Tonight's Agenda

- 6:30 – 6:45 – Networking
- 6:45 – 7:00 – Introduce new members
- 7:00 – 7:15 – New science
- 7:15 – 8:30 – Presentation
- 8:30 – 9:00 – Q&A
- 9:15 - ???? – Afterwards!

Higher Dimensions Of Space

Part II

Larry Smith

My Credentials

Summary of Part I
Kaluza-Klein Theory

- In 1921, Theodor Kaluza (with later revisions by Oskar Klein) reformulated General Relativity in *five* dimensions and wound up *predicting* electromagnetism.
- In this theory, electric charge was momentum along the new axis.
- The 5^{th} dimension was unseen because it was calculated to be only some 10^{-31} (later revised to 10^{-35}) meters in size.
- This theory, while provocative, didn't match up with experiment.

Summary of Part I
Bosonic String Theory

- String theory (1970) treats all particles as vibrating strings of energy.
- Originally it was a theory of bosons (force particles) but did not handle fermions (matter particles).
- It worked only in 26 dimensions and *required* a graviton particle.
- It was the among the first quantum theories of gravity!

- This was a major step forward. Physics has yet to reconcile General Relativity and Quantum Mechanics.

Summary of Part I
Superstring Theory

- String theory was later modified to handle fermions by incorporating the concept of supersymmetry.
- The new theory was called superstring theory.
  - These days, when we refer to string theory, we normally mean superstring theory.
- This new theory required only 10 dimensions, not 26.

Summary of Part I Sparticles

- Supersymmetry postulated that every normal particle (boson or fermion) had an associated partner particle called, generically, a sparticle.
- So there is (if supersymmetry is correct) a new (s)particle, the partner of the electron, called the selectron.
- An electron can be transformed into a selectron and back again.
- And similarly for all other particles.
- In one shot this theory doubled the number of types of particles in the universe.
- These may be part of dark matter.

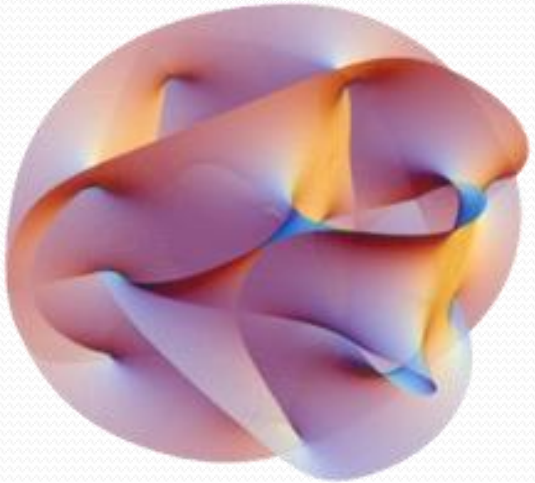
Particles and Sparticles

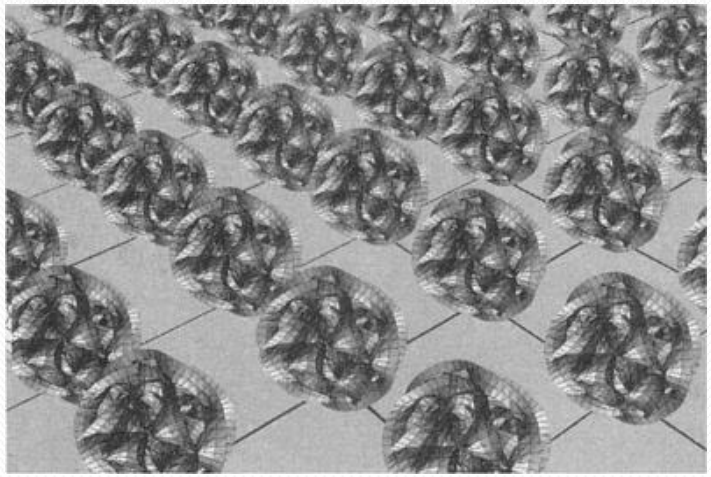
Normal Particle	Superparticle
Electron	Selectron
Quark	Squark
Top Quark	Stop Squark (I kid thee not!)
Neutrino	Sneutrino
Photon	Photino
Graviton	Gravitino
W particle (Weak force carrier)	Wino
etc	

Summary of Part I
Calabi-Yau

The other 6 dimensions are curled up into a Calabi-Yau space, each around 10^{-35} meters in size.

These extra dimensions are at every point in our normal concept of space.





