String Theory: Theory of Strings

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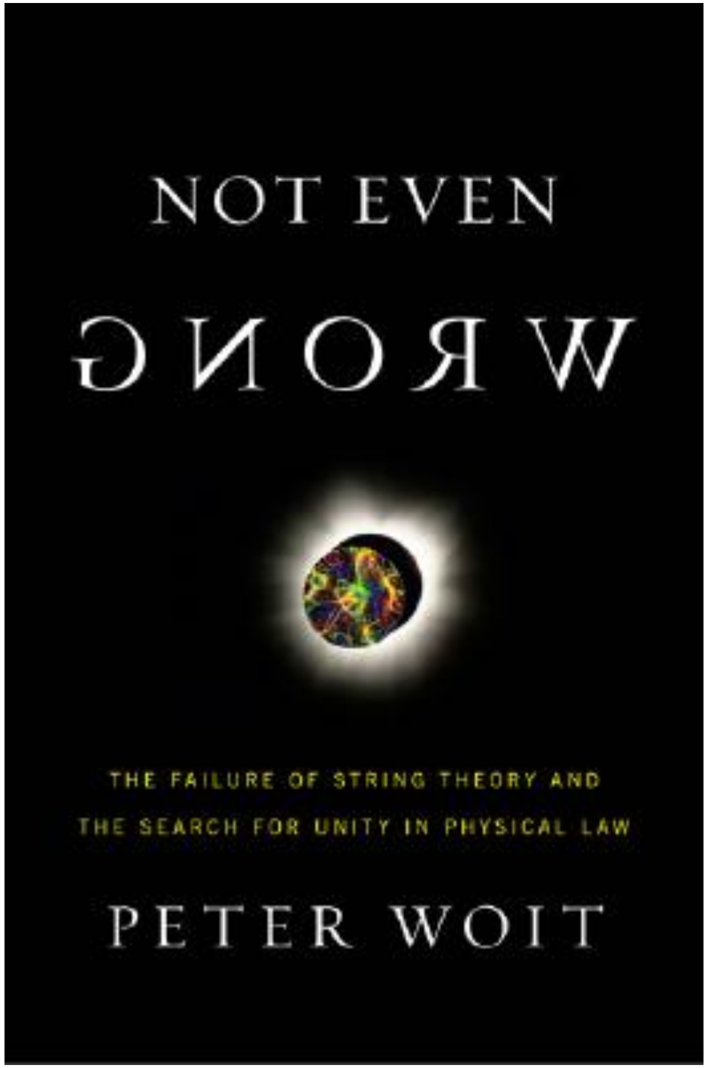
PsiStar, 1 November 2012

String theory has received **no love** recently:



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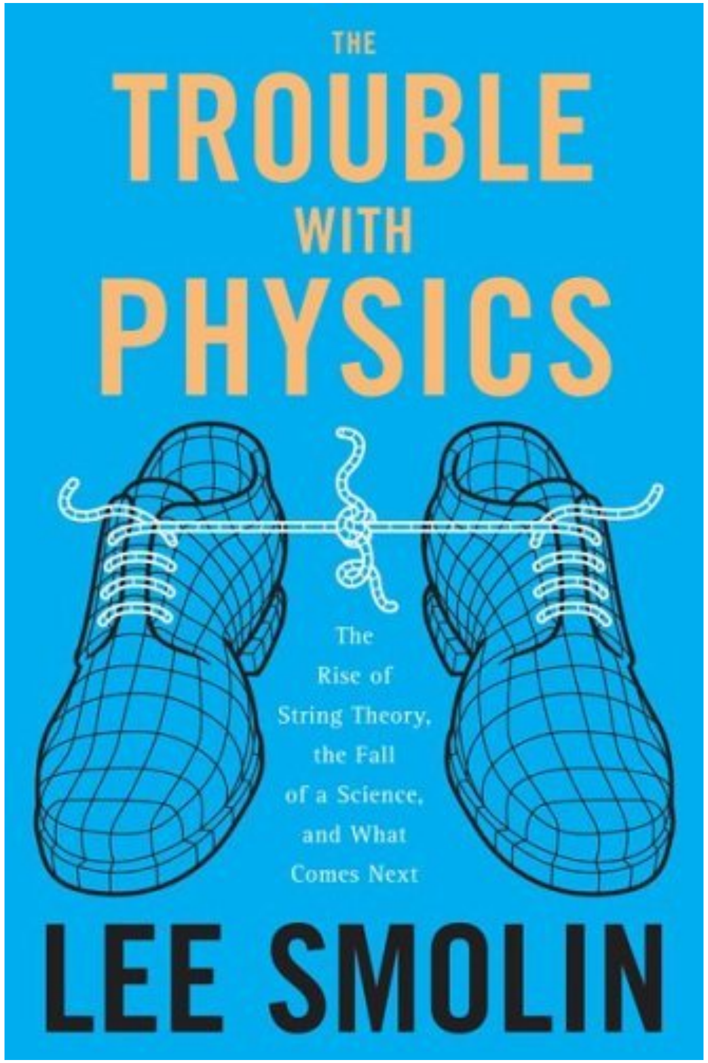
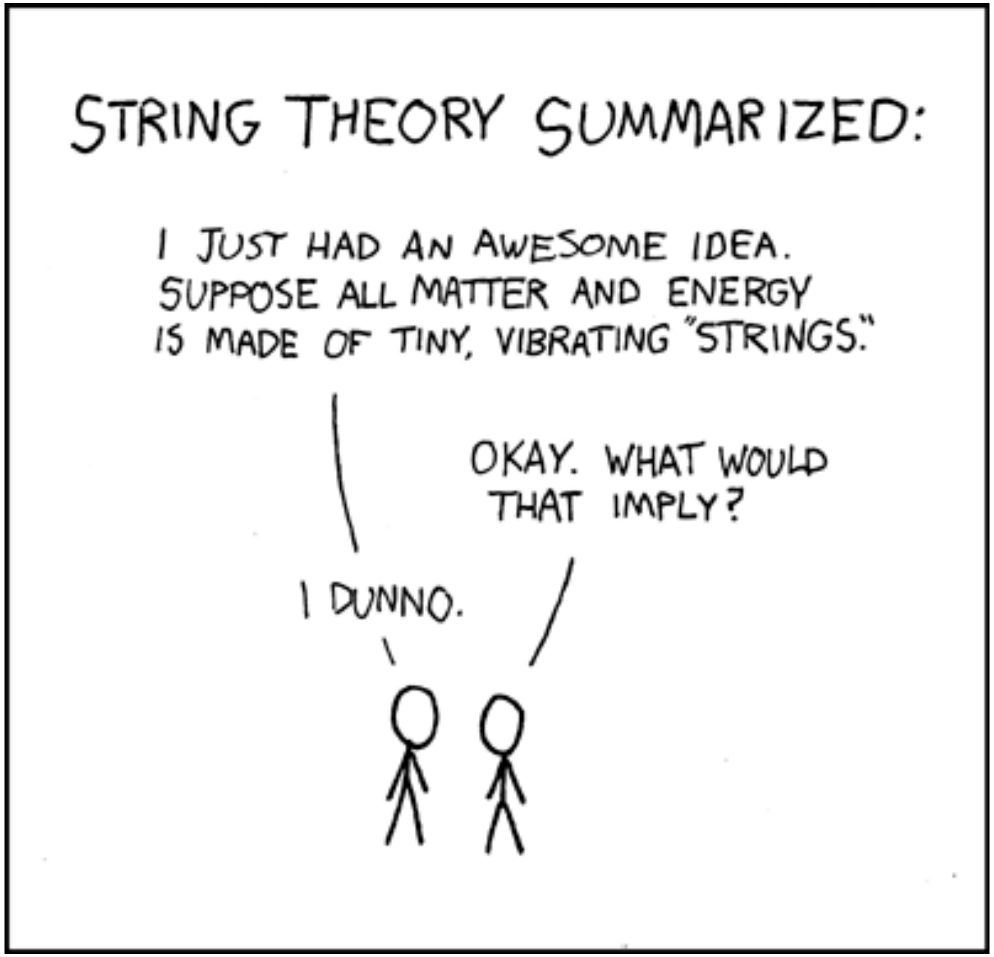



