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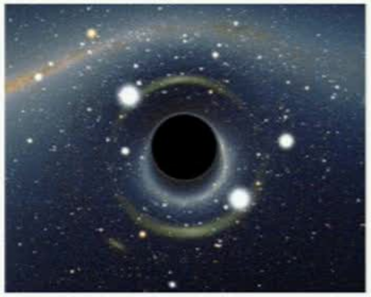
Abstract: <p>Amanda Peet, University of Toronto and Perimeter Institute
String Theory LEGOs for Black Holes
Perimeter Institute Public Lecture
WEDNESDAY, May 6 at 7:00 pm
Mike Lazaridis Theatre of Ideas
Perimeter Institute
31 Caroline St. N., Waterloo</p>

<p><a
href="https://prod5.agileticketing.net/WebSales/pages/info.aspx?evtinfo=41086~b872f9ab-a60c-4e69-a7ff-845da8df201e&epguid=20a1ea4d-8346-4280-93a3-1fa6988560e0&">Tickets available online on Monday, April 20 at 9:00 am.</p>

My research interests

- Ever since I was a little kid growing up in Aotearoa (NZ), I have looked at the world through scientist eyes.
- 25 years ago I moved to America do to my PhD. At Stanford I got really interested in two subjects: (a) string theory and (b) black holes, which can form in our universe when very massive stars run out of gas and undergo runaway gravitational collapse.



- Black holes are fascinating because they pose deep questions about how quantum physics and the force of gravity work together.
- My goals for tonight are to explain
  (a) the basic idea of string theory and why we bother with it,
  (b) why we need it to investigate black hole physics,
  (c) why its toolkit is so amazingly versatile and powerful.

- Style note: I will try to keep this **humble** and **accessible**.
  I am here tonight because I *dared* myself to explain my rather abstract theoretical physics research to the lay public.

Building UniverseOS with string theory

Nature of physics

- Our basic drive is to find interesting systems, poke them, and see what happens.
- For much of the 20th century, most physicists classified themselves as either experimentalists or theorists. In the 21st century, physics is more like a holy trinity of effort. Physicists
  1. measure the physics in a laboratory (experiment);
  2. model the physics with mathematics (theory);
  3. simulate the physics on a computer (computation).

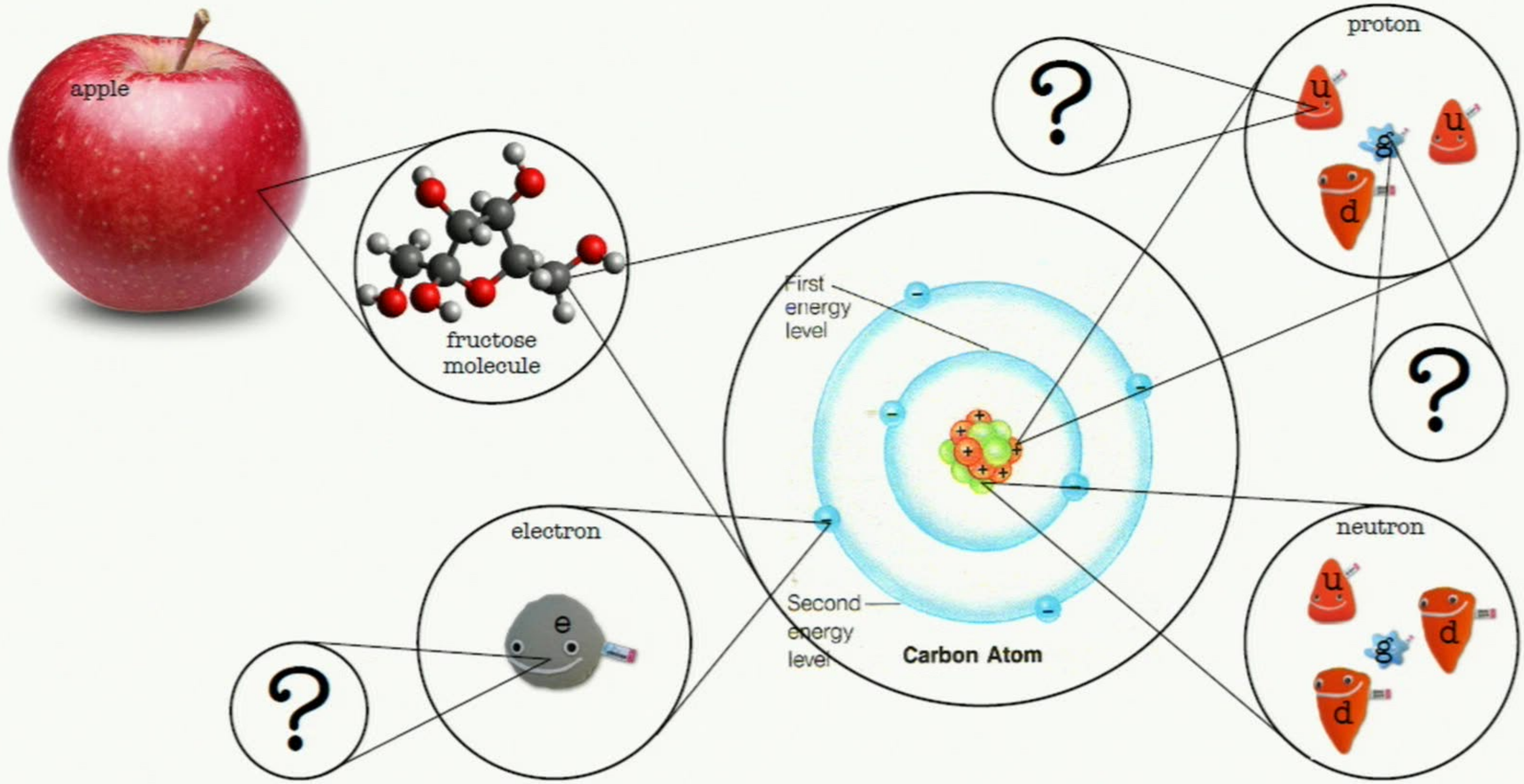
  I am in the second category.