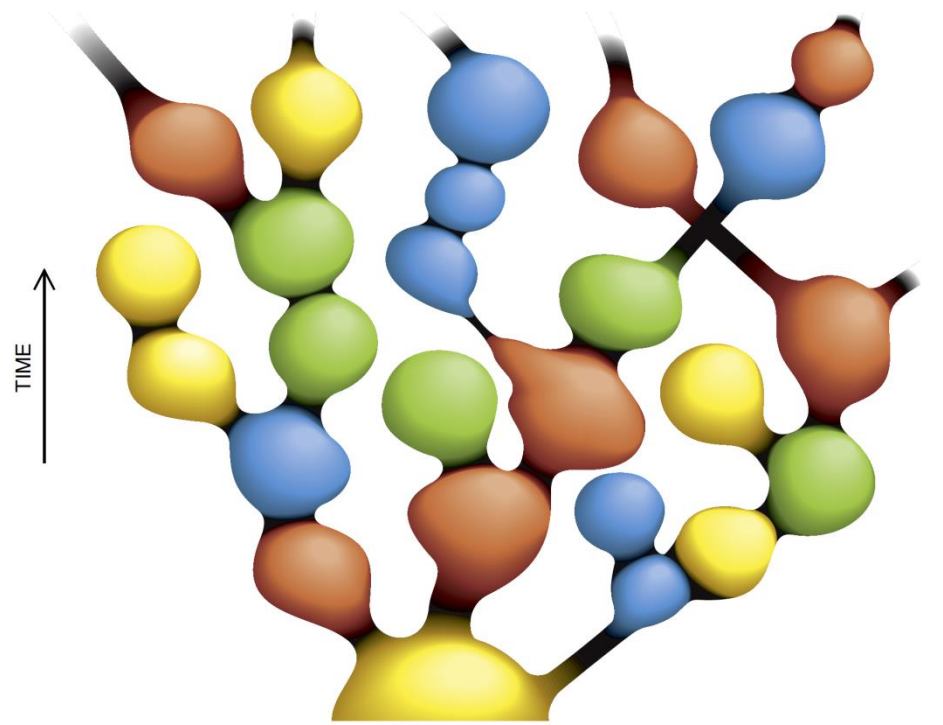
Summary of Part I
Calabi-Yau Explanatory Power

- The exact shape of the Calabi-Yau space determines many of the constants of the universe (e.g. the mass of the electron, the relative force of gravity vs. electromagnetism, etc).
- It can also explain why matter comes in 3 generations.
  - Leptons – Electron, muon, tauon + their respective neutrinos.
  - Quarks – up/down, strange/charm, top/bottom.

Summary of Part I
The Goldilocks Universe

- Calabi-Yau spaces can be wrapped up in perhaps 10^{500} ways (maybe 10^{1000}!).
  - Some say that superstring theory loses all predictive power with an essentially infinite number of possible universes.
- Our universe is finely tuned. If the forces of nature were just a few percent different, life could not exist.
- The Multiverse theory says that there are many universes, each with a different Calabi-Yau shape, and most with the wrong parameters for life.
  - But with 10^{500}+ possibilities, we would be in one of the universes that was "just right".

The Multiverse



OK, Now on to the New Stuff!

An Embarrassment Of Riches

- String theory had a problem.
  - There's *one* theory of gravity.
  - There's *one* theory of electromagnetism.
  - There's *one* theory of quantum mechanics.
- There were *five* superstring theories!
  - Each one using string theory to describe the universe from different points of view, and each self-consistent.
- That's not good. We'd prefer a *unique* theory of the universe.

The Five String Theories

- Type I
- Type IIa
- Type IIb
- Heterotic ("hybrid vigor") O, based on the mathematical symmetry group SO(32)
- Heterotic E, based on symmetry group E8 x E8