STRING THEORY SUMMARIZED:
I JUST HAD AN AWESOME IDEA. SUPPOSE ALL MATTER AND ENERGY IS MADE OF TINY, VIBRATING "STRINGS."
OKAY. WHAT WOULD THAT IMPLY?
I DUNNO.

xkcd

The New Yorker, January 8th, 2007

LOLcats

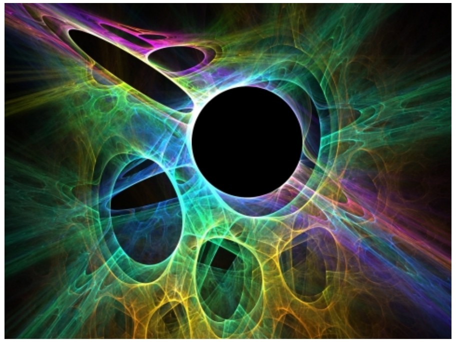
[sic]

Yet despite all this **negative** press, string theory continues to be an active area of research.

The goal of this lecture is to give you some idea of **what** string theory is, and **why** people continue to take it seriously despite all the vituperation directed at it.

But **before** I can do that, I need to give you some idea of how particle physicists see the universe.

LET'S GET STARTED!

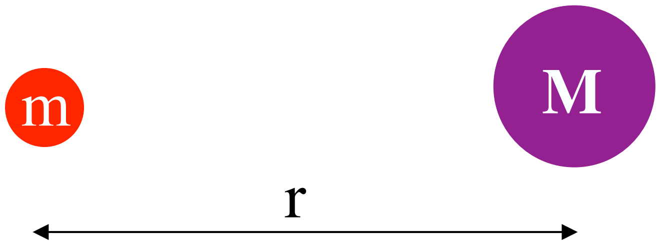


The Four Forces

We can explain everything in physics with four fundamental forces. Let's go through these one by one, in order of familiarity.

Gravity: Acts on all objects with mass, although you really only see one example of this every day: The Earth, and everything else!

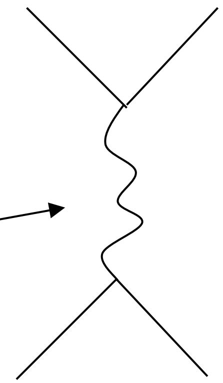
However, it' s true that **all** objects attract each other gravitationally.



$$F_{grav} = G\frac{mM}{r^2}$$

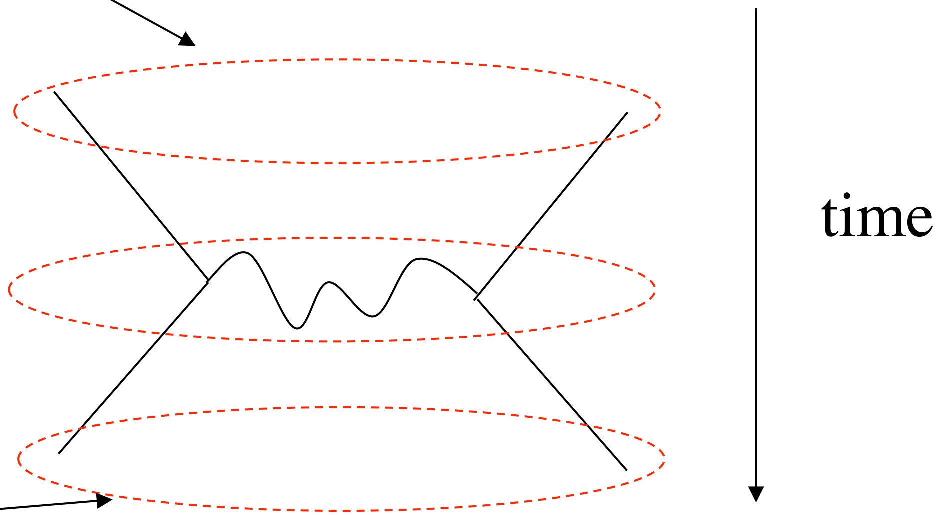
In particle physics, we describe the interactions by the exchange of a messenger particle, which is how the interacting objects know about each other.