- String theorists like me want to explain the structure and origin of particles, forces, and spacetime, all the way from subatomic to cosmological scales. In other words, we dare to seek the operating system of the entire universe at once – not just a killer app!
- What **dynamic range** is involved? So big it pushes the limits of human imagination: about sixty powers of ten (10^{-33}cm to 10^{+28}cm). In musical terms, this would correspond to ranging over about 200 octaves. For comparison: the Guinness world record for vocal range is 10 octaves.

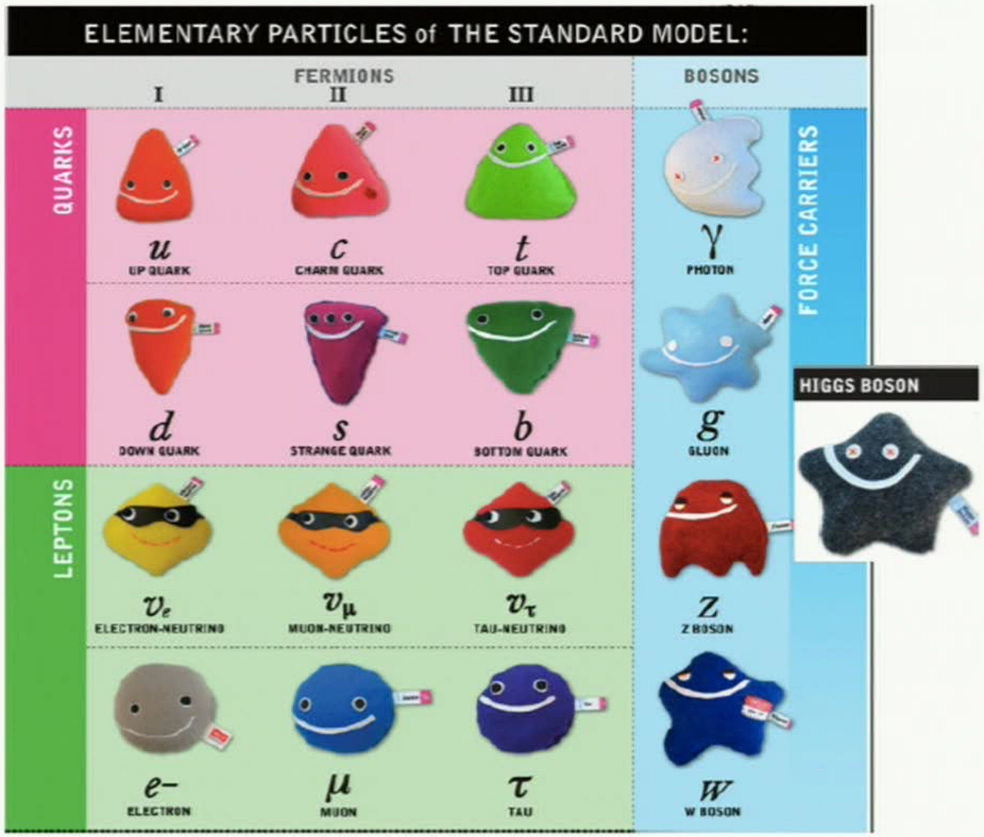
Size does matter

- Humans are optimized for mm to km distance scales. If we want to go smaller or larger, we need microscopes or telescopes, like the Large Hadron Collider near Geneva or the Hubble space telescope in orbit.
- Old science joke: sociology is just applied psychology, psychology is just applied biology, biology is just applied chemistry, and chemistry is just applied physics. Real moral of the story: different tools are appropriate to different length scales – e.g. societies, mitochondria, or Higgs bosons.
- Building a theory is a bit like wiring up a mixer. Dials and sliders on your dashboard indicate how strongly the various components interact; physicists call them **couplings**.

Subatomic structure



Elementary particles



- How do we distinguish between different subatomic particles?
  All observers agree on 3 things:-

1. rest **mass**, which stays fixed regardless of energy/momentum;
2. intrinsic **spin**, which cannot be removed from a particle without changing its identity;
3. **charges**, if any, e.g. electric.

- Spin can be integer (*bosons*) or half-integer (*fermions*). Force messengers are bosons while matter is made of fermions.

String as LEGO

- When we learn about atoms and molecules in school, we are taught that the fundamental constituents of everything are elementary *particles*. The key feature of a particle is that it is pointlike – structureless.
- But what experimental evidence do we have that electrons and quarks are actually pointlike? Even the LHC, humanity's most powerful machine yet, can only reach down to about 10^{-20}m. (If you blew up that LHC scale to my size, I would be nearly as big as the Milky Way.)
- String theory is a brilliantly simple idea: the LEGOs of the universe are tiny one-dimensional vibrating strands of energy known as *fundamental strings*. These strings are much smaller than the molecules in the macroscopic kind of string that a kitten plays with.

