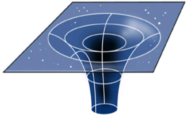
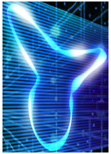
Stephen Hawking's Black Hole Information Paradox and String Theory

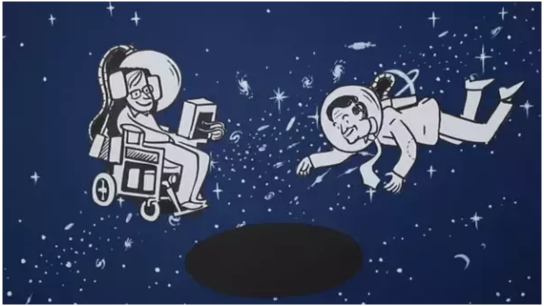


Prof. A.W. Peet
University of Toronto Physics
Science Rendezvous lecture
11 May 2019 @ 13:00-13:30 in MP103
Slides: ap.io/archives/outreach/sr19/



Four decades ago, Stephen Hawking posed a paradox about black holes and quantum theory that still challenges physicists' imaginations today. One of the most promising approaches to resolving it is string theory, a part of modern physics that has wiggled its way into the popular consciousness. We will describe how the string toolbox allows study of the extreme physics of black holes in new and fruitful ways.

Black Hole Puzzles



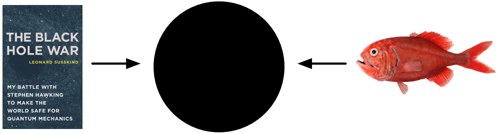
Gravity and black holes

- If we throw a ball up, it falls back down. If we launch it faster than 40,270 km/h, it escapes from Earth's gravity. If we launch it just right, speed balances perfectly against gravity and it *orbits*.
- Black holes happen when big stars run out of gas to burn and collapse under their own weight. They are denser than neutron stars, a teaspoon of which weighs a billion tonnes.
- A BH has such immensely strong gravity that inside a special region near its core, *nothing* can escape – not even light! Hence, "black hole". The edge of this Region Of Doom is known as the **horizon**. A bit further out, light can pile up.

- At the heart of a BH is the **singularity**, where the fabric of spacetime becomes infinitely warped. The closer you get, the worse you get shredded, eventually into subatomic spaghetti. Even the forces that power nuclear bombs are not strong enough to resist this gravitational shredding force. But don't worry: there aren't any BHs anywhere near our solar system that could endanger us!
- Einstein's famous theory of General Relativity invented in 1915 is a pretty great theory of gravity. But it doesn't know what happens at a singularity. We need to build an *upgraded* theory to find out.

Hawking's black hole information paradox

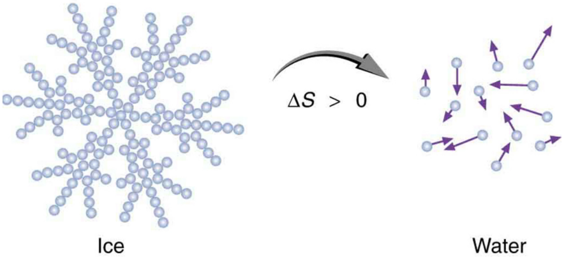
- Stephen Hawking worried a lot about a related puzzle: what happens to information that falls into a black hole? Can any information ever come out, or is it all lost, gone forever?
- In 1974-75, he proved something very surprising by combining quantum theory and Einstein's General Relativity (GR): black holes are not completely black, they emit weak radiation!
- The **Hawking temperature** of BH radiation only knows about properties of the BH that you can measure from far away: its mass, and how fast it spins (and also its force charges, if it has any).
- If we throw a 1kg book into a BH, some Hawking radiation comes out. If we throw in a 1kg fish instead, the radiation is *identical*. It knows nothing about differences between books and fishes.



- Hawking realized this was a pretty deep problem: **black holes in GR eat information**! Oops.