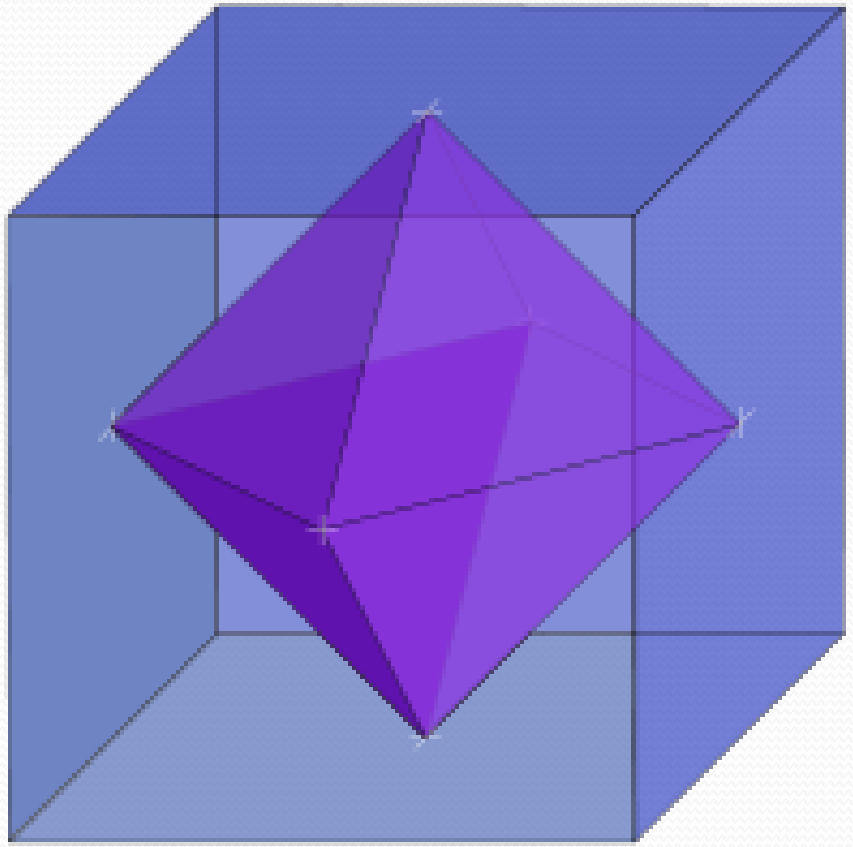
As an example of how these are different theories, Type I describes both open and closed strings, while the others describe only closed strings.

The Second Superstring Revolution

- In 1995, Ed Witten (drawing on the work of others) stunned the physics world by showing that there was an 11th dimension that should be incorporated into string theory.
  - Previous analyses made a mathematical simplification that implicitly assumed that an extra dimension was zero in size.
- He called this M-Theory, where "M" stands for Mystery, Mother, Membrane, etc.
  - "The Theory Formerly Known as Strings"

Duality

- Sometimes in math and physics, there are two (seemingly) totally different ways to describe the same thing.
- For example, take a cube and connect the midpoints of each side. You get an octahedron.
  - And vice-versa.
- At times you can prove theorems about an octahedron more easily if you think about it as a kind of cube.
  - And vice-versa.
- Electricity and magnetism are also dual.