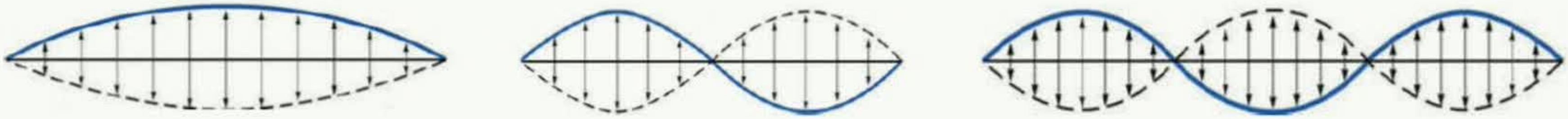
- Key feature of strings is their **versatility**: they can vibrate in different ways corresponding to different subatomic particles. In this sense, string theory is a symphony of Nature. ♪ ♫

Force unification

- How can a string possibly represent a particle? Easy peasy. Move far away from the string and take your glasses off. At low resolution, a string looks just like a particle would.
- String theory contains two types of strings: **open strings** with ends (kinda like a jump rope) and **closed strings** without ends (kinda like a rubber band).
- The lowest mode of vibration of an open string, called the *groundstate*, has zero mass and spin 1. These are the vital statistics of
  1. photons that transmit the electromagnetic force;
  2. gluons that transmit the strong nuclear force binding quarks inside protons and neutrons;
  3. W,Z bosons that transmit the weak nuclear force essential for powering nuclear fusion in stars.
- The groundstate of a closed string has zero mass and spin 2. These are the vital statistics of
  4. gravitons that transmit the gravity force.
- Unification of gravity with the other three forces was something Einstein dreamed of achieving. Unfortunately he did not live to see it.

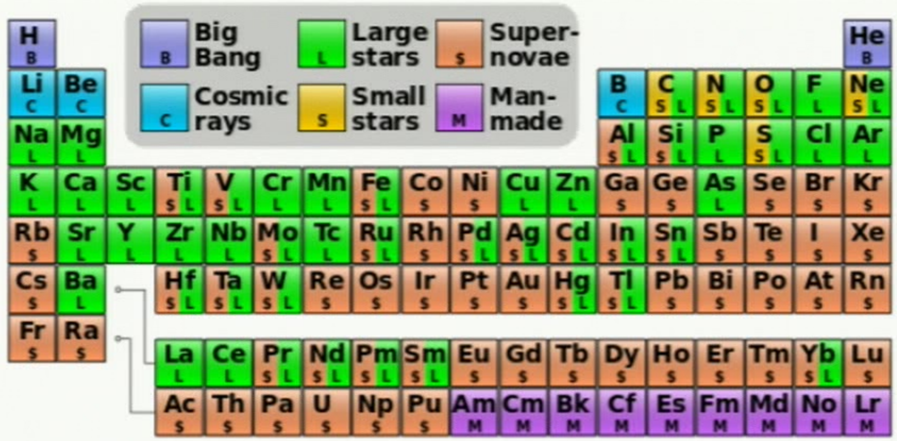
Prediction of gravity and extra dimensions

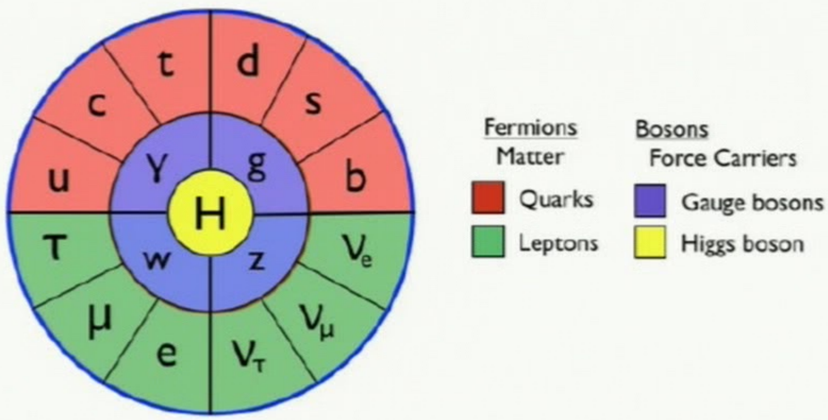
- The groundstate of a string corresponds to the lowest possible frequency produced by vibration in an organ pipe or a cello string. Excited states correspond to higher harmonics of the musical instrument, and they represent interacting particles with higher mass and spin.

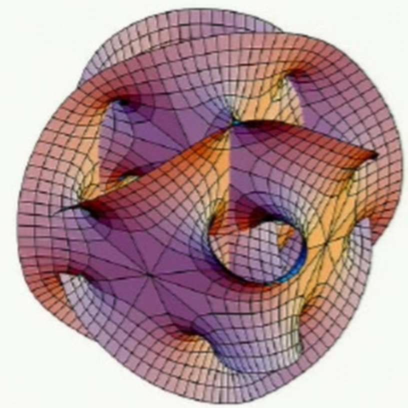


- Amazing feature: when you work out the quantum theory of strings, you **get gravity for free!** This does not impress most modern humans, because gravity was discovered centuries before string theory was. Had string theory been discovered first, it would be famous for having correctly predicted the existence of gravity and its inventors would probably have Nobel Prizes.
- String theory also predicts extra dimensions of space, tightly curled up and hidden from view. Strings, unlike particles, can *wrap* around them. This has profound consequences for spacetime.
- Superstring theory, with all its complicated moving parts, is capable of describing all the discovered subatomic particles in the Standard Model of particle physics – plus possible zoos of undiscovered ones as well. It unifies forces and matter. It even describes the emergence of spacetime itself.

