String Theory: Physics from the Ultra-Small to the Universe

Amanda Peet
University of Toronto Physics
CIAR Cosmology & Gravity Program

CIAR 20/20 Vision Conference
1000h, Monday 17 June 2002
Motivation ...
The Popular Perception

"It's all string theory to me."

New Yorker magazine
String Theory: a Sub-Discipline of Physics

- Particle Physics Theory
- Early Universe Cosmology Theory
- Mathematics
- Data from Accelerators and Cosmology
Enormous Dynamic Range

- String Theory is ambitious program!
- Aim: to explain origin and structure of fundamental matter and interactions, from subatomic to cosmological scales.

$10^{-33}\, cm \quad \Rightarrow \quad \Rightarrow \quad \Rightarrow \quad 10^{+28}\, cm$

- An underlying idea:
  - at low energy (today), broken symmetries
  - at high energy (past), restored symmetries.
How We Do Research

Tools:  Pen, paper, computer, collaborators, blackboard.

Speed:  Very fast-moving.

Preprints:  Electronic since 1991 (http://arxiv.org/)

Topics:  “Why?” questions
What Came Before
String Theory ...
Standard Model of Particle Physics

• Two types of fundamental matter seen, so far:
  – Leptons: \( (e, \nu_e), (\mu, \nu_\mu), (\tau, \nu_\tau) \)
  – Quarks: \( (u, d), (c, s), (t, b) \)

• Four fundamental interactions:

<table>
<thead>
<tr>
<th></th>
<th>Gravitational</th>
<th>Electromagnetic</th>
<th>Weak Nuclear</th>
<th>Strong Nuclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons:</td>
<td>✓</td>
<td>✓ (+,-)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Quarks:</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Range:</td>
<td>Infinite</td>
<td>Infinite</td>
<td>(10^{-16}) cm</td>
<td>(10^{-13}) cm</td>
</tr>
<tr>
<td>Strength now:</td>
<td>Weakest</td>
<td>Weak</td>
<td>Weaker</td>
<td>Strong</td>
</tr>
</tbody>
</table>
**Unification Hints**

- Fundamental “constants” describing strengths of interactions are *not* actually constant, but vary with energy:
  - Strong Nuclear gets weaker at higher energy,
  - Electromagnetic, Weak Nuclear, Gravity all get stronger.

- Variation effect involves
  - Special Relativity: Physics of the Very Fast,

- Extrapolating upwards suggests **unification at ultra-high-energy**.

- **Unification at String scale** $10^{16} \, ^\circ C < Temp. < 10^{32} \, ^\circ C$

- **Extreme Physics!** Beginning of Universe / Inside Black Holes.
Cartoon of Evolution of Universe

- **At beginning:**
  - incredibly hot tiny universe
  - no atoms, or even protons or neutrons: no binding possible
  - quarks and leptons interchangeable
  - all interactions same, and of same strength

- **Soon afterwards:**
  Universe inflated very fast, particle creation, leftover radiation...
Unity of Interactions and Matter

• Fundamental particles in Nature labelled by mass, and (intrinsic) spin.

• Dichotomy in Standard Model of Particle Physics:
  – Matter particles: $s=\frac{1}{2}$ “fermions”,
  – Interaction-transmitting particles: spin $s=0,1,2$ “bosons”.

• Theoretical unity via supersymmetry: boson-fermion pairing.
  – Unique and natural extension of symmetries of Nature.
  – Useful for helping solve other problems as well.

• Supersymmetry broken at low-energy: no sparticles seen yet.
Superpartners

- Massive effort underway in theory and experiment communities to hunt for superparticles!

<table>
<thead>
<tr>
<th>Particle</th>
<th>spin</th>
<th>Super (“mirror world”) partner</th>
<th>spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>leptons, quarks</td>
<td>$s = \frac{1}{2}$</td>
<td>sleptons, squarks</td>
<td>$s = 0$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$s = 0$</td>
<td>Higgsino</td>
<td>$s = \frac{1}{2}$</td>
</tr>
<tr>
<td>photon, W, Z, gluon</td>
<td>$s = 1$</td>
<td>photino, Wino, Zino, gluino</td>
<td>$s = \frac{1}{2}$</td>
</tr>
<tr>
<td>graviton</td>
<td>$s = 2$</td>
<td>gravitino</td>
<td>$s = \frac{3}{2}$</td>
</tr>
</tbody>
</table>

- All extra particles have cosmological consequences.
  - Sparticles may provide “dark matter” of universe.
Accountability ...
Accelerators

Particle physics: probe shorter distance with higher energy

ring 6 km across

detector several metres tall
CMB (etc.)