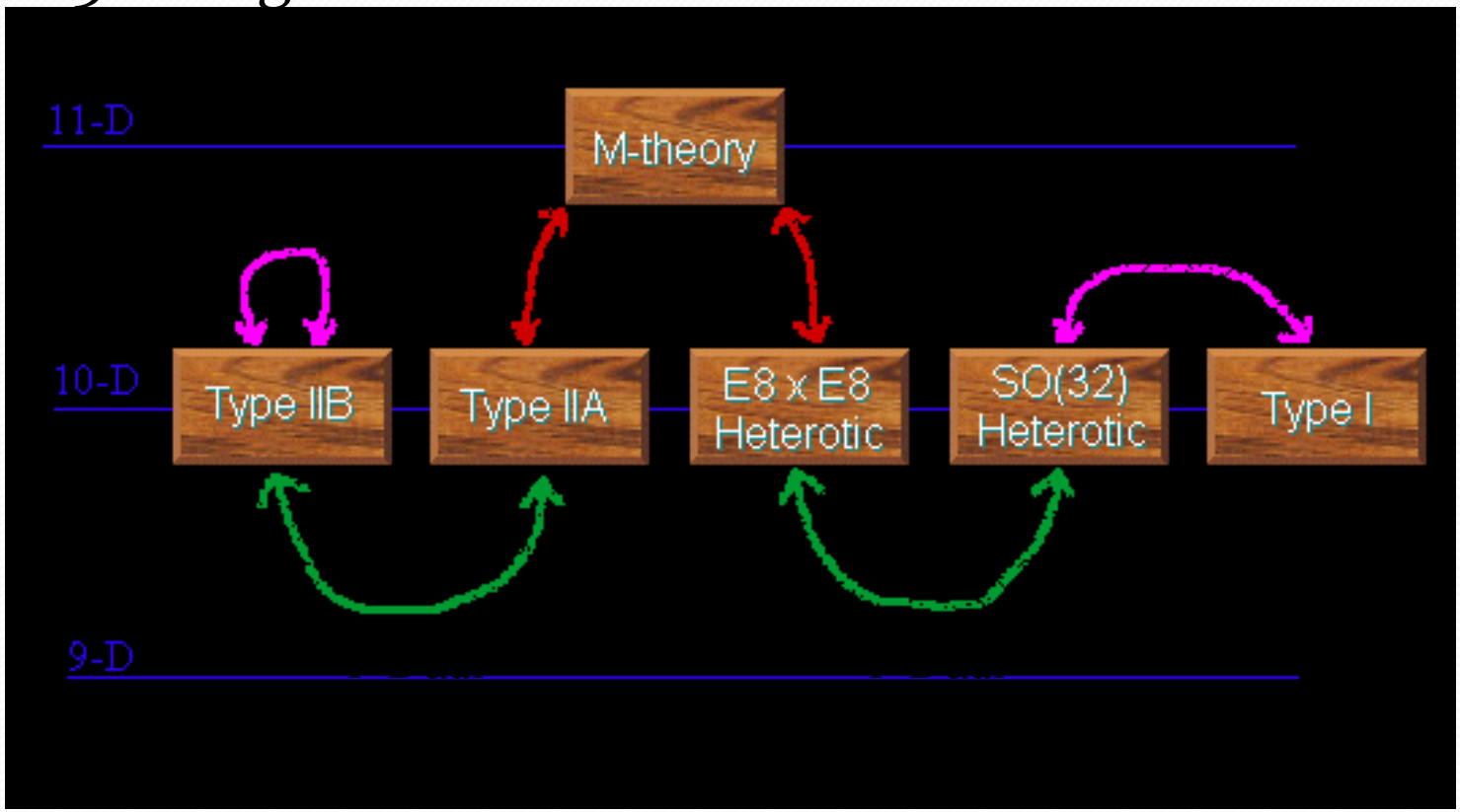


One Theory To Rule Them All

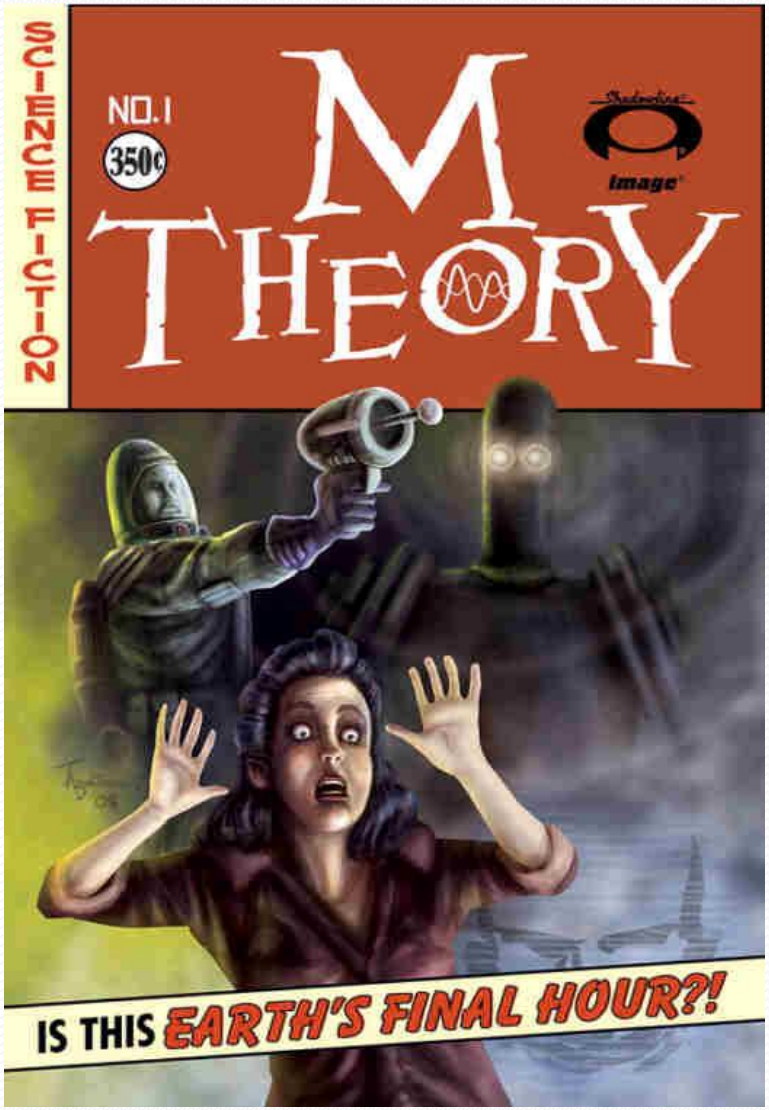
- Each of the previous 5 string theories was shown to be a version of the more general M-Theory.
- They were related to each other by several dualities, known as S-Duality and T-Duality.
- So there is a unique theory after all.