Onion layers







Building Gravity 3.0

- So, is everything you thought you knew from high school wrong? No! Just *upgraded*.
- Newton built Gravity 1.0. For him, gravity was a force transmitted instantaneously across space.

  Key feature: unification of the terrestrial and celestial effects of gravity. It taught us enough to send humans to the Moon.
- Einstein built Gravity 2.0: General Relativity (GR). For him, gravity was the geometry of the smooth fabric of spacetime.

  Key feature: causality is baked into gravity. GR **superseded** Newtonian gravity: it could handle describing more experiments.

  Correspondence principle: when gravity is weak everywhere, and all speeds stay much slower than light, you get back Newton's theory.
- Various groups are working to build Gravity 3.0, i.e., quantum gravity. (Maybe our different pathways to quantum gravity will converge in the end.)

  String theory says **gravity is the lowest vibration mode of closed strings** and it also obeys the correspondence principle (✓). The string toolbox has proven especially fruitful in the past two decades.

Aesthetics

- Mathematics has proven itself as an unreasonably effective way of working with the laws of Nature. This is why it is the language of modern theoretical physics. Math influences our standards of beauty in physics, but it is *not* the final arbiter. Usefulness for describing the natural world is.
- Theoretical physicists studying interesting phenomena prefer to be able to *calculate* rather than just daydream about a topic. We like to have a model, even if it is not yet fully accurate or realistic.

- I use string theory in my research because it has **best ratio of features to bugs**. It is my LEGO set.

Hawking's black hole information puzzle

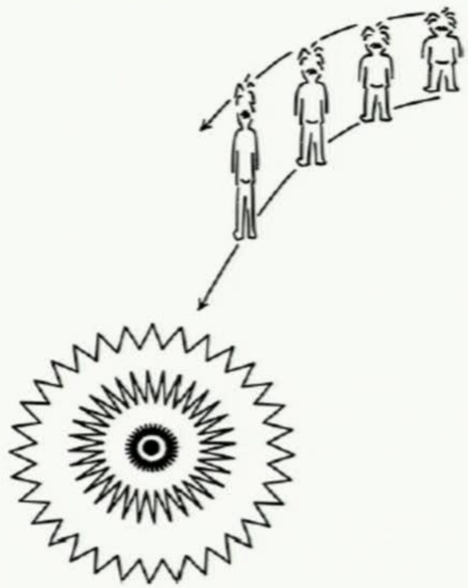
Anatomy of a BH: horizon

- Launch a satellite just right, and Earth's gravity will balance perfectly against speed and inertia. If too slow it would fall back to Earth; if too fast it would escape.
- Black holes have such strong gravity that, inside a certain radius from their centre, *nothing* can escape – not even light. Hence the name "black" hole. This surface of doom is known as the **event horizon**. If you get too close and fall inside, you can never escape, regardless of your rocket power.
- An object is called a black hole if it is dense enough to be contained within its own event horizon. Earth fails to qualify: it would have to fit inside a ping-pong ball to be a BH.

- If you replaced our sun by a sun-mass BH, our orbit would be exactly the same as it is right now. We would just not be getting any sunlight or warmth. The key is not to get too close.

Anatomy of a BH: singularity

- At the heart of a BH is the **singularity**, where the curvature of spacetime becomes infinite. Even nuclear forces are not strong enough to resist matter being shredded into fundamental constituents. For small enough BH, astronauts get shredded even before they cross the horizon.



- The violent singularity signals a serious internal problem with Einstein's theory of GR. Einstein's equations fall flat on their face, and can no longer predict any physics there. Instead they answer every question with "infinity". This is why we need quantum gravity.