Astrophysics: probe early universe by looking back in time
(universe expanding fast; speed of light finite)
What Led To String Theory ...
The Asymmetrical Treatment of Gravity

- **Quantum Field Theory (QFT)** is mathematical framework for Standard Model of Particle Physics: 3 interactions + particles.
- In Particle Physics, gravitational interaction is
  - largely ignored, because so weak;
  - treated only classically.
- Gravity last force to go quantum-mechanical, because *weakest*. Quantum gravity inaccessible in today’s accelerators.

- **Einstein’s General Theory of Relativity (GR)** is mathematical framework for classical theory of gravitational interaction. *Very* different than classical theories of other 3 interactions.
- GR describes **space-time as a dynamical fabric**, which is warped by matter, and causes matter to move.
A Theoretical Disaster and How to Fix It

- Twin pillars of 20th C. experimental physics, Quantum Field Theory & General Relativity, are fundamentally incompatible. Oops!!

- Need quantum theory of gravity that:
  - predicts sensible physics in extreme regimes, e.g. birth of universe, black holes;
  - reduces back to Einstein’s theory in ordinary regimes, e.g. solar system;
  - is internally consistent - strong constraint!
  - unifies all forces and matter together.

- Unique theory which does all this (as of now) is SUPERSTRING THEORY.
String Theory!
(... At Last!)
**Aboriginal String**

- All “particles” – matter and force-carriers (e.g. electron, quark, photon) are actually tiny vibrating *superstrings*, a.k.a. *strings*.

- String theory naturally lives in **ten dimensions of spacetime**. Necessary to roll up other six, inaccessible at low-energy now. **Properties of internal space enable differentiation of “particles”**.

- **Interactions** described solely by *splitting and joining of strings*. Smooth process. **Gravity automatic!**
Extra Dimensions of Space

• Theories incorporating this idea go back over 80 years.

• Macroscopic ant can walk in only one direction - the second one is just curled up so small it goes unnoticed.
• Microscopic ant would think twig surface is two-dimensional.

• State-of-the-art experiment says:
  – if we’re allowed in, extra dimensions must be $< 10^{-17} cm$
  – if only gravity is allowed in, they must be $< 0.15 mm$
Spacetime as Quantum and Dynamical

- Spacetime used to be the playing field of particles, interactions.
- But in string theory, we can smoothly:
  - tear the fabric of space, change its topology;
  - change the number of dimensions of space.

- So spacetime as a fundamental idea is probably doomed!
  Big spacetimes $>>$ string size must arise *dynamically* – how?

- Some of the remaining, intriguing questions:
  - Why does time run forwards?
  - Was there anything before the Big Bang?
  - Should quantum theory be applied to the whole universe?
  - Is our Universe a lucky cosmological accident?
String Theory: Where the Buck Stops

- Are there more layers of the onion?
- We reckon No – have strong indicators that the buck stops here: At ultra-high energy, things get big again.

\[
\Delta x = \frac{hc}{E} + l_s^2 \frac{E}{hc}
\]

- Minimum distance ~ string scale
- Want to understand
  - Fundamental degrees of freedom of string theory, and dynamical principles that govern them
  - Particle Physics applications: proton decay (diamonds aren’t forever!), quark confinement (this is US$1M question!), …
  - Early Universe Cosmology applications: dark matter, dark energy, particle/antiparticle excess, birth of universe…
Some Recent Progress We’ve Made

• **Black hole** is big fat classical spacetime in string theory
  – Event horizon = place of no return for infalling observer,
  – **Singularity** at centre – where GR+QFT breaks down.

• Near singularity, advantage of having string theory is that we know how to *calculate* there using full quantum string theory.

• Some spacetime singularities are so bad that whole spacetime must be thrown away. Others get resolved by stringy effects:
  – “enhançon”: stringy minimum-distance phenomenon in different clothing
  – “dielectric-brane” expansion
  – “spacelike branes” may help resolve spacelike (unavoidable) singularities; most progress to date on avoidable singularities
The End ...
Where to Learn More

www.superstringtheory.com

(Images used with permission)