Dualing Theories

- All 5 string theories are duals of each other.

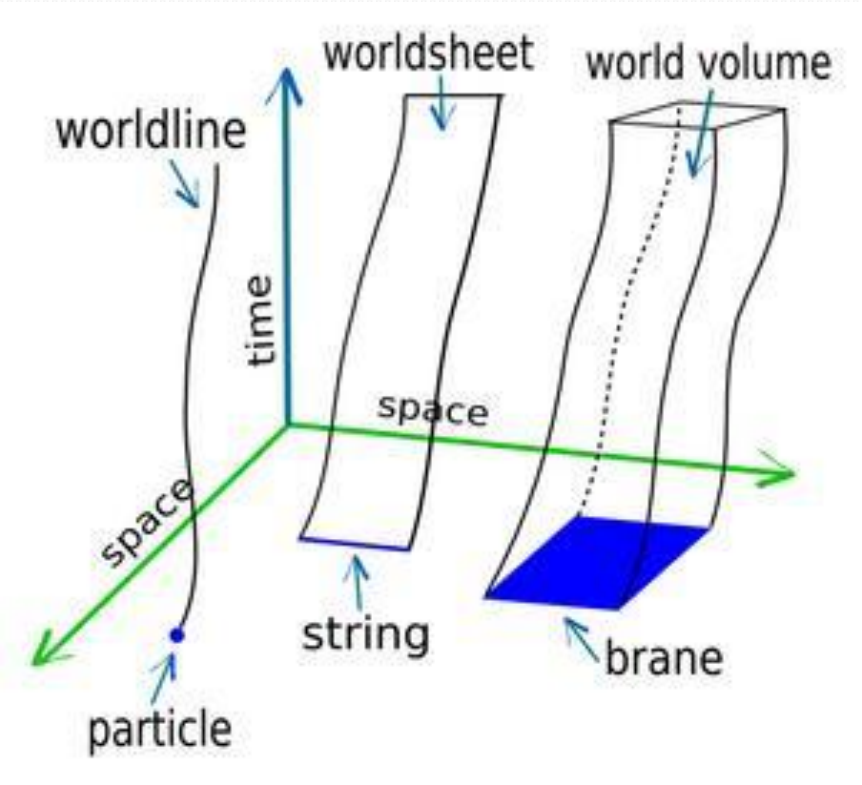


One of the many scholarly papers on M-Theory



Brane New World

- The most important new concept was that membranes (aka *branes*) were crucial.
- A geometric point in the 10-D theory was now extruded into an additional dimension and became a 1-D string.
- An old 1-D string became a 2-D membrane.
- And so on…



Higher Dimensional Branes

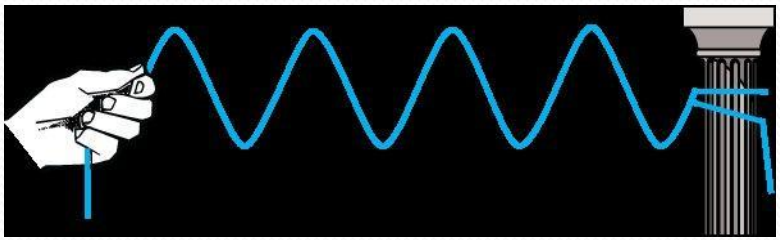
- Branes could come in any number of dimensions up to 10.
- These are called 1-branes, 2-branes, … 10-branes.
  - In general, these are called *p-branes*.

Brane Sizes

- Branes do *not* have to be compactified.
- They can be large, perhaps even infinite in size.
- The remaining dimensions can still be compacted into Calabi-Yau shapes.