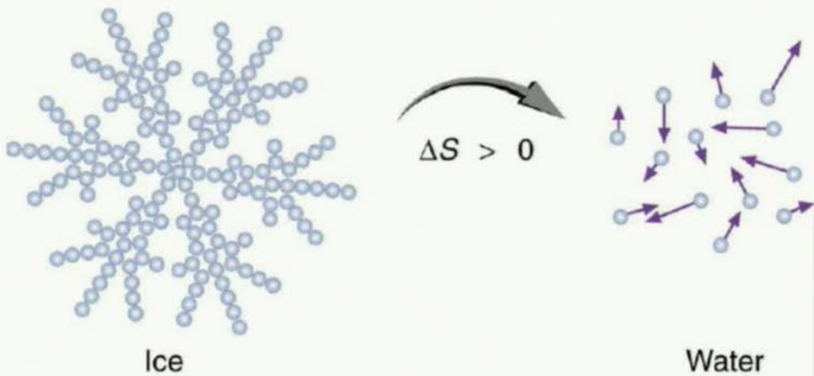
Hawking's BH information loss paradox

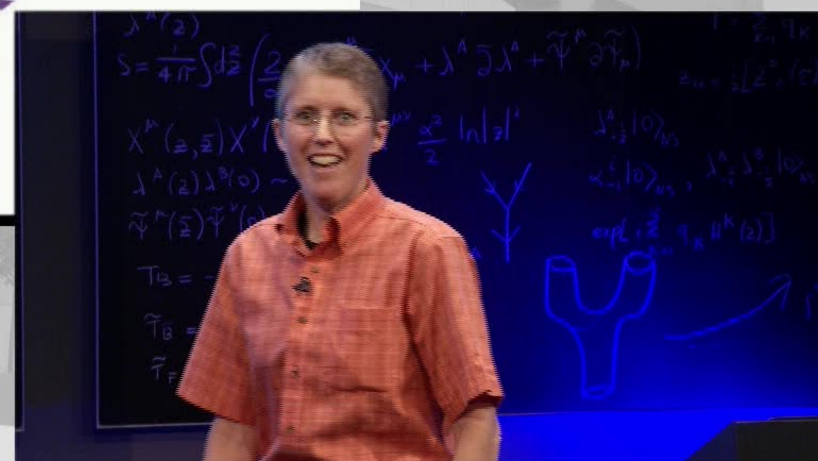
- Stephen Hawking went straight for the jugular in his research on BHs.
- In 4D, BH cannot have frills or bling. From outside the horizon, you can only know the mass M, spin J, and charges Q if it can have any. You remain ignorant of everything behind the horizon.
- Hawking proved something very surprising in 1974-75 by combining GR and quantum theory tools: black holes emit radiation. The Hawking temperature only knows about M, J, and Q. For real-world astrophysical BHs it is colder than the CMBR, but it still matters in principle.
- If you throw a 1kg book into a BH, you get out weak Hawking radiation. If you throw in a 1kg fish instead, H.radiation will be identical. It knows nothing about differences between books and fishes.

- Hawking realized this had profound implications: **black holes in GR lose information**. *Yikes!*

Thermodynamics

- Idea: since a BH has a temperature, it can be studied as a thermal system.
- In the 19th C, physicists invented *thermodynamics* to help figure out how to build more efficient engines. This toolset lets you describe a very large number of molecules in a gas in terms of just a few gross properties, like temperature, pressure, and energy density.
- **Entropy** S encodes the amount of energy that is wasted as heat in a thermodynamic process. Alternatively, it encodes the degree of disorder of a physical system. e.g.: a tidy bedroom has low entropy while a messy bedroom has high entropy. Or, in terms of H_2O molecules,





Entropy of BH

- 2nd Law of Thermodynamics: the entropy of a closed system never decreases with time. Perfectly efficient engines cannot exist. There is no such thing as a free lunch.
- For gases, if you know the quantum physics of one molecule, you can *derive* all the relevant thermodynamic properties.

  Ludwig Boltzmann discovered a formula for the entropy S in terms of the number of ways W a quantum system could be configured,

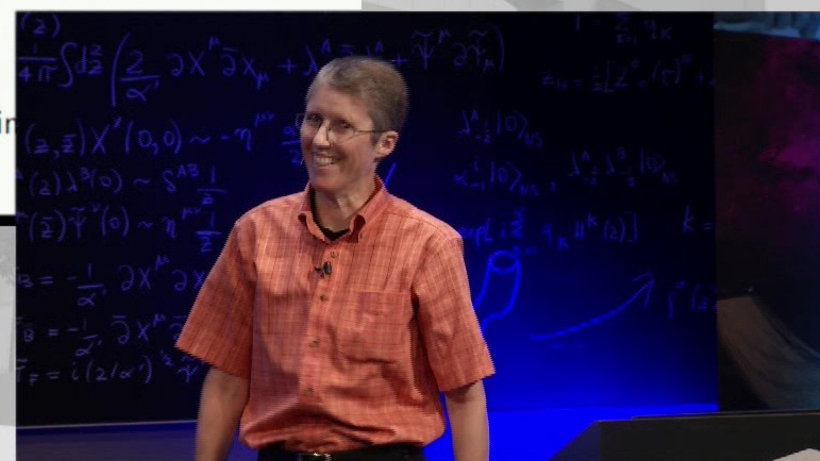
  $$S = k_B \log(W)\,.$$

  He was so in love with it he had it engraved on his tombstone!

- A century later, J.Bekenstein and S.Hawking found the thermodynamic **entropy of a black hole**

  $$S_{BH} = \frac{k_B c^3}{4 G_N \hbar} \times \textit{horizon area}\,.$$

  The BH entropy quantifies our ignorance about what lies behind the horizon.
- Researchers like me want to explain this entropy of BHs starting from first prin
  To find this holy grail, we need a working theory of quantum gravity.



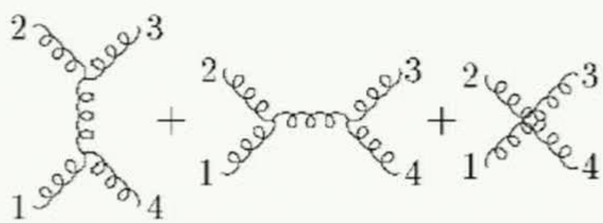
Clash of the 20th century titans: GR vs QM

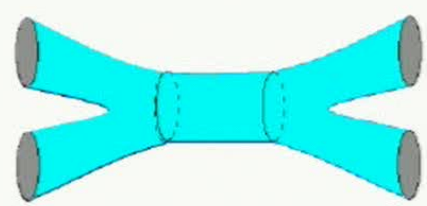
- General Relativity, born in 1916, is an exquisitely well tested theoretical description of very heavy things – like planets, stars, galaxies, even the cosmos.
- Quantum Mechanics, born in the 1920s, is an exquisitely well tested theoretical description of very small things – like molecules, atoms, quarks.
- Both GR and QM have nearly a century's worth of solid data backing them up.
- Unfortunately, GR and QM are fundamentally incompatible. GR is all about the smooth fabric of spacetime geometry, whereas QM has random jumpiness baked in. This is not just a minor niggle. It is a deep theoretical emergency – like having roads governed by incompatible traffic rules.