Particle physicists talk about these interactions through **Feynman diagrams**



Particles come in

They exchange a graviton (talk)



Particles go out

All forces can be summarized by saying what's interacting and what the messenger particle is!

The other three forces:

Electromagnetism: Acts on all objects with **charge** (electrons, protons, etc.) and is mediated by the **photon**. This is responsible for more or less everything you see every day.

Strong Force: Acts on **quarks**, and things made up of quarks (a proton is made up of three quarks); the messenger particle is the **gluon**. This is what keeps the stuff inside the nucleus of an atom from breaking apart.

Weak Force: Acts on **leptons (e.g. electrons, neutrinos) and quarks**; the messenger particles are the **W and Z**. This is a nuclear force that's reponsible for certain decays.

And that's it! Let's summarize:

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

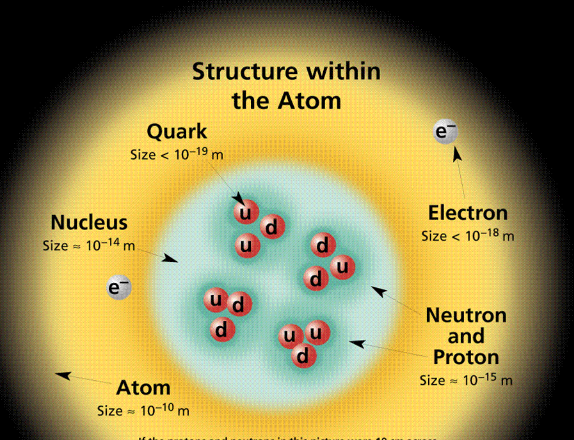
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

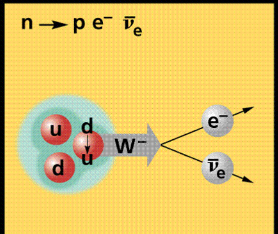
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

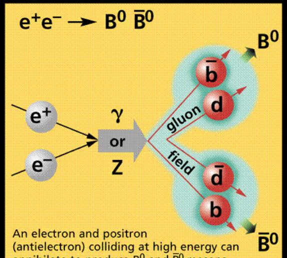
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

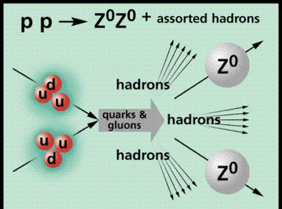
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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"The Standard Model"

viewed as the exchange of mesons

PROPERTIES OF THE INTERACTIONS

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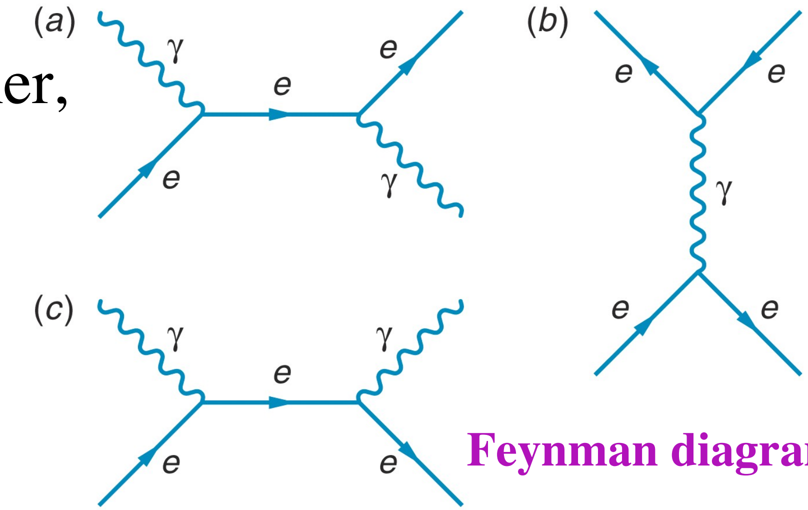
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

However, this chart is somewhat deceptive.

There's a major problem here!

