String Theory for Pedestrians

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Outline

Fundamental Interactions

What is String Theory?

Modern String Theory
  String Phenomenology
  Gauge/Gravity Duality
  Physical Mathematics

Conclusions
Fundamental Interactions

- **Four fundamental forces of nature**
  - Electromagnetic Interactions: Photons
  - Strong Interactions: Gluons
  - Weak Interactions: $W$- and $Z$-bosons
  - Gravity: Graviton (?)

- **Successful theoretical models**
  - Quantum Field Theory
  - Einstein Gravity

- **Tested by high-precision experiments**
Gravity

- General Relativity

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \]

- Matter ↔ Curvature of spacetime
- No Quantum Theory of Gravity!
  - Black Holes
  - Big Bang
Particle Interactions

- Strong, weak and electromagnetic interactions can be described by the **Standard Model of Particle Physics**
  - Quantum Field Theory
  - Gauge Theory
Unification of Forces

- Can we find a unified quantum theory of all fundamental interactions?
  - Reconciliation of two different theoretical frameworks
  - Quantum Theory of Gravity
- Why is unification a good idea?
  - It worked before: electromagnetism, electroweak interactions
  - Evidence of unification of gauge couplings

![Graph showing unification of interactions helped by SUSY](image)

- Open problems of fundamental physics should be solved.
History of the Universe

- Physics of the early universe
Energy Budget of the Universe

- Only about 5% of the matter in the universe is understood.
- What is dark matter? Extra particles?
String Theory Fact Sheet

- String theory is a quantum theory that unifies the fundamental forces of nature.
- Point particles are replaced by extended objects called strings.
- String theory requires a ten-dimensional space-time.
- String theory requires supersymmetry.
- **String compactification** relates ten-dimensional string theory to our four-dimensional world.
- Via **string dualities** different compactifications can give the same four-dimensional physics.
### Point Particles vs. Strings

Point Particle

\[ X^\mu(\tau) \]

Worldline

String

\[ X^\mu(\tau, \sigma) \]

Worldsheet

- **Polyakov action**

\[
S[X^\mu, g_{mn}] = - \frac{T}{2} \int d^2 \sigma \sqrt{\det g_{mn}} g^{mn} \frac{\partial X^\mu}{\partial \sigma^m} \frac{\partial X^\nu}{\partial \sigma^n} G_{\mu\nu}
\]
Unification of Forces

- All particles and interactions come from string vibrations and interactions.

  - **Closed Strings**
    - Gravitational interactions
    - Lowest excitation: graviton

  - **Open Strings**
    - Gauge interactions
    - **D-branes**: objects where open strings can end
    - Different D-brane configurations lead to different gauge theories
Supersymmetry

- String Theory requires SUSY
  - Otherwise the lowest excitation of the string is a tachyon.
  - The vacuum is unstable
- SUSY is a symmetry between bosons and fermions.
  - Every particle has a superpartner with the same quantum numbers except for the spin
  - This doubles the particle spectrum.
- SUSY particles are dark matter candidates.
- At low energies SUSY must be broken.
- SUSY at the TeV scale is also useful in other contexts.
- SUSY searches at LHC
Extra Dimensions and Compactification

- String theory requires a ten-dimensional space-time.
  - Otherwise it is not a consistent quantum theory.
  - Conformal anomaly
- String compactification
  - The additional dimensions are small and curled up, so that our world appears effectively four-dimensional.

**Small “Extra” Dimensions**

Imagine them like a tightrope...

| A person can only walk forward and backward (one dimension) | An ant can also walk from side to side (two dimensions) |
String Compactifications

- The mathematical properties of the extra dimensions determine 4D physics:
  - particle masses, coupling constants, ...

\[ \langle \psi_1 \psi_2 \psi_3 \rangle^{10D} = \langle \psi_1 \psi_2 \psi_3 \rangle^{6D} \otimes \langle \psi_1 \psi_2 \psi_3 \rangle^{4D} \]

- Most famous examples: Calabi-Yau spaces.
Dualities

• Different string compactifications lead to the same four-dimensional physics.
  • Dualities map hard problems into simple(r) ones.