Temperature and entropy

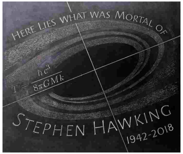
- In the 1800s, physicists developed Laws of Thermodynamics to figure out how to build more efficient heat engines. They allow you to describe flows of heat and work for a huge number of molecules of a substance in terms of just a few gross properties, like the temperature and the pressure.
- The **entropy** teaches us the amount of energy that is wasted as heat while work gets done. It describes the degree of disorganization of a system. e.g.: a tidy bedroom has low entropy while a messy one has high entropy; ice has lower entropy while water has higher entropy.



- BHs have a temperature. Do they also obey Laws of Thermodynamics and have an entropy? Yes!

Black hole entropy puzzle

- To find the entropy S from first principles, physicists use Ludwig Boltzmann's general formula
$$S = k_B \log(W)\,.$$
The more ways W a given system can be arranged, the more entropy it has. Boltzmann was so proud of this formula that it is engraved on his tombstone.



- About a century later, laws of black hole thermodynamics were discovered. Jacob Bekenstein and Stephen Hawking found the **black hole entropy formula**
$$S_{BH} = \frac{k_B c^3}{4\hbar G_N} \times (\mathit{horizon\ area})\,.$$
S_{BH} represents our ignorance about how the BH was made. It is *huge*, and depends on the mass and spin (and force charges) of the BH. Hawking was so proud of his black hole temperature formula that it is engraved on his tombstone.
- Researchers like me want to **explain** this S_{BH}, by starting from first principles and counting W. In 1996, Andrew Strominger and Cumrun Vafa achieved the first example of this. How did they do it?

Building UniverseOS

Building UniverseOS

- Before we talk about the how, let us talk a bit about the why.
- What do physicists do all day? We find interesting systems, poke them, and analyze 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 3-in-1 effort. In teams of varying sizes, we

  1. measure the physics in a laboratory (experiment);
  2. model the physics with mathematics (theory);
  3. simulate the physics on a computer (computation).

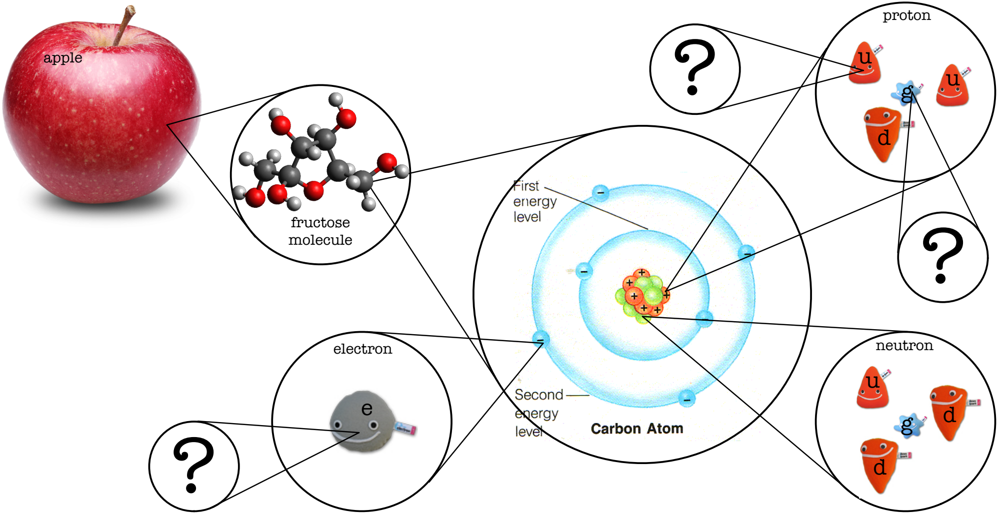
  I am in the second group. My favourite force is gravity.

- Researchers like me want to explain the structure and origin of particles, forces, and spacetime, all the way from tiny subatomic distances out to the edge of the visible universe. In other words, we dare to **seek the underlying operating system of the cosmos** – not just to build a killer app!