- Can we just sweep this under the rug? How about we let GR stick to governing heavy things, and let QM stick to governing small things, and pretend those Venn diagrams never overlap?
- Nope – there might be physical systems that are *both* heavy *and* small. There are two, in fact. The clash between GR and QM grows to epic proportions in **black holes and the big bang**.

How string theory merges GR and QM

- When building Gravity 3.0 we bring in biases about which concepts are more fundamental. GR/QM?
- Major features of quantum theory:-
  1. Energy comes only in discrete lumps (like integers) called *quanta*.
  2. Electrons, neutrons, etc. have wave-like behaviour – giving interference and diffraction. Quantum wavelength scales like 1/momentum, so more energy gives us better resolution.
  3. Physics at the microscopic level has a random jumpiness to it. This changed the way we think about determinism. What physicists can predict with precision is probabilities for various outcomes.
- Main symptom of GR's sickness as a quantum theory: at very short distance (very high energy), probability for scattering of gravitons grows to above 100%. This is obviously nonsense. Upshot: while GR is a mighty fine low-res theory of gravity, it is no good at high-res.
- String theory solves the clash by making a bigger tent. Doing QM of *strings* gives GR + upgrades.
- Particles are pointy. Strings are extended, softer objects. They interact by smoothly splitting or joining in a more spread-out way. This is the crux of how **string theory heals sicknesses of GR**.



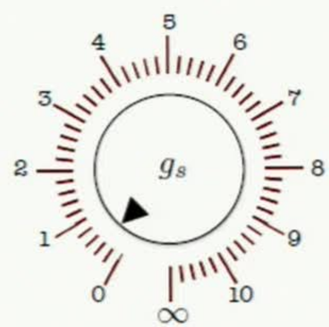


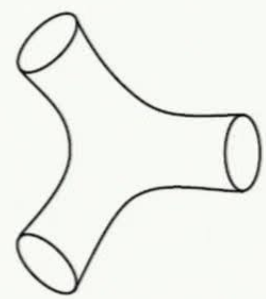
String theory basics

- We have already met the two basic types of strings, open and closed:-

or, in LEGO terms,

- Strings have a tension that sets the energy scales of string theory. Measure everything in these units. If you make the string vibrate more, that costs more energy.
- String theory has a basic parameter known as the **coupling**, denoted by g_s. This number controls the string interaction strength and the quantum probability of spontaneously emitting a string.

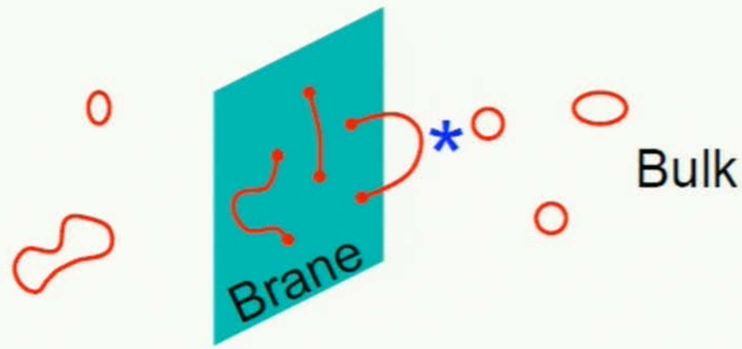




- We are best at doing calculations when g_s is small. (This story is called *perturbation theory.*) When g_s is large, this opens up the 11th dimension of M theory.

Branes

- In 1995 it was realized that there are more than just strings in string theory. There are also extended objects of various dimensions called (mem)**branes**. They fluctuate too, e.g. by bending.
  0. dimensional branes look like particles,
  1. dimensional branes look like strings,
  2. and higher dimensional branes look like generalized membranes – e.g. a trampoline.
- Branes arise in string theory as places where open strings end. This is enough to determine their dynamics entirely, starting from what we already know about strings. No extra input is required.

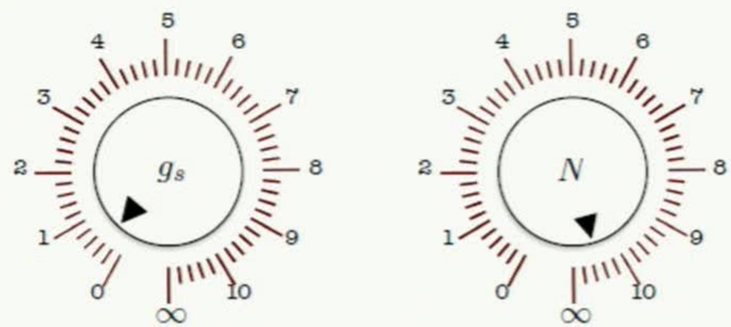


- In string units, brane tension is $1/g_s$. This means that when g_s is weak, branes are relatively heavy compared to fundamental strings. When g_s is strong, they are relatively light.

Brane warping of spacetime fabric

- Consider a system made of a whole stack of branes piled on top of one another.

