Where are we Headed?

What questions are driving developments in fundamental physics?

What ideas/theories are physicists exploring today?

- Quantum Gravity, Stephen Hawking & Black Hole Thermodynamics
- A Few Flaws of the Standard Model
- String Theory, Supersymmetry & Extra Dimensions
Quantum Gravity

Another in our series of theorist’s puzzles….

We believe that the world operates according to quantum mechanics, but Einstein’s General Relativity is a Classical Theory.

Recall that we faced the same situation with electromagnetism. “Quantizing” electromagnetism plus inventing renormalization to deal with the infinities of quantum field theory resolved matters.

Can General Relativity be similarly quantized?
The answer is yes. But, ….

The renormalization procedure leads to new complications:

- An infinite number of new interactions must be added to Quantum General Relativity beyond Einstein’s original theory.
- These new interactions continue to be geometrical in character and become important only at microscopically small distances.
- The successes of classical General Relativity are unaffected.
- Quantum General Relativity only makes sense as an “effective field theory”, valid at distances larger than the Planck scale.
The Planck scale …. We have come across three important constants of nature in our lectures…..

- The speed of light \( c \)
- Planck’s constant \( h \)
- Newton’s constant \( G \)

It is natural to work in units of length, time and mass where each of these constants takes the numerical value 1, \( c=h=G=1 \). These are called Planck units or natural units.

In terms of the units we’re used to ….

The Planck length is unimaginably small!

\[
\begin{align*}
l_{pl} & \approx 10^{-33} \text{ cm} \\
t_{pl} & \approx 10^{-43} \text{ s} \\
m_{pl} & \approx 10^{19} \text{ GeV} \approx 10^{-5} \text{ g}
\end{align*}
\]
Quantum Gravity becomes important at the Planck Scale

Quantum General Relativity only makes sense for lengths much bigger than the Planck length.

Quantum fluctuations in the spacetime metric become large at the Planck scale.

If we try to use a Planck energy probe to study the structure of spacetime at small distances, a black hole forms.....
Another big question for quantum gravity - How are curvature singularities resolved?

Classical General Relativity predicts infinite curvature at the centers of black holes & at the Big Bang.

Physicists believe that if a theory predicts an infinite result, this is a sign of the theory breaking down. The hope is that the ultimate short distance theory of quantum gravity will smooth out the infinities of classical GR.

The nature of spacetime at distances smaller than the Planck scale is still very much of a mystery.
Stephen Hawking & Black Hole Thermodynamics

Another very interesting set of questions for quantum gravity are concerned with Hawking’s discovery that black holes are, in fact, not entirely black after all .....

- In 1972 Hawking showed that when quantum mechanics is turned a black hole will radiate at a non-zero temperature.

\[ T_{BH} = \frac{\hbar c^3}{16\pi^2 M_{BH}} \]

- Large black holes are cold and small black holes are hot.

\[ T_{BH} \approx \left( \frac{M_{SUN}}{M_{BH}} \right) \times (6 \times 10^{-8} K) \]

- As black holes radiate, they lose mass and evaporate!

\[ \tau_{BH} \approx \left( \frac{M_{BH}}{M_{SUN}} \right) \times 10^{7.1} s \]
The Hawking Temperature of a black hole is part of a larger set of results known as Black Hole Thermodynamics.

There are 0th, 1st, 2nd and 3rd laws of BH thermodynamics, which are in very close analogy with the laws of ordinary thermodynamics.

The 2nd law says that entropy always increases. The black hole entropy is proportional to the area of the event horizon.

\[ S_{BH} = \frac{c^3 A}{8\pi G h} \]

For an ordinary system, like gas in a box, the entropy counts the number microscopic states accessible to the system.

A major question for Quantum Gravity is identifying the nature of the BH microstates that the BH entropy counts?
A Few Flaws in the Standard Model

The standard model is incredibly successful experimentally, almost frustratingly so. But it has a number of obvious flaws that make it clear that it cannot be the last word on particle physics…..

Arbitrary Numbers…..

• The standard model is built out of a particular group. What picked out this group?

• Why 3 generations of quarks & leptons? Why the complicated structure of each generation?

• Over 20 dimensionless constants are necessary to specify the detailed masses and couplings of the standard model. What picks these out?

\( SU(3) \times SU(2) \times U(1) \)
The standard model itself points to a partial resolution of its problems. **Grand Unification**

The coupling constants of the 3 gauge groups are functions of energy and at high energies they all approach each other, indicating that all three have a common origin in a larger gauge symmetry group.

This GUT symmetry group must be **spontaneously broken** to the product of the 3 low energy gauge groups.

Spontaneous symmetry breaking is already part of the standard model. The weak symmetry group SU(2) is broken down in nature by the **Higgs Mechanism**.
Spontaneous Symmetry Breaking

• Physics may have a symmetry, but the vacuum does not as in the **mexican hat potential**!

• The brim of the hat is symmetric, but the **Higgs field** must pick out a particular point on the brim and break the symmetry.

• Spontaneously broken symmetries are restored at high temperatures, i.e. in the very early universe. The symmetry breaking **phase transitions** as the universe cools are important events in the history of the universe.