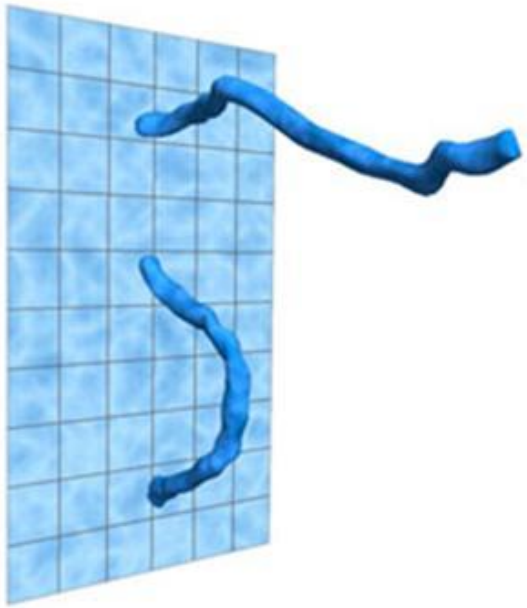
Boundary Conditions

- In general, things that vibrate don't do so infinitely throughout all of time and space.
- They're anchored, often at both ends.
- Imagine pumping a skipping rope, one end in your hand and the other end tethered to a post.



Why We Can't See Other Branes

- Open strings have a boundary condition. Their ends are restricted to starting and ending on a brane.
- Closed strings (loops) can't be so restricted.
- Closed strings always represent gravitons.
- All other particles of matter and forces are open strings.



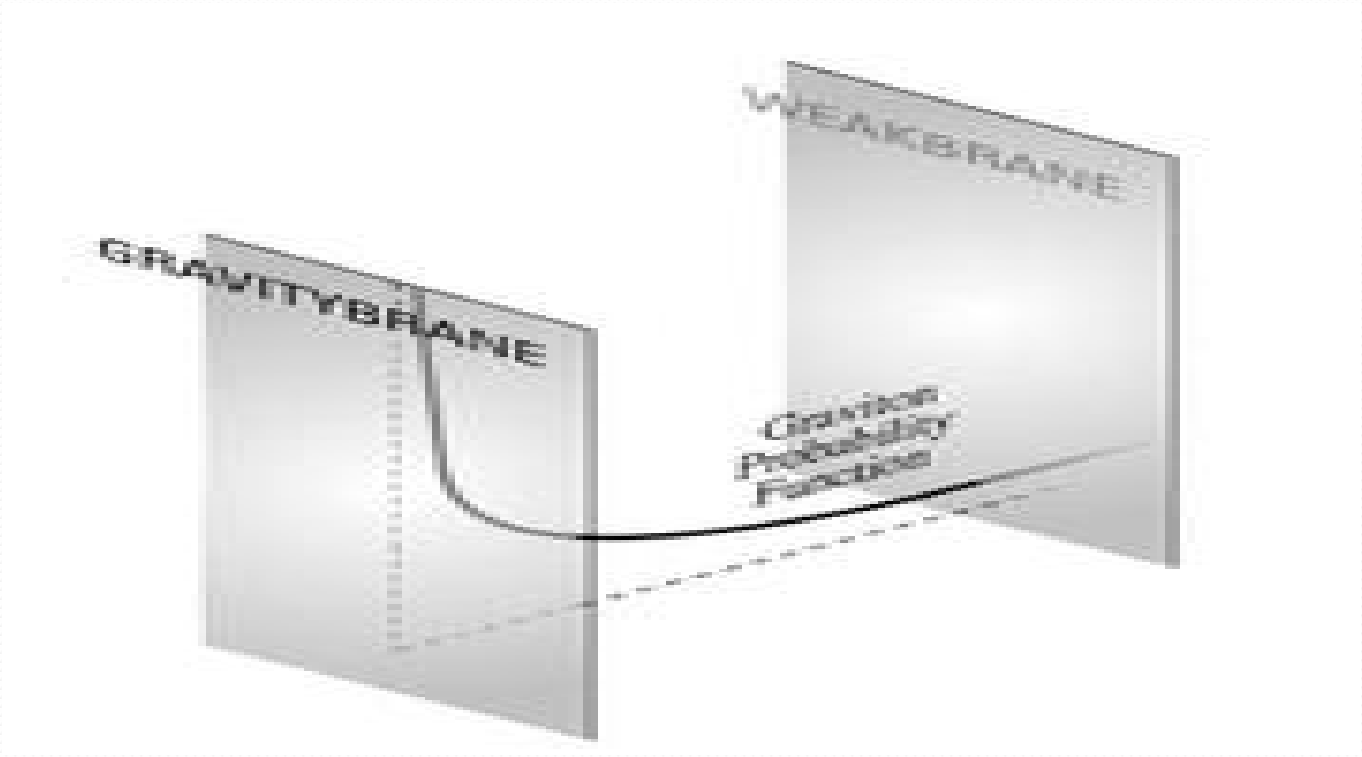
3-Branes

- Our entire universe may be a 3-brane embedded in a larger (e.g. 4-) brane.
- With the exception of gravity, all matter and forces could be restricted to our 3-brane.
- So if there were another 3-brane "near" us (in a 4-D sense), we intrinsically couldn't see it.
  - Remember, photons etc. are restricted to our brane.
- Maybe the science fiction writers have been right all along.
- And maybe dark matter may be on another brane!