Size does matter

- What **dynamic range** is involved? So big it pushes the limits of imagination: over sixty powers of ten (10^{-35}m to 10^{+27}m). In musical terms, this would correspond to a range of over 200 octaves. For comparison: the Guinness world record for human vocal range is only 10 octaves.
- Humans are optimized for mm to km distance scales. To probe smaller or larger scales, we need microscopes or telescopes, like the Large Hadron Collider or the Hubble Space Telescope.
- Building a theory in physics is a bit like wiring up a mixer. Dials and sliders on your dashboard indicate how strongly the various components interact with each other.

What lies beneath?



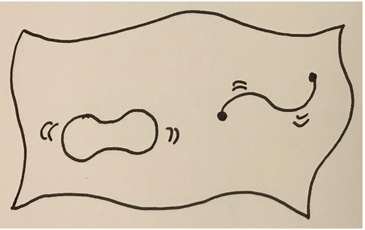
Clash between Quantum Mechanics and General Relativity

- Quantum Mechanics (QM) is a very well tested theory for describing very small things – like molecules, atoms, electrons, and Higgs bosons.
- General Relativity (GR) is a very well tested theory for describing very heavy things – like planets, moons, stars, galaxies, and the entire visible universe.
- Both QM and GR have nearly a century's worth of solid data supporting them.

- Unfortunately, **QM** and **GR** are fundamentally **incompatible**. GR is all about the smooth fabric of spacetime geometry, whereas QM has random uncertainty baked in. This is not just a minor issue. It is a *deep theoretical emergency* – like having roads governed by incompatible traffic rules.

- Professionally, we could ignore this problem if nothing in the universe was *both* heavy *and* small. But two things we care about are: **black holes** and the **big bang**. To analyze them, we need a theory of Quantum Gravity that upgrades Einstein's. String theory is the leading candidate.

String Theory



String theory

- String theory heals the epic clash of QM and GR by making a bigger tent that incorporates both.
- When we learn about atoms and molecules in school, we are taught that the basic constituents of everything are elementary *particles*. The key feature of a particle is that it is pointlike (zero dimensional). It has no structure inside it.
- 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^{-19}m. If you blew up that tiny scale to my size, I would be nearly as big as the Milky Way.
- String theory is the idea that the LEGOs of the universe are actually tiny one-dimensional vibrating strands of energy known as **fundamental strings**. This is the only generalization of elementary particles that works properly!

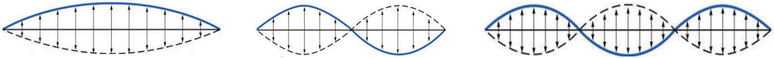
- These strings are much smaller than the molecules in the macroscopic kind of string that a kitten plays with.
- Key feature of fundamental strings is **versatility**: they can vibrate in different ways, corresponding to different subatomic particles. In this sense, string theory is a symphony of Nature. ♪ ♫

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 and **closed strings** without.
- The least expensive vibration of an open string has mass 0 and spin 1. This describes
  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 least expensive vibration of a closed string has mass 0 and spin 2. This describes
  4. gravitons that transmit the gravity force.
- Unification of gravity with the other three forces was something Albert Einstein dreamed of achieving. Sadly, he did not live long enough to see it get invented.

Stringy phenomena

- When physicists figured out how to do the quantum theory of strings, gravity popped out for free! This idea did not win a Nobel Prize because gravity was discovered long before string theory was.
- Particles are pointy. Strings are extended, softer objects. They interact by smoothly splitting or joining in a more spread-out way. This is the key to how **string theory heals GR's problems**.
- Strings can vibrate in a huge variety of different ways. This makes them versatile enough to describe particles and phenomena already discovered, as well as propose new things to look for.



- String theory predicts extra dimensions of space, tightly curled up and hidden from view. Strings and [mem]branes in its spectrum can *wrap* around those hidden dimensions, which has profound consequences for spacetime. The heart of a BH in our universe might not be 4D!
- Superstring theory, with all its complicated moving parts, is capable of describing all the subatomic particles known to particle physicists – plus possible zoos of as-yet undiscovered ones as well. It unifies forces and matter. It even describes the emergence of spacetime itself, and counts S_{BH} for some types of BH. We are still hard at work chasing a solution to Hawking's information paradox.

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