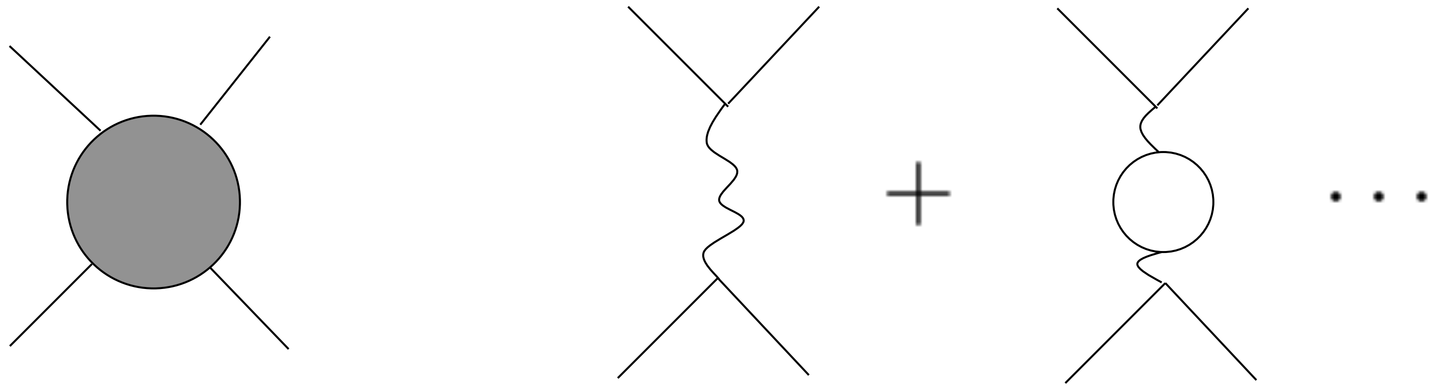
The Problem With Gravity

For particles scattering off one another, one must compute amplitudes:



But you need to sum over all the different ways this can happen!

Feynman diagrams



probability of two particles scattering off each other = ways of doing it like this + ways of doing it like this + . . .

Sometimes, these diagrams give infinite probabilities!
This is bad – you can't even have probability > 1.

Can fix it = **Renormalizable**

Can't fix it = **Non-renormalizable**

Gravity is **NON-RENORMALIZABLE**:
There's no way to sensibly describe it using this language!

The problem comes from scatterings which happen
at **very short distances** – these contribute big numbers.

We need to describe quantum gravity without getting infinities.

Quantum Gravity

The problems with gravity all come from quantum effects, where stuff blows up. Can we find a consistent quantum theory?

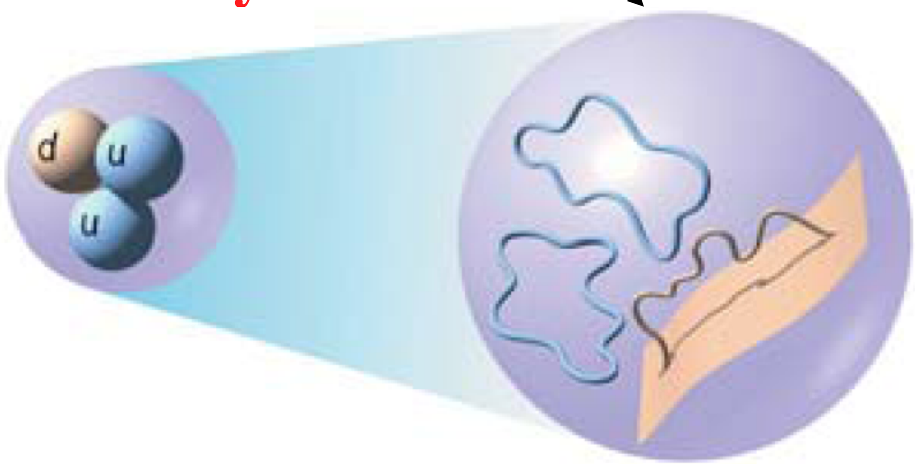
It's difficult!