Branes and the Hierarchy Problem

- The force of gravity is some 10^{37} times weaker than the electromagnetic force. This is called the *Hierarchy Problem*.
- Lisa Randall has proposed that we're on one brane where gravity is weak, but is strong on a nearby brane.
- Gravitons can travel between the branes, but weaken by the time they get here.
- The gap between branes is called the *bulk*.
- The LHC could detect higher dimensions via gravitons leaking into the bulk. This would show up as a violation of the law of conservation of energy.

Gravity in the Bulk



Branes and the Big Bang Theory

- Neil Turok (director of the Perimeter Institute) and Paul Steinhardt (of Princeton) have proposed the *ekpyrotic* ("out of (cosmic) fire") model to explain the Big Bang.
- This required two branes to collide and rebound every trillion years or so and thus release energy.
- This avoids a singularity (infinite density) at the Big Bang.
- And it may have left traces in the Cosmic Background Radiation.
- Maybe it's just as well that CBS didn't call their show *The Ekpyrotic Model*.

Experimental Evidence for Higher Dimensions

The Third Superstring Revolution?

- In 1967, Sir Roger Penrose proposed the concept of 4-dimensional objects called *twistors* to try to explain how space and time aren't truly fundamental objects.
- In a series of paper in the 90's, Ed Witten incorporated twistors into string theory and proposed a way to do string theory in twistor space, whose dimensionality is necessarily the same as that of traditional 3+1 spacetime.
- Hence twistor string theory is a possible way to eliminate the need for more than 3 spatial dimensions when doing string theory.
- However, Witten has said that "I think twistor string theory is something that only partly works."
- So the jury may still be out on 4-D string theory.

So? 10 or 11?

- It turns out that 10-dimensional string theory is *dual* to 11-dimensional M-Theory.
- This means you can assume the universe is 10-dimensional and prove your theorems. And as a bonus, you'll have proved a corresponding theorem in an 11-dimensional world.
  - And vice-versa.
- And sometimes it's easier to prove a theorem in, say, 11-D than it is to do so in 10-D.
  - And vice-versa.

So How Many Dimensions Does the Universe Have?

- On the assumption that M-theory is correct, and does describe our universe, the answer is…
- Either 10 or 11. Take your pick.
- Both ways of looking at it describe identical physics. There's no way of telling them apart.

Bottom Line

- (Super)string theory predicts that we live in a 10/11 dimensional world.
- It can explain a number of aspects of the universe that the Standard Model can't.
- But it's still totally theoretical. At this point it's just "marks on paper".
- All experiments show just 3+1 dimensions and no sign of supersymmetry.
- But stay tuned for the latest news, especially from the LHC!

Alfonso X (the Wise) 1221 - 1284

- If I had been present at the creation, I would have given some useful hints for the better ordering of the universe.

Thank You

Suggested Reading

- Subtle is the Lord, by Abraham Pais.
  - A biography of Einstein. Most biographies concentrate on the facts that he played the violin, that he met Charlie Chaplin, that he was offered the presidency of Israel, etc. But this is the biography I think he would have liked best. It concentrates on his scientific life. And when you get to the tensor equations embedded in the text, just *bleep* over them.
  - He has other books on Einstein, Bohr and Teller. I particularly liked *Inward Bound*, a history of the early days of particle physics (and physicists).

Suggested Reading

- Warped Passages, by Lisa Randall.
  - She was the first tenured woman in the Princeton University physics department and the first tenured female theoretical physicist at MIT and Harvard.
  - Her specialty is creating mathematical models of new concepts in physics, often involving higher dimensions.
  - Watch the video of her being interviewed on PBS by Charlie Rose at http://video.google.com/videoplay?docid=-4515421972882480 9&q=tvshow%3ACharlie_Rose&hl=en#

Suggested Reading

- The Elegant Universe, by Brian Greene.
  - A very readable introduction to modern string theory. It gets a bit technical when he talks about his (to him) big discovery, but you forgive a lot when the rest of the book is this good.
- The Fabric of the Cosmos, by Brian Greene.
  - Like his previous book, but not limited to just string theory.
- http://www.youtube.com/watch?v=YtdE662eY_M

Suggested Reading

- The Road to Reality, by Sir Roger Penrose.
  - At over 1,000 pages, this is an absolutely amazingly comprehensive book on practically all aspects of particle physics, cosmology, quantum mechanics and more.
  - There's lots of readable prose, but there's also a lot of mathematics thrown in for those who can handle it.
  - But even if you can't hack the math, there are enough fascinating nuggets in the prose that it's a treasure trove of information for the physics enthusiast.

