation of the phenomenon (Huggett and Wütrich, 2013, 282). It may be wrong to say that the structures described by non-commutative geometry deserve the name 'spacetime' at all. They are, however, indistinguishable from spacetime for practical purposes at large distance scales. In other words, the description of reality as spatiotemporal provides a good approximation to non-commutative geometry, but only in certain domains which the spacetime picture identifies as large distance scales. Moreover, the observable quantity in noncommutative geometry which corresponds (when its value is large) to spatial length has a smallest possible value (Martinetti *et al.*, 2012). In both these senses, non-commutative geometry may indeed describe the breakdown of spacetime at small distances.

But although non-commutative geometry has been widely explored by string theorists, they do not employ it in fundamental string theories. Instead, its physical relevance arises from the fact that, in certain limiting cases, string theories behave like quantum field theories on noncommutative geometries (Seiberg and Witten, 1999). For example, in some string theories the strings interact with a gauge field called a Kalb-Ramond B-field; physically, the idea is something like electrically charged strings moving under the influence of the electromagnetic field. These theories are well-approximated by noncommutative field theories when the strength of the B-field is great. But the string theories themselves exist on ordinary manifolds. So where noncommutative geometry is useful in string theory, it is only as an approximation to more fundamental string theories with ordinary geometry. So when we ask what spacetime is like, we may ask that question in the non-fundamental noncommutative field theories–in which case spacetime does seem to break down at short distances–or we may ask in the in more fundamental string theories, where spacetime does not break down. Obviously the more fundamental theory is the place to look if we're wondering about the spatial properties of fundamental objects like mereological simples.

So the usefulness of noncommutative geometry in string theory does not at present suggest that there are minimum-sized regions. Perhaps in the future fundamental string theories will themselves be formulated in noncommutative geometries, in which case they may lend some support to the notion of minimum-sized regions. But string theory does not seem to be heading in that direction as of now.

What if it does head in that direction in the future? Even then, I maintain we will not be compelled to accept the reality of extended simples. There are two reasons for this, one mathematical and the other one physical. First, the mathematical point: a spacetime with minimum distances need not be a spacetime with simple regions of minimum size. For such a spacetime could be composed of extensionless points, with the minimum length given by primitive relations of distance between the points. This is a very ordinary way of describing ordinary (commutative) discrete geometries. We treat them as lattices built from points, with a minimum distance between any two points. A minimum-sized region is then (assuming a square lattice) composed of the eight points forming the corners of the smallest possible cube. This picture leaves no room for extended spatial simples. Now, noncommutative geometry does not involve anything analogous to a classical picture involving minimum-sized cubes. But it is made up of objects which are the direct analogues of extensionless points.[6] So while there is a minimum length in noncommutative geometry, this does not equate to minimum-sized simple regions.

Second, the physical point. As Huggett and Wütrich point out, calling noncommutative geometry a picture of "spacetime" at all seems to stretch the concept past its breaking point. Noncommutative geometries are arguably an entirely new sort of possible physical background for field theories to exist in. At large scales they act like ordinary spacetimes, and at very small scales they exhibit the equivalent of minimum length. But it seems likely that the scale at which "spacetime" becomes a bad name for noncommutative geometry is larger than the minimum length they exhibit.

Let me explain. Call the noncommutative equivalent of spatial length *the L-observable.* For large values of the L-observable, this quantity is nearly indistinguishable from spatial length, and it is a good approximation to the truth to treat this quantity as if it *is* spatial length. But the L-observable is not spatial length, and at low values it does not behave much like spatial length at all. There is also a minimum value the L-observable can take on. Does this mean there is a minimum length in noncommutative geometry? Only at best as an approximation to the truth, and only if the L-observable's minimum value is large enough that the L-observable acts like spatial length until it reaches that minimum value. But in fact, the L-observable stops acting like spatial length when the difference between non-commutative geometry and ordinary geometry starts to make a physical difference–and the difference begins to appear at greater values of the L-observable than its minimum value.

Fine, one may reply–all that means is that the minimum-sized regions are the largest regions where the L-observable acts like spatial distance. But there is no unique size below which the L-observable stops behaving like spatial distance. Rather, as a matter of degree, the L-observable behaves less and less like spatial distance as its value gets smaller and smaller. When it stops approximating spatial distance well enough is a vague matter of fact at best, and probably also depends on which of its properties we are interested in. So to say that there are minimum spatial distances in noncommutative geometry because the L-observable has a minimum possible value is to distort the relationship between the L-

[6]These "points" are actually pure states on the noncommutative algebra of the geometry; see Doplicher *et al.* (1995, 188).

observable and spatial length (which is not itself a quantity that exists in noncommutative geometry, if Huggett and Wütrich are right).

## 4.2 Distance in string theory

One other complication arises in the string-theoretic picture of spacetime. This complication is due to another sort of duality relation between theories, like the holographic duality appealed to by Greene. This second sort of duality, $T$-duality, strongly suggests that spatial distance is not one of the fundamental properties in string theory.

Huggett and Wütrich (2013, 280-281) present an argument against fundamental distance in string theory, beginning from T-duality. As in the holographic case, the duality relation holds between superficially distinct string theories, and establishes that they are physically equivalent. In this case the theories connected by the duality are markedly different in their spatial distance properties. The duality applies to string theories with *compact* spatial dimensions: theories in which one or more spatial dimensions is limited in size in the same way as the circumference of a circle is. In such theories, when you start off in the direction of one of these compact dimensions, after traveling a distance equal to the radius of the compact dimension you will end up back where you started.

Call $R$ the radius of a given compact dimension in a given string theory. What T-duality shows is that this string theory is dual to another string theory whose compact dimension has radius $1/R$. So distance along the compact dimension is a quantity that varies when we transform our string theory to a physically equivalent theory. But it's not as if distance along the compact dimension is supposed to be a distinct sort of quantity from distance along other dimensions, any more than the distances along two orthogonal directions are different according to our ordinary understanding of space. So it would seem that spatial distance is not a physically significant quantity in string theory. If it were, it would not change when we transform between physically equivalent versions of the theory.

Huggett and Wütrich's argument bolsters Greene's earlier suggestion that the fundamental reality described by string theory is non-spatial. If this is correct–and in particular if Huggett and Wütrich are right that spatial distance is not a fundamental quantity in string theory–it is hard to see how to even make sense of the claim that string theory posits extended simples. For whatever simples the theory posits will lack any properties such as length or area, which depend on spatial distance for their definition. The concept of extension may simply fail to apply to the fundamental entities in string theory.

Ultimately, questions like this will have to be posed in the context of M-theory, and even more than string theory, M-theory remains an unknown quantity. But from where we stand now, the claim that string theory posits extended simples may not even make sense. And if it does make sense, there is very little evidence in its favor and plenty that counts against it.


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