String Theory: Alexander or Ozymandias?

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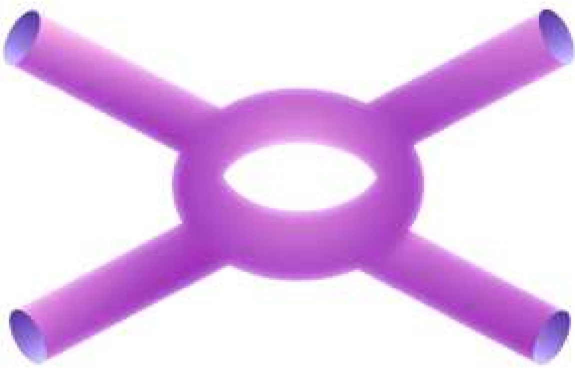
Research Consilium, 19th October 2011

Talk Structure

- Introducing the protagonists
- String theory through the ages
- Where does string theory fit in?
- Taking the string out of string theory

String theory



String theory

String theory is

- The theory obtained from the quantum mechanical description of a relativistic string
- A proposed unification of the fundamental forces through the oscillatory harmonics of a string.
- The dominant approach to a quantum theory of gravity in theoretical particle physics

Direct experimental evidence for string theory

Alexander the great

Pupil of Aristotle who died aged 33 with an empire stretching from the Adriatic to the Himalayas.

Ozymandias of Egypt

I met a traveller from an antique land
Who said, "Two vast and trunkless legs of stone
Stand in the desert. Near them, on the sand,
Half sunk, a shattered visage lies, whose frown
And wrinkled lip, and sneer of cold command,
Tell that its sculptor well those passions read
Which yet survive, stamped on these lifeless things,
The hand that mocked them and the heart that fed.
And on the pedestal these words appear:
"My name is Ozymandias, king of kings:
Look on my works, ye Mighty, and despair!"
Nothing beside remains. Round the decay
Of that colossal wreck, boundless and bare
The lone and level sands stretch far away.

Percy Shelley, 1818

A and O

Both were empire-builders, both lived long ago and both are dead.

Subsequent cultural influence varies widely

Alexander:

Ozymandias:

Dead language, name a Greek transliteration, second largest Egyptian city called Alexandria...

String Theory

String theory is a dominant paradigm in modern theoretical physics.

Thousands of physicists worldwide work on it.

However it has achieved this status without any direct experimental support.

Why is this so, and what will be the ultimate fate of the subject?

String Theory

The popular view of string theory has changed over time.

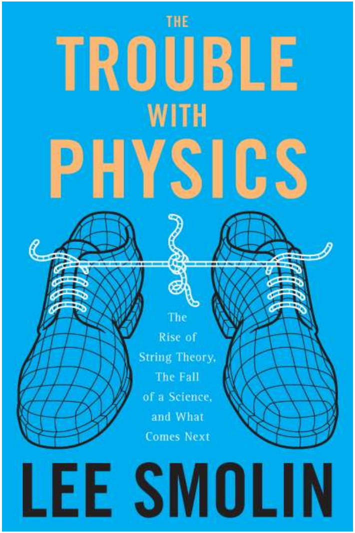
String theory: hard subject for clever people...

"It's all string theory to me."

New Yorker, September 1998

String theory: hard subject for clever people...

String theory: science in knots...



String theory: faeces tauri...

New Yorker, January 2007

String theory

Where does string theory fit in to physics?

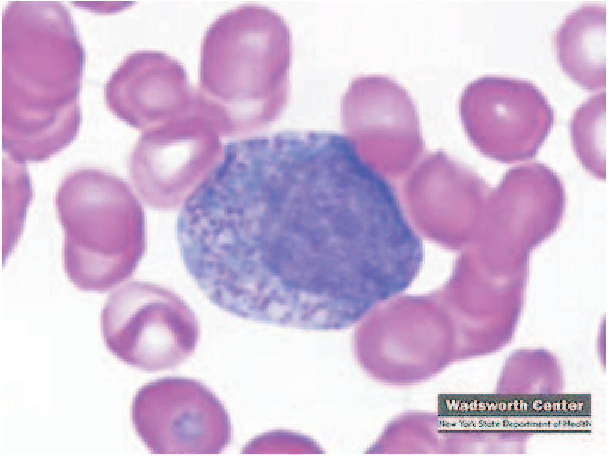
Let us review the known length scales in physics and what happens at each of them.

One metre

Described by Newtonian mechanics - most visible force is the gravitational pull of the earth.