Options: 1) String Theory

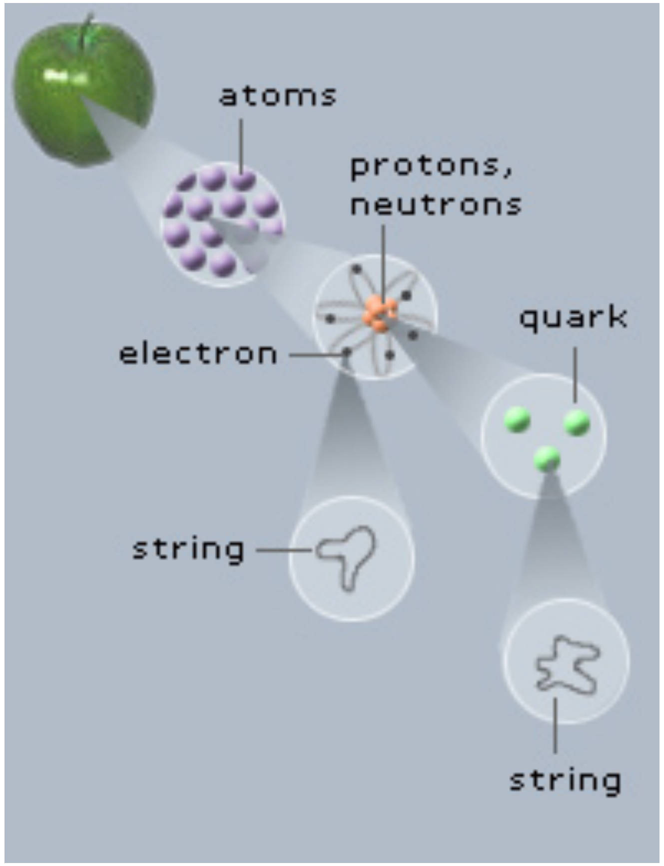
2) Loop Quantum Gravity

3) ????

4) Give up!



String Theory: The Best Theory EVER



The idea behind **String Theory** is simple: The fundamental constituents of nature are not point particles, but strings.

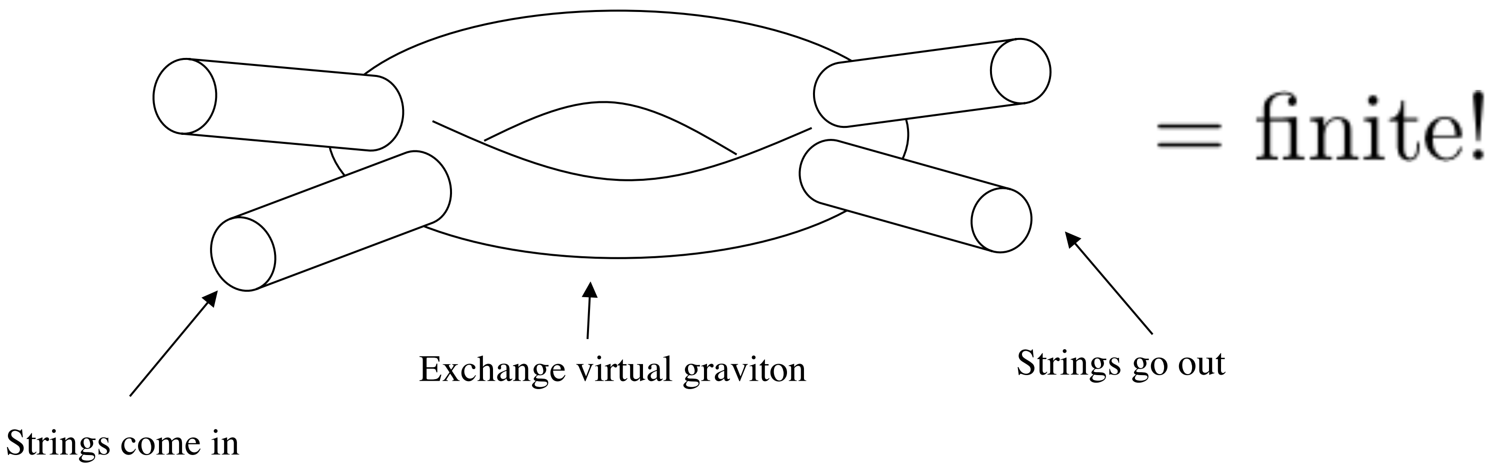
In order to see the stringy structure, you need to do experiments to see distance scales of (around) 10^{-34} m!