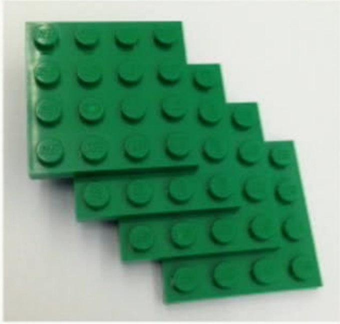
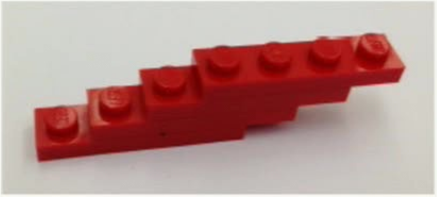
- How much do branes warp the fabric of spacetime? The answer depends on (a) how close you are to them, and on (b) the number $g_s N$, the string coupling g_s times the number of branes N. (This is like having a multiplicative sound mixer.)
- To keep good control of our string calculations, we needed to keep g_s small. But if we want a good amount of warping, we need $g_s N$ to be sizeable. We can have both as long as N is large.



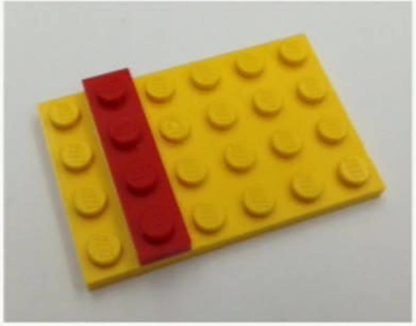
- So starting from string ingredients, we can build big fat spacetimes! We just need **lots of branes**.

Cooking BH with 1-branes and 5-branes

- A first-year graduate student can calculate forces between branes of various dimension.
- Branes of the same dimension that are parallel feel no attractive/repulsive forces from each other.

e.g.  or 

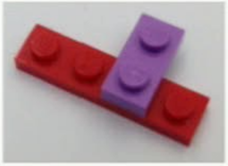
- Another no-force combination: a 5-brane along with a 1-brane parallel to one of its dimensions.



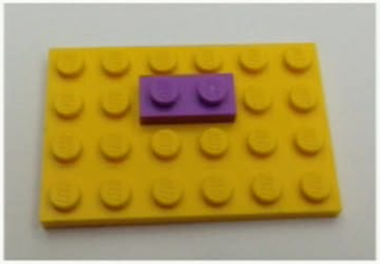
- This is useful because 1-branes and 5-branes carry two different types of charges, as well as mass.

Adding momentum

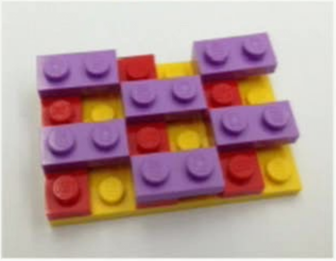
- Open-strings-with-momentum (purple) feel **no force** from 1-branes (red) parallel to momentum.



- Open-strings-with-momentum feel no force from 5-branes (yellow) parallel to momentum, either.



- Since red guys and yellow guys feel no force, and red guys and purple guys feel no force, and yellow guys and purple guys feel no force, we can safely combine all three together at once.



Wrapping up the branes and getting BH entropy

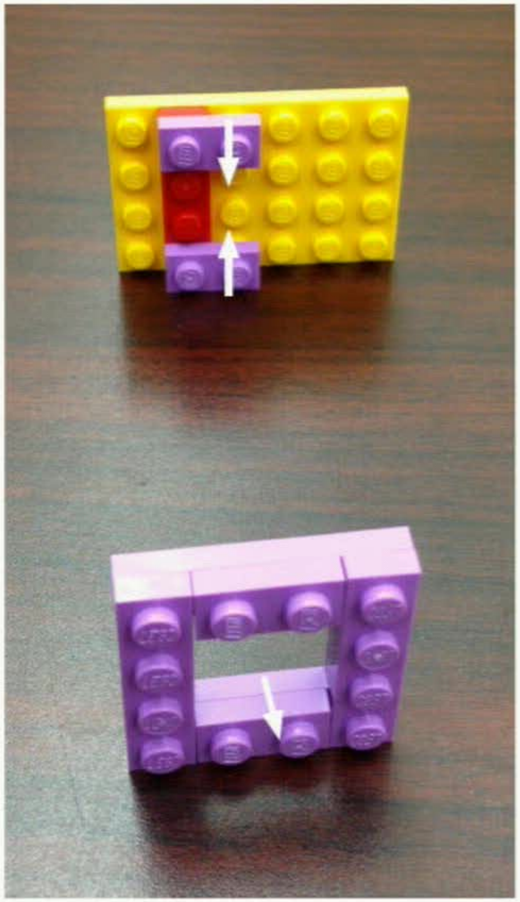
- BH are compact objects, not extended like branes. So to make a BH we have to **wrap** up any brane ingredients on small rolled-up dimensions of space.
  1. Wrap up the 5 dimensions of the 5-branes on five circles.
  2. Wrap up the 1 dimension of the 1-branes on one shared circle.
- Superstring theory lives in 10D. Rolling up 5D gives 5D left over for the resulting BH.

