M-Physics

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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?
Building block particles: quarks and leptons

plus their antiparticles:
Force-carrying particles: gauge bosons

Plus the Higgs Boson to give mass to the W, Z, quarks and leptons=
``The Standard Model” SU(3) x SU(2) x U(1)
Two views of the forces

**Force-carrying particles**

The particle view of nature is a description that works exceedingly well to describe three of the four observed forces of nature.

**Riemannian geometry**

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! Electric charge quantized.
Supersymmetry

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

2) Global\{Special Relativity\}
   \{supersymmetry square root of \{Local \{General Relativity\}\}\}

   Implies gravity! (See PvN lectures)

3) Places an upper limit on the dimension of spacetime \(D=11\)
Three younger physicists, Nobel Symposium Marstrand 1986
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"?
Finally, the maximum space-time dimension permitted by supersymmetry is $D = 11$, whereas superstrings exist in $D = 10$. The recent discovery of a supersymmetric theory of a three-dimensional extended object in $D = 11$ may resolve this old puzzle. We do not yet know whether this “supermembrane” is consistent at the quantum level, but the orthodox claim that only strings can be quantum consistent now looks much less certain.
Many of the supergravity theories that we used to study a few years ago are now known to be merely the field theory limit of an underlying string theory\(^1\). For example, \(N = 2\)a supergravity in ten dimensions is just the field theory limit of the Type IIA superstring. What are we to make, therefore, of supergravity theories which cannot be obtained from strings such as \(N = 1\) supergravity in eleven dimensions\(^2,3\)? This is a particularly puzzling example since it is
0-branes, 1-branes, 2-branes,...p-branes.

<table>
<thead>
<tr>
<th>Particle</th>
<th>String</th>
<th>Membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>p=0, d=1</td>
<td>p=1, d=2</td>
<td>p=2, d=3</td>
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OXFORD ENGLISH DICTIONARY

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
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
1995 M-theory revolution

- Five different string theories and D=11 supergravity unified by eleven-dimensional M-theory: strings plus branes
``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”
NOVELTIES OF M-THEORY

Branes as well as strings (M-branes and D-branes)

Subsumes D=11 sugra and five D=10 strings

Non-perturbative: eg Interchanges T duality (R goes to 1/R) with S-duality (e goes to 1/e).

KK quantization = Dirac monopole quantization

Microscopic origin of Bekenstein/Hawking black hole entropy

Gauge/gravity duality, incorporates “Holography”

The “Braneworld”
We have recently constructed a self-dual Type IIB superthreenbrane [26] which represents a new point \((d = 4, D = 10)\) on the brane-scan. Earlier no-go theorems [17] are circumvented because there are spin 1 fields on the worldvolume. In fact, the gauge-fixed theory on the worldvolume is described by a \(d = 4\) \(N = 4\) Maxwell supermultiplet.
Story so far: Unification

Electricity

Electromagnetic force

Magnetism

Electro-weak force

Weak nuclear force

Strong nuclear force

Grand unified force

5 Different Theories

D=10 String M-theory

Gravitational force

+branes in D=11

Faraday 1831

Glashow, Weinberg, Salam 1967

Georgi, Glashow 1974

Green, Schwarz 1984

Witten 1995
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!
M-theory has even more!
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.”
David Gross, Nobel laureate and string theorist

``The landscape idea? I hate it ''

“Never, never, never, never give up!”
``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.”
``I will describe what I see as the framework for quantum cosmology, on the basis of M theory. I shall adopt the no boundary proposal, and shall argue that the Anthropic Principle is essential, if one is to pick out a solution to represent our universe, from the whole zoo of solutions allowed by M theory.”

``In general anthropic reasoning aims to explain certain features of our universe from our existence in it. One possible motivation for this line of reasoning is that the observed values and correlations of certain parameters in particle physics and cosmology appear necessary to ensure life emerges in our universe. ”
An Extensive Landscape with a Hawking Party

KONINCK, Philips 1619 - 1688
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:

![Diagram of quarks and leptons]

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

2012 Higgs but no supersymmetry (yet)
Gravitational waves observed 2015
Also confirmed black holes
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
- Quantum entanglement: predicted 1935, discovered 1982
- Bose-Einstein condensate: predicted 1925, confirmed 1995
- The cosmological constant, predicted 1917, confirmed (?) 1998
- The Higgs boson, predicted 1964, discovered 2012
- Gravitational waves, predicted 1916, discovered 2015

Predicted but not yet confirmed

Extra dimensions (1926)
Supersymmetry (1971)
M-theory (1995)
Repurposing string theory

1970s Strong nuclear interactions

1980s Quantum gravity; ``theory of everything”

1990s AdS/CFT: QCD (revival of 1970s); quark-gluon plasmas

2000s AdS/CFT: superconductors

2000s Cosmic strings

2000s Fluid mechanics

2010s Black hole/qubit correspondence:: entanglement in Quantum Information Theory
Falsifiable predictions

Early result 2006:
STU black holes imply 5 ways to entangle three qubits
Already known in QI; verified experimentally

Later result 2010:
STU black holes imply 31 ways to entangle four qubits
Not already known in QI: in principle testable in the laboratory
\( \frac{1}{2} \) BPS and non-BPS

\[
\text{SO}(4,4)
\]

\[
\text{SO}(2;3;\mathbb{R}) \times [(5+1)^2]
\]

PhysRevLett.105.100507
$\frac{1}{2}$ BPS and non-BPS

$S_0(4,4)$

$\text{SO}(2;3;\mathbb{R}) \times [(5+1)^2]$
So is M the Full Monty?
So is M the Final Theory?

It is too early to tell