Ten micrometres

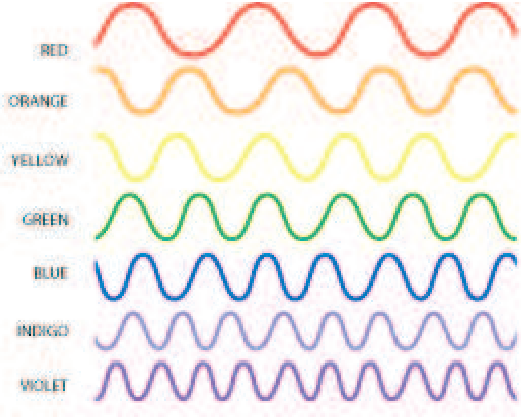
0.00001 (10^{-5}) of a metre



Typical size of a human cell - dominant interactions are electromagnetic

Five hundred nanometres

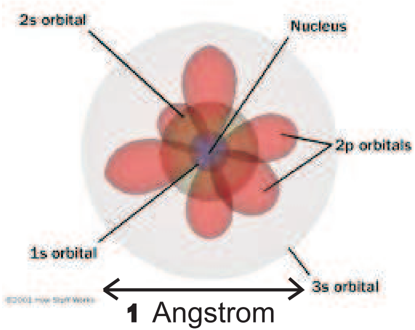
0.0000005 (5×10^{-7}) of a metre



Wavelength of visible light

One Angstrom

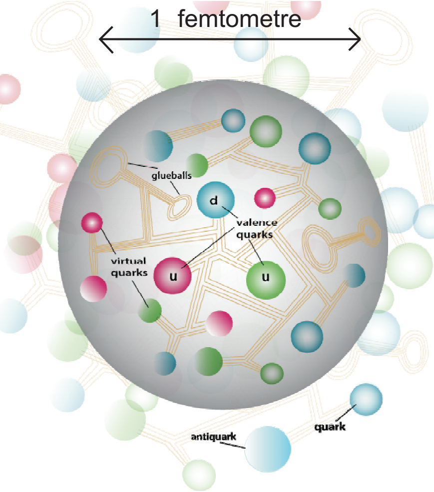
0.0000000001 (10^{-10}) of a metre



Atomic scale - described by quantum mechanics 1926-style

One femtometre

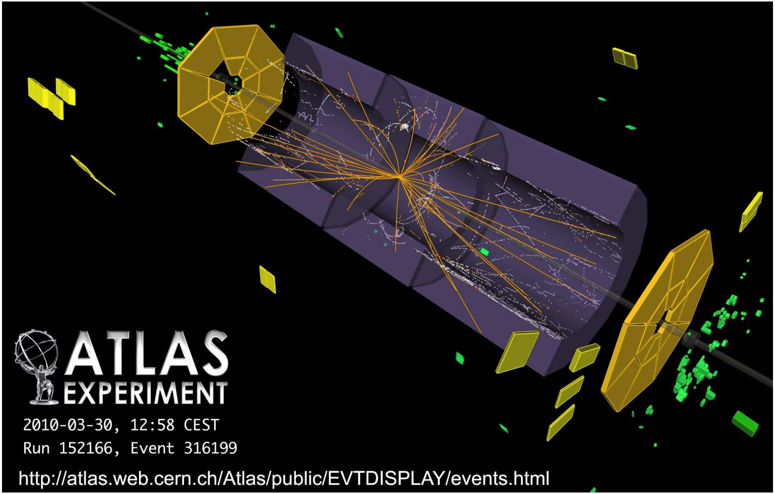
0.000000000000001 (10^{-15}) of a metre: the radius of a proton



Proton is held together by the strong nuclear force.