- Keeping the rolled-up dimensions tame requires care. Warping from branes tends to squeeze the spacetime fabric for directions parallel to them, and stretch it for directions perpendicular to them.
  1. For shared circle, 1-brane and 5-brane squeezing balances momentum stretching. ✓
  2. For other circles, squeezing from 5-branes balances stretching from 1-branes. ✓
- The resulting 5D black hole – carrying mass, and purple, red, yellow charges – was constructed by A.Strominger and C.Vafa in 1996. Famously, they calculated the entropy of the string/brane system using Boltzmann's formula and got *exactly* the Bekenstein-Hawking entropy,

$$S_{BH} = 2\pi\sqrt{N_m N_1 N_5}\,.$$

String Hawking radiation

- Our system was made from 5-branes, 1-branes, and momentum. You can sprinkle in a few open strings with momentum pointing in the *opposite* direction, which turns on a finite temperature, without appreciably disturbing the setup of the system.
- If opposite-momentum open strings meet the regular ones, then they can interact and join up their ends to make a closed string. Closed strings *can* escape from the branes, unlike open strings.
- These **escaped closed strings** were created according to the rules of string mechanics, which is very different from the toolset used by S.Hawking 40 years ago. Yet amazingly, they give the *same spectrum* of emitted radiation, even for spinning BH!
- This beautiful agreement of entropy and **Hawking radiation** spectra works for our 5D BH with purple, red, and yellow charges. It can also be done for 4D BH with four types of charges.
- Astrophysical BH have *zero* charges, while we need large N. We are working on making our microscopic models more realistic.



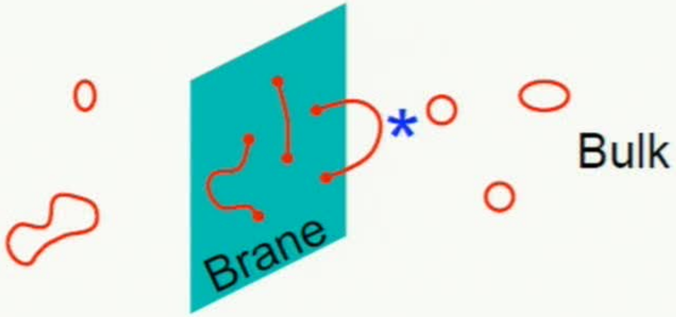
Holograms

- Holograms are fascinating because you can encode 3D information in a 2D image.

- In late 1997 J.Maldacena discovered the first working model of the idea that the world may be a hologram, which originated with G.'t Hooft and L.Susskind years earlier. They had been motivated by the fact that the Bekenstein-Hawking entropy of a BH scales like its horizon *area*, not volume.
- Holography originated in string theory, not in other approaches to quantum gravity. It is one of the most important discoveries in theoretical physics I have seen in my career, and it surprised a lot of smart people.
- Holography has been applied to modelling the quark-gluon plasma, condensed matter physics, and cosmology. Successes have been only partial so far, because our LEGO set is not fully realistic.

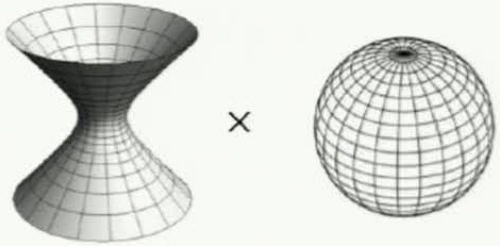
3-branes

- The first working model of holography was obtained by staring at a bunch of 3-branes, in close-up.
- What fluctuates in this system? We have interacting
  1. **open strings** ending on the branes, and
  2. **closed strings** moseying around in the bulk.
- Open strings have endpoints living on the 3-branes. Their lowest mode of vibration is a massless spin-1 gauge boson like the gluon. So the low-res approximation to open string physics is a gauge theory, in 4D (3+1).
- Closed strings live in the full 10D (9+1). Their lowest mode of vibration, massless spin 2, describes the fabric of spacetime. What is the shape of this geometry?
- The full physics of a bunch of 3-branes is very complicated. Open and closed strings interact, so their physics cannot be cleanly separated. String oscillators and quantum loops give plenty of corrections to crude low-res approximations.



AdS = CFT

- Maldacena invented a very clever **decoupling limit** of our system of many 3-branes. It turns off interactions between the open strings and the closed strings, cuts through all the mess, and creates something beautiful. It was a stunning insight.
  1. For open string physics on the branes, the decoupling limit is a low-energy (low-res) limit. It strips away the complicated string/loop corrections and gives just the 4D gauge theory. This theory is called a Conformal Field Theory (**CFT**) because it has tons of symmetry.
  2. For closed string physics in the bulk, the decoupling limit zooms in on the near-core region of the geometry of 3-brane spacetime. Gives string theory – quantum gravity – living on $AdS_5 \times S^5$. The 5D Anti de Sitter (**AdS**) part is the most important piece of this.



- Whether you think in open string *or* closed string terms, you still have the same stack of 3-branes. Therefore, **4D CFT = 5D AdS**! So *the 4D CFT is the hologram for quantum gravity in 5D AdS.*
- This even works when you heat the system up to finite temperature. It involves BH in AdS.

Summary

String theory as UniverseOS

2. Nature of physics
3. Size does matter
4. Subatomic structure
5. Elementary particles
6. String as LEGO
7. Force unification
8. Prediction of gravity and extra dimensions
9. Onion layers
10. Building Gravity 3.0
11. Aesthetics

Hawking's BH info puzzle

12. Anatomy of a BH: event horizon
13. Anatomy of a BH: singularity
14. Hawking's BH information loss paradox
15. Thermodynamics
16. Entropy of BH
17. Clash of the 20th century titans: GR vs QM
18. How string theory merges GR and QM

String models of BHs+holograms

19. String theory basics
20. Branes
21. Brane warping of spacetime fabric
22. Cooking BH with 1-branes and 5-branes
23. Adding momentum
24. Wrapping up the branes and getting BH entropy
25. String Hawking radiation
26. Holograms
27. 3-branes
28. AdS = CFT
29. Advanced remarks