• If the Higgs field does not condense uniformly, then there can be topological defects, such as **magnetic monopoles, cosmic strings, domain walls and textures**.
The yellow theory involves adding yet another symmetry known as *supersymmetry*, which interchanges bosons & fermions.
All particles in nature are either **Bosons** or **Fermions**

**Bosons** have integer spin angular momentum and **Fermions** have 1/2 integer spin.

Identical fermions cannot occupy the same energy level, while bosons can. For electrons in atomic orbitals, this is the Pauli Exclusion Principle.

In Quantum Mechanics, angular momentum is quantized in units of

\[ h = \hbar / 2\pi \]
Fermions & Bosons

“Force Carriers” - photons, gluons, W’s, Z’s & also gravitons - are bosons

“Matter Particles” - quarks and leptons - are fermions

Supersymmetry pairs fermions with bosons having the same masses, but none of the particles in the standard model have known superpartners. Therefore, if SUSY exists, it must also be spontaneously broken.

Superpartners all have amusing names. The partner of a gluon is a **gluino** and the partner of a quark is called a **squark**.
The main shortcoming of the Standard Model is that it doesn’t include Gravity….

There is no compelling theoretical “glue” that holds Quantum General Relativity to the Standard Model. They coexist well enough, but they are not made of the same theoretical stuff.

Physicists look towards a yet grander unification ….. a “Theory of Everything”

String Theory has emerged over the last 20 years as a promising candidate
What is String Theory?

In short the idea is that instead of fundamental particles, the world is made of fundamental strings.

String theory strings are very, very small. So that, from our larger perspective, they appear to be particles. The stringiness of string only becomes apparent at the Planck scale.

The different particles in our world are all different modes of vibration of string.

Particle physics as we know it corresponds to only the very lowest energy vibrational modes of string. The infinitely many higher energy modes are responsible for fixing up short distance physics.

One of the light vibrational modes of string acts like the graviton!
How does one do String Theory?

- The starting point is relatively simple. As string moves through time it sweeps out a surface.

The Feynman’s Path Integral formulation of quantum mechanics can be used to calculate the probability for a string to move from one configuration to another, including splitting & joining.

The probability is given roughly by summing over all possible surfaces that connect the initial and final configurations with a weighting factor that depends on the surface..... In the simplest version of string theory, this weighting factor is proportional to the area of the interpolating surface.

Of course, in practise this is a reasonably complicated calculation!
What does one learn from carrying out this procedure?

- **String theory contains gravity.** For energies below the Planck scale, string theory works much like quantum general relativity, with the coefficients of all the infinite number of geometrical interactions required by renormalization specified.

- **String theory incorporates supersymmetry.**

- **String theory can accommodate realistic Grand Unified gauge groups**

- **String theory lives in 10 spacetime dimensions!**

**But we only know about 4 spacetime dimensions. So, how can this possibly be reasonable?**
Extra Dimensions?

• Clearly there are not more than 3 large spatial dimensions in which we can walk … However, extra dimensions are not at all ruled out, if they are very tightly curled up….

• Remember that it takes very high energies to probe very short distances. If the **compactification scale** is shorter than we can probe at particle accelerator experiments, then there is no contrary evidence. Given that the natural length scale in string theory is the Planck scale, this even seems reasonable….

• With six extra dimensions, many different compactifications are possible. In string theory, the choice of compactification manifold determined many properties of physics in the remaining 4 extended spacetime directions: the gauge group, the number of generations, the masses & couplings of particles….

• How the compactification manifold is picked out, or even why 6 dimensions should want to curl up, remains a very important open issue in string theory. So, in some sense, the problems of the standard model have just been shifted over. However, at least now they are in the realm of the scientific ….
A few more stringy bits of info…..

• String theory has been around since 1969, though it was invented for a very different purpose…..

• In 1983 it was shown by Michael Green & John Schwarz that string theory was a viable candidate for a “theory of everything”. This led to an explosion of research interest, which is still going on after nearly 20 years.

• String theory has been able to retain a very highly of research interest and activity because there are both hard unresolved problems and actual new ideas that appear every few years…..

• In 1995, Joe Polchinski showed that string theory is, in fact, not just a theory of strings, but contains “branes” of other dimensions as well. A particle is a 0-brane, a string is a 1-brane, a membrane is a 2-brane, etc.

• Polchinski’s discovery helped set off the “2nd string revolution”. Branes, particularly D-branes, on which strings can have ends, turn out to play enormously important roles in string theory.
• In 1996, making use of branes, Andy Strominger & Cumrun Vafa, showed how string theory can account for Black Hole entropy at least in certain limits....

• No discussion of string theory is complete without mention of Edward Witten, who has played a huge role in the development of the subject. Witten is especially known for exploiting physicists techniques, such as supersymmetry & quantum field theory, to derive startling new results in mathematics, or much simpler ways of viewing known results.
One Concluding Topic

• Fundamental physics is alive and well with both interesting problems and ideas, but faces a sort of post-modern dilemma

• The development of theory has far out-stripped the capacity for meaningful experimental input. The Planck scale in energy is 16 orders of magnitude beyond what we can probe in experiments….. Can one really do physics under these circumstances?

• On the other hand, fundamental physics has many well established, but still unexplained, experimental results. Why do we appear to live in 4 dimensions….. Perhaps it is enough to try and account for what we already know in a consistent fashion?