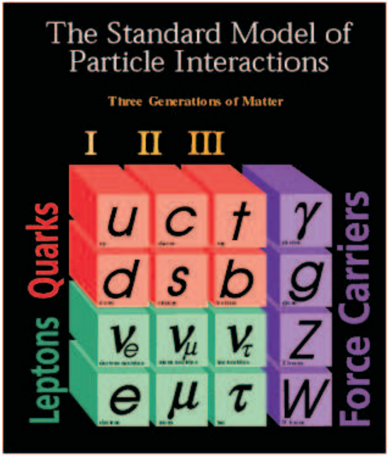
One picometre

0.000000000000000001 (10^{-18}) of a metre: scale probed by the LHC



Scale probed by the LHC - described by the Standard Model

The Standard Model



The Standard Model

$$
\begin{aligned}
L(\ldots) = & -\frac{1}{4g_s^2}G_A^{\mu\nu}(x)G_{A\mu\nu}(x) - \frac{1}{4g_w^2}W_a^{\mu\nu}(x)W_{a\mu\nu}(x) - \frac{1}{4g_y^2}V^{\mu\nu}(x)V_{\mu\nu}(x) + \\
& + [D_\mu^{(W,V)}\phi(x)]^\dagger D^{(W,V)\mu}\phi(x) - \lambda(\phi^\dagger(x)\phi(x) - \phi_o^2)^2 + \\
& + \bar{\psi}_{Li}^{(l)}(x)i\gamma^\mu(\partial_\mu + W_{a\mu}(x)T_w^a + V_\mu(x)Y_w)\psi_{Li}^{(l)}(x) + \\
& + \bar{\psi}_{Ri}^{(l)}(x)i\gamma^\mu(\partial_\mu + V_\mu(x)Y_w)\psi_{Ri}^{(l)}(x) + \\
& + \bar{\psi}_{Li}^{(l)}(x)\cdot\frac{\phi(x)}{\phi_o}M_{ij}^{(l)}\psi_{Rj}^{(l)}(x) + \bar{\psi}_{Ri}^{(l)}(x)M_{ij}^{(l)\dagger}\frac{\phi^\dagger(x)}{\phi_o}\cdot\psi_{Lj}^{(l)}(x) + \\
& + \bar{\psi}_{Li}^{(q)}(x)i\gamma^\mu(\partial_\mu + W_{a\mu}(x)T_w^a + V_\mu(x)Y_w + G_{A\mu}(x)T_s^A)\psi_{Li}^{(q)}(x) + \\
& + \bar{\psi}_{Ri}^{(q)}(x)i\gamma^\mu(\partial_\mu + V_\mu(x)Y_w + G_{A\mu}(x)T_s^A)\psi_{Ri}^{(q)}(x) + \\
& + \bar{\tilde{\psi}}_{Ri}^{(q)}(x)i\gamma^\mu(\partial_\mu + V_\mu(x)Y_w + G_{A\mu}(x)T_s^A)\tilde{\psi}_{Ri}^{(q)}(x) + \\
& + \bar{\psi}_{Li}^{(q)}(x)\cdot\frac{\phi(x)}{\phi_o}M_{ij}^{(q)}\psi_{Rj}^{(q)}(x) + \bar{\psi}_{Ri}^{(q)}(x)M_{ij}^{(q)\dagger}\frac{\phi^\dagger(x)}{\phi_o}\cdot\psi_{Lj}^{(q)}(x) + \\
& + \bar{\psi}_{Li}^{(q)}(x)\cdot\frac{\tilde{\phi}(x)}{\phi_o}\tilde{M}_{ij}^{(q)}\tilde{\psi}_{Rj}^{(q)}(x) + \bar{\tilde{\psi}}_{Ri}^{(q)}(x)\tilde{M}_{ij}^{(q)\dagger}\frac{\tilde{\phi}^\dagger(x)}{\phi_o}\cdot\psi_{Lj}^{(q)}(x) + \\
& + \theta\frac{g_s}{32\pi^2}G_{A\mu\nu}(x)\tilde{G}_A^{\mu\nu}(x)
\end{aligned}
$$

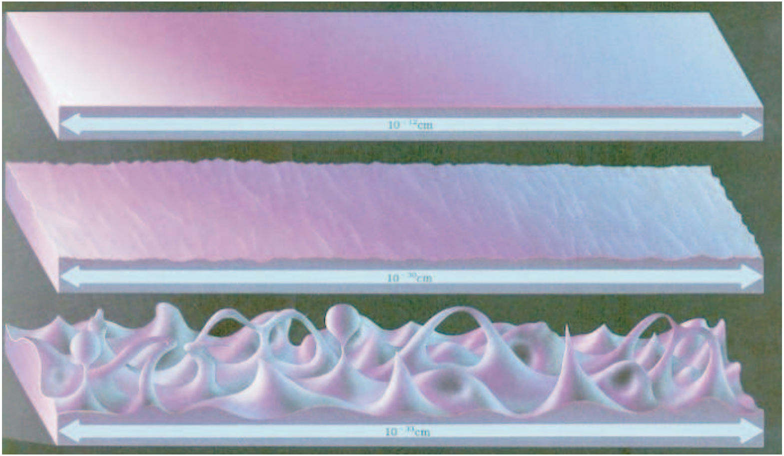
IMG by M. Di Pierro

The Standard Model

- The Standard Model uses quantum field theory to describe the forces and interactions of the known particles.
- It was formulated in the 1970s and has successfully described all data from particle colliders since then.
- It has approximately twenty input parameters not explained by the Standard Model. These have a clear structure (for example $|\theta_{QCD}| \lesssim 10^{-8}$).
- It encapsulates all our knowledge of small-scale physics.
- The LHC searches for evidence of new physics beyond the Standard Model.

