Eleven Dimensions of the Unifying Theory

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Friends of Imperial College
Two Pillars of XX Century Physics

• Quantum Mechanics: applies to the very small; atoms, subatomic particles and the forces between them.

• General Relativity: applies to the very large; stars, galaxies and gravity, the driving force of the cosmos as a whole.
Central Quandary of XXI Century Physics

• Quantum mechanics and general relativity are mutually incompatible!

• Microscopic scale: Einstein’s theory fails to comply with the quantum rules that govern the subatomic particles.

• Macroscopic scale: black holes are threatening the very foundations of quantum mechanics.

New scientific revolution? M-theory?
When is a particle `elementary'?
The building blocks: quarks and leptons

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
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<tbody>
<tr>
<td>u</td>
<td>e</td>
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<td>c</td>
<td>μ</td>
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<tr>
<td>t</td>
<td>τ</td>
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</tbody>
</table>

The Generations of Matter

- Generations I
  - u
  - e
- Generations II
  - d
  - μ
  - ν_e
- Generations III
  - s
  - τ
  - ν_μ

Plus their antiparticles:

- u
- d
- s
- ν_e
- μ
- ν_μ
- τ
- ν_τ
- t
- ν_t
- gluon
- annihilation
- top, anti-top
- anti-top
Four fundamental forces

<table>
<thead>
<tr>
<th>Carried By</th>
<th>Weak (Electroweak)</th>
<th>Electromagnetic</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graviton (not yet observed)</td>
<td>$W^+$ $W^-$ $Z^0$</td>
<td>Photon</td>
<td>Gluon</td>
</tr>
<tr>
<td>Acts on</td>
<td>All</td>
<td>Quarks and Leptons</td>
<td>Quarks and Charged Leptons and $W^+$ $W^-$</td>
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</tbody>
</table>

Plus the Higgs Boson to give mass to the $W$, $Z$, quarks and leptons = ``The Standard Model``
The particle view of nature is a description that works exceedingly well to describe three of the four observed forces of nature.

The geometric view of nature works very well for describing gravity at astronomical distance scales.
All-embracing theory?

If current ideas are correct, will require three radical ingredients:

1) Extra dimensions
2) Supersymmetry
3) Extended objects (strings, branes..)
Fifth dimension

- Kaluza and Klein imagined a small circle at each point of 4D spacetime

D=4 perspective:
Einstein’s gravity PLUS Maxwell’s electromagnetism!
Supersymmetry

1) Unifies bosons (force-carrying particles) with fermions (building block particles)

2) Implies gravity!

3) Places an upper limit on the dimension of spacetime:

\[ D = 11 \]
Early 1980s: D=11 supergravity:

Admits solutions in which seven dimensions are curled up a la Kaluza-Klein.

Different geometries yield different theories in 4D.

Some choices gave the right bosons (graviton, photon, gluons, W, Z, Higgs) but none gave the right fermions (no left-right asymmetry).

Moreover, gave infinite probabilities for quantum processes.
Particles versus strings

Particle physics interactions can occur at zero distance -- but Einstein's theory of gravity makes no sense at zero distance.

String interactions don't occur at one point but are spread out in a way that leads to more sensible quantum behavior.
1984 superstring revolution:

• Replace particles by strings:

gravity and quantum theory are reconciled.
String theories:

- **String vibration modes correspond to particles**
- **Crucially, they include the “graviton”**
- **Strings require ten space-time dimensions; six must be “curled-up”. Solves left-right problem.**

- *Heterotic SO(32) : closed superstrings*
- *Heterotic E8 x E8 : closed superstrings*
- *Type I : open and closed superstrings*
- *Type IIA : closed superstrings*
- *Type IIB : closed superstrings*

PUZZLES:

- Why five different ten-dimensional string theories?
- What about eleven dimensions?
- If strings, why not “branes”? 
0-branes, 1-branes, 2-branes,...p-branes.

Particle
p=0, d=1

String
p=1, d=2

Membrane
p=2, d=3
BRANE

Physics.

Brit. /bren/, U.S. /bren/ [Shortened < MEMBRANE n.]

I. Simple uses.

1. An extended object with any given number of dimensions, of which strings in string theory are examples with one dimension. Also with prefixed numbers, or symbols representing numbers, as 2-brane, p-brane.

1988

M. DUFF et al. in Nucl. Physics B. 297 516: We shall be concerned only with extended objects of one time and two space dimensions, i.e. ‘2-branes’... Possible ‘p-brane’ theories exist whenever there is a closed p + 2 form in superspace.

1996

Sci. Amer. Jan. 75/2 He [sc. M. J. Duff] found that a five-dimensional membrane, or a ‘five-brane’, that moved through a 10-dimensional space could serve as an alternative description of string theory.

II. Compounds.

2. BRANE-WORLD, a world model in which our space-time is the result of a three-brane moving through a space-time of higher dimension, with all interactions except gravity being confined to the three-brane.
The Brane Scan:

D = spacetime dimension

d = p + 1 = worldvolume dimension

R = real
C = complex
H = quaternion
O = octonion

String in D = 10 but
Membrane in D = 11
Strings in D=10 from membranes in D=11

As the underlying space, shown here as a two-dimensional sheet, curls into a cylinder, the membrane wraps around it. The curled dimension becomes a circle so small that the two-dimensional space ends up looking one-dimensional, like a line. The tightly wrapped membrane then resembles a string.

In fact it is the Type IIA string.
EDWIN ABBOTT:

FLATLAND 1884

STRINGLAND 1987
"Sorry, I know you've got charm but I'm really into branes."