Suggested Reading

- Flatland, by Edwin A. Abbot
  - A classic, written in 1884. It tries to help us (more or less) 3-dimensional beings understand the 4th dimension by imagining how a 2-D being might envision a 3-D world.
- Sphereland, by Dionys Burger
  - A pastiche sequel to Flatland, written in 1965.
  - Set in Flatland, it introduces us to the concept of curved space (e.g. their scientists find out that the sum of the angles in a triangle is > 180º).
- The two novels are available at The World's Biggest Bookstore as a twofer.

Suggested Reading

- Hiding in the Mirror, by Lawrence M. Krauss
  - Probably better know for his book, *The Physics of Star Trek*, Krauss is an award-winning particle physicist and cosmologist at Arizona State University.
  - Subtitled *The Mysterious Allure of Extra Dimensions, from Plato to String Theory and Beyond*.

Suggested Reading

- The Cosmic Landscape (String Theory and the Illusion of Intelligent Design), by Leonard Susskind.
  - Susskind is one of the originators of string theory. In this book he talks widely about extra dimensions, Calabi-Yau spaces, branes, the Anthropic Principle, etc, etc, etc.
    - YouTube has many of Susskind's lectures at Stanford. Just search it for *Susskind*. Note that most of these are university-level lectures, but you can probably get some ideas from them.
    - His lectures are also available on iTunes.
    - See http://en.wikipedia.org/wiki/Leonard_Susskind for a list of them.

Suggested Reading

- The Inflationary Universe, by Alan Guth.
  - This theory (since partially confirmed by an analysis of the Cosmic Background Radiation) posits that starting only 10^{-36} seconds after the Big Bang, and lasting until 10^{-32} seconds, a chunk of space expanded by a factor of 10^{78}! This became our universe.
  - Other chunks could have expanded into a different universe, and the laws of physics there could be radically different from those in our universe. This is one aspect of the Multiverse theory.

Suggested Reading

- The Shape of Inner Space: String Theory and the Geometry of the Universe's Hidden Dimensions, by Shing-Tung Yau.
  - As in Calabi-Yau
  - Not the best written popular science book I've ever read. Probably best obtained from the library.

Suggested Reading (Off Topic)

- This book is off-topic, but is too good not to plug!
- Black Holes and Time Warps (Einstein's Outrageous Legacy), by Kip Thorne.
  - From *Publisher's Weekly* -- Thorne, the Feynman Professor of Theoretical Physics at CalTech, here offers an accessible, deftly illustrated history of curved spacetime. Covering developments from Einstein to Hawking, he takes his readers to the very edge of theoretical physics: straight through wormholes--and maybe back again--past hyperspace, "hairless" wormholes and quantum foam to the leading questions that drive quantum physics. He even addresses the tabloid taunt that has tantalized him since 1988: Do quantum laws allow time travel? (In his foreword, Hawking suggests, "Maybe someone will come back from the future and tell us the answers.") Thorne is rigorous, modest and, true to the spirit of science, determined that readers move beyond the appeal of exotic answers and grasp the significance of quantum questions. This volume, a model of style, format and illustration, will speak eloquently to the readership, ranging widely in scientific literacy and interest, that such theoretical physics writers as Hawking and Feynman have established.

Suggested Reading

- The Trouble With Physics, by Lee Smolin
  - The other point of view. There are other candidates for a quantum theory of gravity (including Causal Dynamic Triangulations and Smolin's own Loop Quantum Gravity), which need only 4 dimensions.
  - This book explores the weaknesses of string theory and criticizes the academic world for being too "faddish" on the subject, and discouraging research into alternatives.
  - As with all of Smolin's books, it's well written and interesting.

Suggested Watching

- What Banged? by Neil Turok -- http://www.perimeterinstitute.ca/index.php?option=com_content&task=view&id=551&Itemid=568&lecture_id=6462