Planck Length

0.0000000000000000000000000000000001 (10^{-34}) of a metre



Distance scale by which quantum gravity effects must have become important

String theory

String theory is a proposed quantum theory of gravity

Stringy effects must become important some distance between LHC scales 10^{-18} metres and the Planck scale 10^{-34} metre.

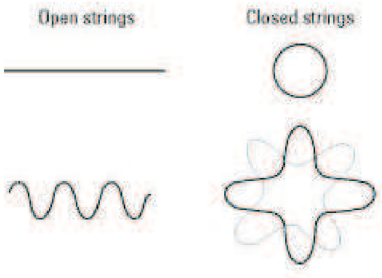
It is not clear where this should be although the expectation is more towards the latter.

What is string theory?

- String theory is a candidate theory of quantum gravity, in which the gravitational force and strong/weak/electromagnetic forces have a unified origin as oscillatory modes of the string.
- String theory is the theory that comes from the quantum mechanical treatment of a relativistic string.
- Different harmonics of strings correspond to different particles.
- ‘String harmonic’ has exactly the same connotation as harmonics on a violin string: higher frequency excitations.

What is string theory?

There are two types of string:



Open strings give Yang-Mills forces and particles (the type in the Standard Model). Closed strings give gravitational forces.

The full theory can be built up from this starting point.

Why string theory?

Why do lots of people work on string theory?

One main reason is that string theory, walks, talks, quacks and calculates like a theory of quantum gravity.

Einsteins equations emerge naturally

The technical formulation of a consistent quantum mechanical string theory is highly restrictive.

In particular, it can only be done for spacetimes satisfying Einstein's equation of general relativity

$$G_{\mu\nu} = 8\pi T_{\mu\nu}^{matter}.$$

This is the meaning of the statement 'string theory predicts gravity'.

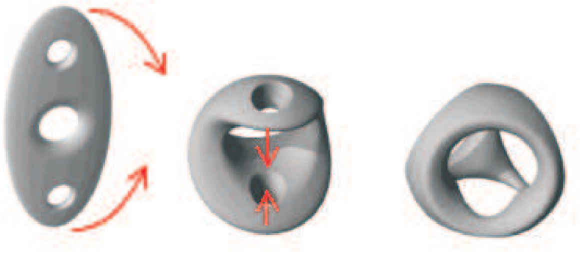
Dimension dynamically determined

The technical formulation of a consistent quantum mechanical string theory is highly restrictive.

In particular, consistency restricts the spacetime dimension to be 10.

For string theory descriptions of the world, this requires six dimensions to be curled up to be small and unobservable (typically at distances smaller than 10^{-18} metres).

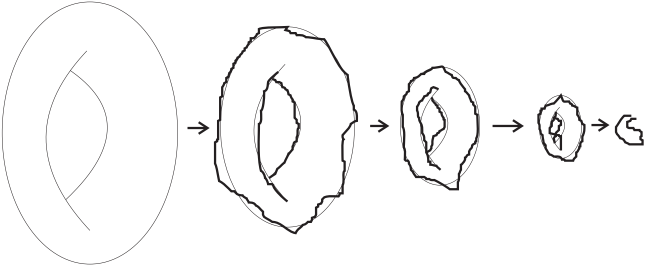
Topology Change



The theory smoothly describes continuous processes in which space-time topology changes.

Classical general relativity breaks down badly in such processes as curvatures become infinite.

Smooth transition between geometric and non-geometric regimes



The theory smoothly describes continuous transitions between long-distance ‘classical geometric’ and short-distance ‘quantum geometric’ regimes.

Why string theory?

Why do lots of people work on string theory?

Another main reason is that string theory is correct.

Maybe not true, but correct.