So no direct tests are possible, yet. (Or really probably ever.)

How does string theory help solve our **gravity problem?**

Remember, **infinities** in gravity come from very high energy (short distance) processes. String theory basically gets rid of these processes by saying that below some length scale, you should do **string Feynman diagrams** instead!

These string Feynman diagrams do **NOT** diverge.



String Theory is Awesome!!!

The Equation That Started It All

info about universe

spacetime coordinate

$$S_{string} = \frac{1}{4\pi\alpha'} \int d^2z\, \partial X^{\mu} \bar{\partial} X^{\nu} G_{\mu\nu}$$

string tension

Area of surface swept out by string

So what's the big problem? Why doesn't EVERYONE love String Theory?

1) String theories must be 10 dimensional

9 space, 1 time. That's a lot!

2) It is very difficult to get the Standard Model

Usually, you get too many particles.

3) Not really testable (yet?)

Need super high energies!

4) Consistent with many different universes

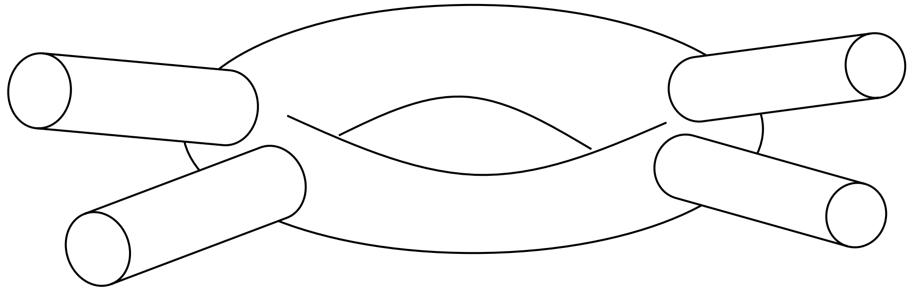
String theory appears to predict a large number of possible parameters.

5) They're just jealous ("fundamental envy")

OK, so what's the **good** stuff?

1. It is a theory of quantum gravity.

Stringy Feynman diagrams are finite. This is **major**! We should take any quantum theory of gravity very seriously, since it is so difficult to engineer one.



2. String Theory predicts supersymmetry (SUSY).

Supersymmetry is the most promising candidate for physics beyond the Standard Model, **explaining** many puzzling aspects of particle physics. But this might not be such a good thing – so far there's no direct evidence of it!

3. String Theory has lead to a ridiculous number of advances in our understanding of math.

Often, results that seem **obvious** in physics are highly **nontrivial** in math. String Theory and supersymmetry have led the way towards tons of new results in math.

4. String Theory has helped us understand difficult puzzles in otherwise difficult Quantum Field Theory problems.

It turns out that there is an **exact** equivalence between a **ten-dimensional** string theory and a **four-dimensional** particle theory. Using this correspondence, we have made progress in understanding theories like QCD.

5. It's fun, in the way that hard math is fun.

Is String Theory really correct?

Who knows? Even if it's not really a theory of physics, we've still learned a lot along the way about many different things.

Science is a creative process – not just memorizing facts!

String theory and its offshoots have brought about some very interesting results in both mathematics and physics, but we **must be honest.**

100 years ago, people **never** would have guessed the progress made during the 20th century. Similarly, we probably can't yet imagine what (or how) people will be thinking 100 years from now – but that shouldn't keep us from trying.

My Personal Opinion

(Not necessarily endorsed by QMUL)

String theory will probably **never** live up to its original promise.

Said another way, I doubt we'll ever really be able to show that it **predicts** our universe, or indeed many of the properties that we'd like it to (particle masses, number of dimensions, etc.)

I think the future of string theory is that it will become more like a **tool**, something we use to understand hard QFT problems.

But there will probably **always** be some people that are trying to understand the mathematical underpinnings. This is like what happened to Quantum Field Theory!

And that's not a bad thing.

Questions?

Feel free to ask me now, or stop by my office (GO Jones 225).

THANKS!