• Perturbative duality:
  • Purely classical quantities get mapped into quantum corrected ones.
  • Tool to compute quantum corrections
  • Example: Mirror Symmetry

• Non-perturbative duality:
  • Strongly-coupled theories map into weakly coupled ones.
  • Tool to analyze strongly-coupled theories
  • Example: Gauge-gravity correspondence
Energy Scales

- **String scale**
  - String Theory does not tell us anything about this.
  - As a theory of quantum gravity it should be valid at the Planck scale.
    - Planck mass: \( m_P = \sqrt{\frac{\hbar c}{G}} \sim 10^{19} \text{GeV} \).
    - Planck length: \( \ell_P = \sqrt{\frac{\hbar G}{c^2}} \sim 10^{-35} \text{m} \).
  - String theory effects may be visible at much lower energies. (TeV scale?)
    \( \Rightarrow \) Stringy corrections to scattering amplitudes.
  - Astrophysics may be able to probe energy ranges up to \( 10^{16} \text{GeV} \).

- **Two more scales**
  - Compactification scale
  - Supersymmetry scale
Is String Theory unique?

- Yes(-ish), in 10 dimensions.
  - Few incarnations that are related via dualities.
- Many solutions in 4 dimensions.
  - Landscape of “string vacua”. \((10^{500})\)
  - How many are really consistent?
  - How many are “viable”?
  - It is not uncommon that physical theories have more than one solution.
String Phenomenology

- **How to build a string model?**
  - Bottom-up: Take your favorite low-energy model beyond the standard model and embed it into string theory.
  - Top-down: Start off with a string compactification and analyze what the physics at low energies is.

- **Statistical analysis** of the string landscape
  - Systematically analyze basic properties of a large class of string compactifications.
  - Warning: potential bias due to choice of dataset!

- Compute **stringy corrections to scattering amplitudes**.
Achievements of String Phenomenology

- String models for **physics beyond the Standard Model**
  - Various approaches: D-branes, F-theory, heterotic string
- **Dark Matter** candidates
- String **inflation and cosmology**
- Statistical analysis of large portions of the landscape
  - Elementary consistency constraints greatly reduce the number of models
- Stringy corrections for TeV string scale.

- Many possibilities
  - proof of concept
  - explicit calculations
  - *not* anything goes
Gauge/Gravity Duality

- **Holography**: pure gravity theory in $d + 1$ dimensions is dual to a pure gauge theory in $d$ dimensions on the boundary of space-time
- **Strong/Weak coupling duality.**
Applications of Gauge/Gravity duality

- Study strongly coupled gauge theory through dual weakly coupled gravity theory
  - QCD, quark-gluon plasma
- Study strongly coupled gravity through weakly coupled dual field theory
  - Black holes
- Beyond fundamental interactions: applications in solid state theory
  - models for *superfluids and superconductors*
- String Theory delivers *new technology*
Physical Mathematics

- **Mathematical Physics**: mathematicians try to make physical theories “well-defined”
- **Physical Mathematics**: physicists find new mathematics via physics methods
- The physics of string compactifications has many connections to mathematics.
- String dualities connect fields of mathematics
Example: Mirror Symmetry

- Same 4D physics when compactifying on two different Calabi-Yaus
  - classical ↔ quantum
  - highly-non-trivial map between physical quantities

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What String Theory can do

- Provides a **consistent unified quantum theory of fundamental forces**.
- Provides **solutions to open problems of theoretical physics**
  - Physics beyond the Standard Model
  - Dark Matter problem
  - Quantum Gravity
- Makes qualitative **predictions about fundamental properties of nature**
  - Extra dimensions
  - Supersymmetry
- It provides **new mathematical tools** for theoretical physics.
What String Theory cannot do (yet)

- It does not make **experimental predictions** that clearly distinguish it from other theories beyond the Standard Model
  - Detection at LHC
  - Cosmic Strings through gravitational waves
- It does not give an indication where the string scale is.
- It **does not single out a string compactification** that describes “our universe”.
Why we should keep doing it

- It can provide answers for many open problems in theoretical physics.
- It is an intriguing theoretical concept.
- It is spectacularly self-consistent at the quantum level.
- It is not still not well-understood.
  - Landscape of vacua
  - Mathematical structure
- It is successful beyond fundamental interactions.
- There are currently no better alternatives.
All the gory details

- **Winter Term:** *String Theory 1* (VO 136.005)
  - Classical bosonic string and its symmetries
  - Quantization, spectrum and unification of forces
  - T-duality
  - Introduction to conformal field theory
- **Summer Term:** *String Theory 2* (VO 136.006)
  - String amplitudes
  - D-branes
  - Superstrings
  - String Compactifications (maybe...)
Thank you for your attention.