Mirror Symmetry

TABLE 4
The numbers of rational curves of degree k for $1 \leq k \leq 10$

k	n_k
1	2875
2	6 09250
3	3172 06375
4	24 24675 30000
5	22930 58888 87625
6	248 24974 21180 22000
7	2 95091 05057 08456 59250
8	3756 32160 93747 66035 50000
9	50 38405 10416 98524 36451 06250
10	70428 81649 78454 68611 34882 49750

number of conics [28] (rational curves of degree two). Clemens has shown [30] that $n_k \neq 0$ for infinitely many k and has conjectured that $n_k \neq 0$ for all k, but it seems that the direct calculation of these numbers becomes difficult beyond $k = 2$ (see also ref. [28]). It is however straightforward to develop the series (5.12) to more terms and to find the n_k by comparison with (5.13). We present the first few n_k in table 4. These numbers provide compelling evidence that our assumption about

AdS/CFT

The AdS/CFT correspondence asserts the exact equivalence of two special theories: 'N=4 Super Yang Mills theory' (a 4-dimensional quantum field theory) and 'IIB string theory on $AdS_5 \times S_5$'.

This remarkable equivalence is meant to be entirely exact.

A major effort over the last ten years has been checking and rechecking this correspondence to ever higher accuracy.

It works.

Why string theory?

Why do lots of people work on string theory?

String theory is not just a theory of quantum gravity.

Applications to Mathematics

String theory has had a significant effect on mathematics and algebraic geometry through the concept of *mirror symmetry*.

This relates the properties of two different geometrical (Calabi-Yau) spaces, and allows hard calculations on one to be replaced by easy calculations on the other.

For example, it allows easy ways to calculate the number of 'different spheres' that can be put inside a Calabi-Yau.

In this case, there is a physics reason why a result should hold, but which is not obvious from a mathematical perspective.

Applications to Quantum Field Theory

The standard language for particle physics is quantum field theory.

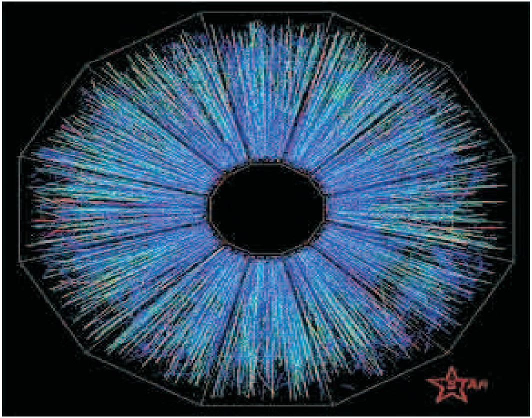
One remarkable discovery is that quantum field theories in d dimensions can be exactly the same as gravitational (string) theories in $d+1$-dimensions.

A consequence is that hard calculations in strongly coupled 4-dimensional quantum field theories can be carried out in weakly coupled 5-dimensional gravitational theories.

This approach has proved enormously fruitful in understanding strongly coupled field theories.

Applications to Quantum Field Theory

One surprising application is that the properties of black holes can be used to model the quark/gluon plasma formed by high-energy collisions of gold ions.



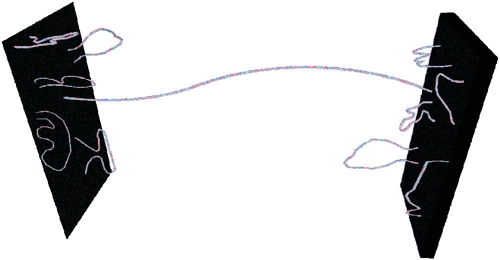
Applications to General Relativity

The development of string theory in the 1980s went in parallel with developments in general relativity.

Relativists discovered many ‘brane’ solutions to higher dimensional general relativity.

These correspond to higher dimensional versions of black holes or membranes.

These were realised in 1995 to fit simply into string theory as an object called a ‘Dirichlet brane’

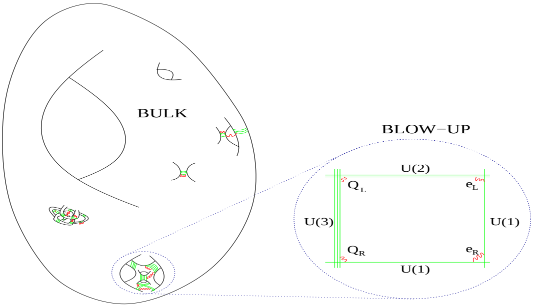


Applications to Particle Physics

String theory naturally contain the gross features of the Standard Model (chiral matter and non-Abelian gauge groups).

It is natural to try and realise string theory constructions of the Standard Model. (cf Andre Lukas's work).

Many modern proposals in particle physics draw on string theory concepts (branes/ extra dimensions).



Conclusions

String theory is a proposed theory of quantum gravity.

It is also much, much more, and most work on string theory has nothing directly to do with quantum gravity.

The success of the theory is due to the wealth of applications to mathematics, quantum field theory, general relativity and particle physics.

This is why so many people work on string theory even though there are no direct ways to probe quantum gravity.

The Answer