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1995 M-theory revolution

- Five different string theories and D=11 supergravity unified by eleven-dimensional M-theory: strings plus branes
Edward Witten, Fields Medalist and string theorist

``M stands for magic, mystery or membrane, according to taste”

“Understanding what M- theory really is would transform our understanding of nature at least as radically as occurred in any of the major scientific upheavals in the past”
M-theory: the theory formerly known as strings
The braneworld

Parallel universes?
Story so far: Unification

Electricity

Magnetism

Weak nuclear force

Electro-weak force

Grand unified force

Strong nuclear force

Gravitational force

5 Different Theories

D=10 String

M-theory

+branes in D=11
Salam +50 Conference
Imperial College
London
100 years of living science

On Saturday 7 July to coincide with the Imperial College Centenary celebrations there will be a series of public talks marking the 50th anniversary of the arrival of the late Nobel Laureate Professor Abdus Salam at Imperial College.

Sir Alexander Fleming Lecture Hall
Imperial College London
Saturday 7th July 2007
9.30 am to 5.30 pm

Lunch and refreshments will be provided

The event is free and open to all on a first-come-first-served by registering at www.imperial.ac.uk/physics/conferences/salam50

Speakers
Sir Richard Sykes, Rector
Imperial College
Professor Emeritus Hoct, Nobel Laureate
University of Heidelberg
Micas Ahmed
President of the Ahmadiyya Muslim Community (UK)
Professor Sabena Hussain
Leicester University of Management Sciences
Formerly Head of Office of External Activities,
Abdus Salam ICTP, Trieste
Dr Gordon Fraser
Salam biographer
Dr Malakkar Laha
Pakistan High Commissioner, UK

Members of the Salam family
Dr Ayesha Rahim (daughter)
Afzal Salam (son), Urwa Salam (son)
Sadaf Jafri (grandson)

Sponsored by Science and Technology Funding Council, UK; Faculty of Natural Sciences, Imperial College
M theory is an ambitious attempt to answer all the Big Questions (A Theory of Everything):

• How did the universe begin?

• What are its fundamental constituents?

• What are the laws of Nature that govern these constituents?

Victim of its own success?
Curling up the extra dimensions on a Calabi-Yau manifold

- Different choices of Calabi-Yau lead to different four-dimensional universes

BUT

There are billions (possibly infinitely many) of them!

This is the "STRING LANDSCAPE"
What does this mean?

Theorists are divided:

• **THE UNIVERSE**: there is one universe with a unique set of fundamental laws.

  OR

• **THE MULTIVERSE**: there are many universes each with different laws: We just happen to be living in one of them!
  • Bio-friendliness explained?
``Most advances in the history of science have been marked by discoveries about nature, but at certain turning points we have made discoveries about science itself. These discoveries lead to changes in how we score our work, in what we consider to be an acceptable theory.”

``Now we may be at a new turning point, a radical change in what we accept as a legitimate foundation for a physical theory. The current excitement is of course a consequence of the discovery of a vast number of solutions of string theory.”
``The landscape idea? I hate it"

“Never, never, never, never give up!”
Lord Rees, cosmologist

``The universe in which we’ve emerged belongs to the unusual subset that permits complexity and consciousness to develop. Once we accept this, various apparently special features of our universe -- those that some theologians once adduced as evidence for Providence or design -- occasion no surprise.”
A unique universe?

The multiverse idea is, in fact, bucking an historical trend towards uniqueness of physical laws. For example, mathematical consistency demands that the fundamental building blocks of matter must come in complete families:

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A universe the same as ours, but without the top quark, for example, is theoretically forbidden (even in string/M-theory).

Sure enough, the top quark (the final missing piece of the jigsaw) was discovered experimentally in 1995.
Murray Gell-Mann, Nobel laureate and string theorist

``If we really live in a multiverse, Physics will have been reduced to an environmental science like Botany.”
Is M-theory testable?

Generic features:

Supersymmetric particles
Extra dimensions
Microscopic black holes
Cosmic strings

If we were lucky, some might be seen at the next generation of accelerators and/or astrophysical observations
CERN's Large Hadron Collider 2008
Planck surveyor 2009
BUT

Landscape problem means there is no definitive "smoking-gun" experimentally falsifiable prediction.

This has lead to accusations that string and M-theory are not SCIENCE

Yet even if we stopped doing M-theory tomorrow, the landscape problem (why one physical universe out of many mathematical possibilities) is one that will have to be confronted by any attempt at a final theory.
BLACK HOLES

- "all light emitted from such a body would be made to return towards it by its own proper gravity" John Michell in 1784 on the concept of black hole

Laplace 1786

Schwarzschild 1916

Oppenheimer 1939
Quantum entanglement

Einstein, Podolsky, Rosen: paradox 1935

John Bell: falsifiable prediction 1964

Alain Aspect: empirical confirmation 1982
Time-lags between Theory and Experiment

**Examples:**

- Black holes: predicted 1784, confirmed 1970s
- Bose-Einstein condensate: predicted 1925, confirmed 1995
- Neutrinos: predicted 1930, confirmed 1956
- Quantum entanglement: predicted 1935, discovered 1982

- Predicted but not yet confirmed:
  - Gravitational waves (1916)
  - The cosmological constant (1917)
  - Extra dimensions (1926)
  - The Higgs boson (1964)
  - Supersymmetry (1971)
So is M the Full Monty?
So is M the Final Theory?

It is too early to tell