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Strings
Black holes and qubits

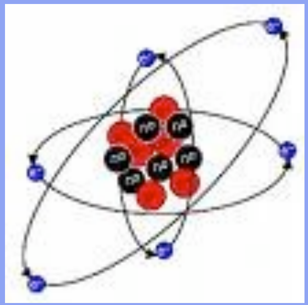
Michael Duff

January 2011

Madrid

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.

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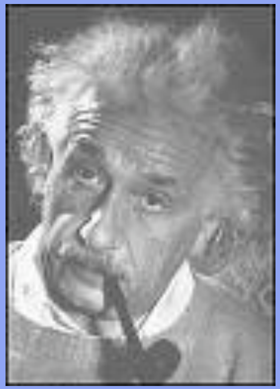
Central Quandary of XXI Century Physics

- Quantum mechanics and general relativity are mutually incompatible!

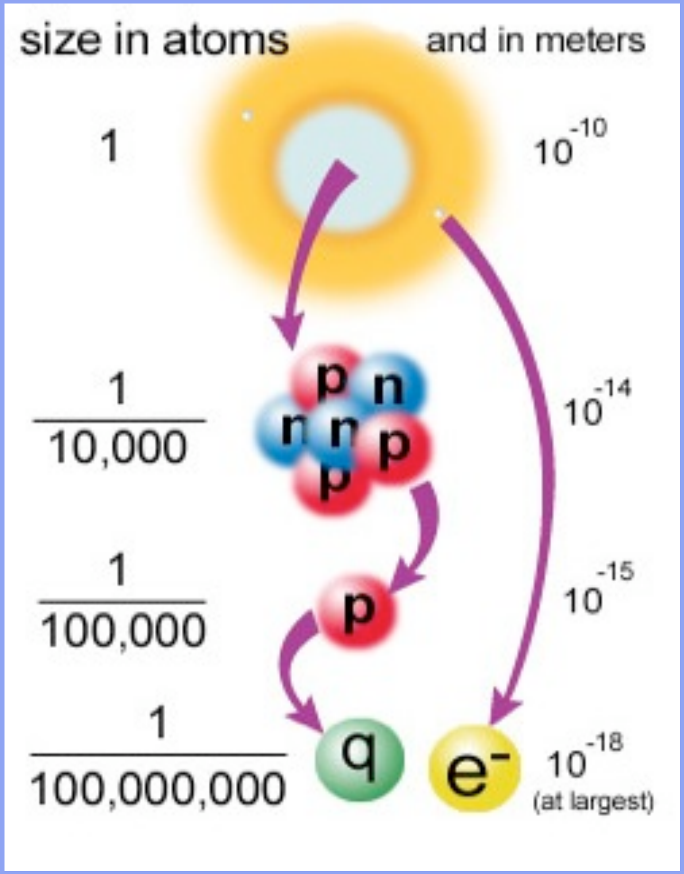
- Microscopic scale: Einstein's theory fails to comply with the quantum rules that govern the subatomic particles.



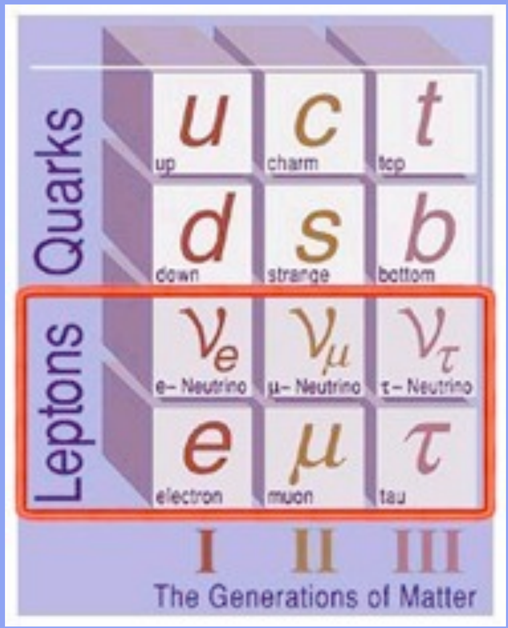
- Macroscopic scale: black holes are threatening the very foundations of quantum mechanics.

New scientific revolution? String/M- theory?

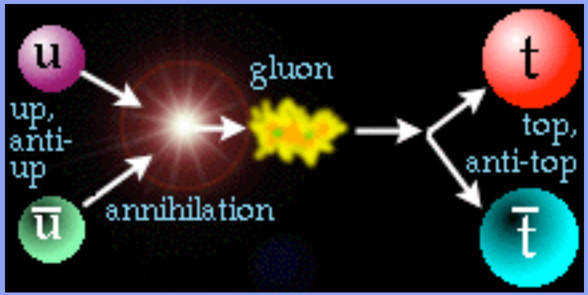
When is a particle ``elementary''?



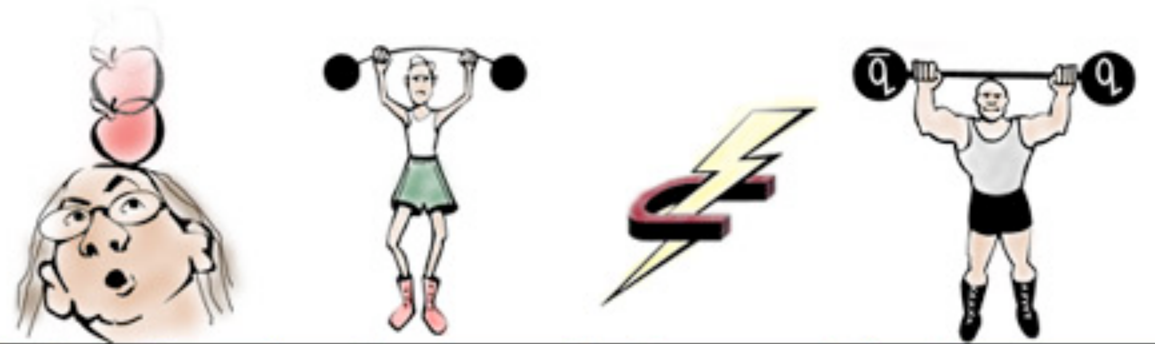
The building blocks : quarks and leptons



plus their antiparticles:



Four fundamental forces



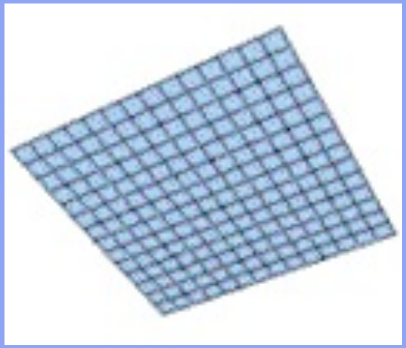
	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	$W^+ W^- Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ W^-$	Quarks and Gluons

Plus the Higgs Boson to give mass to the W, Z, quarks and leptons=

``The Standard Model''

What exactly is a force?

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?

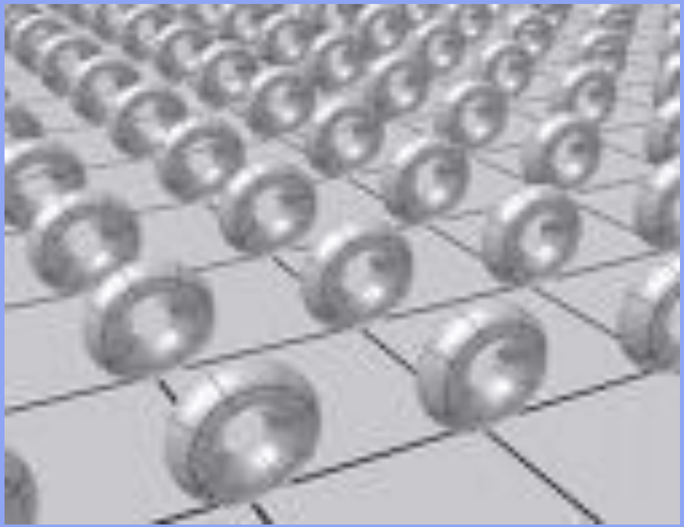
If current ideas are correct, will require three radical ingredients:

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!

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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.

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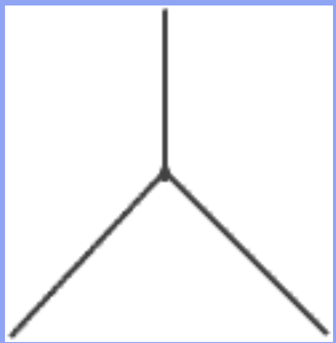
Particles versus strings

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.

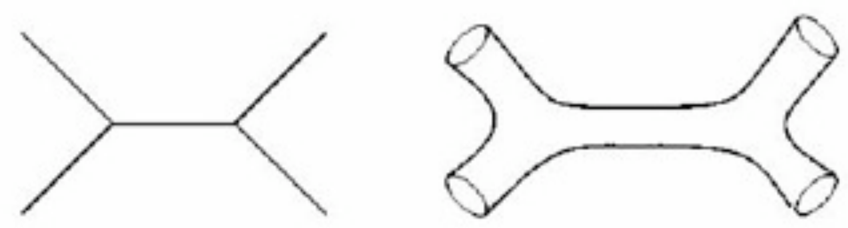


Fig.3: Particle scattering processes (left), string scattering processes (right).

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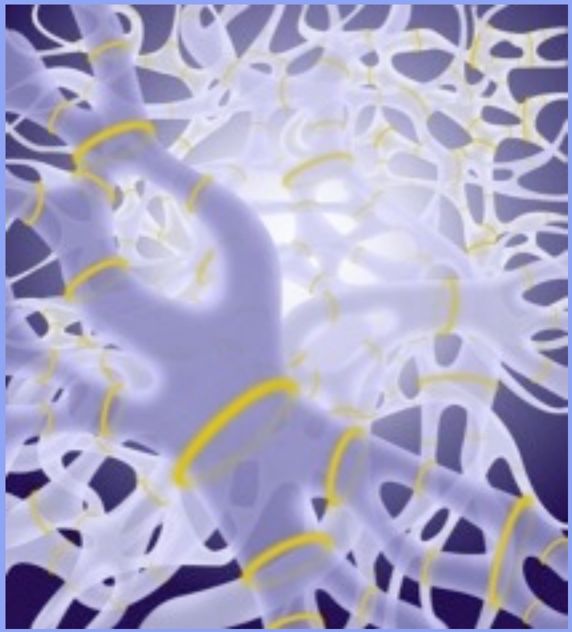
1984 superstring revolution:

- Replace particles by strings:

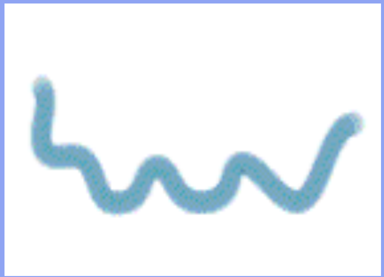


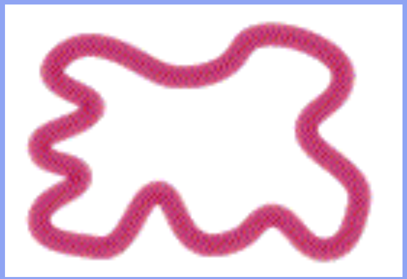
gravity and quantum theory are reconciled.

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"?

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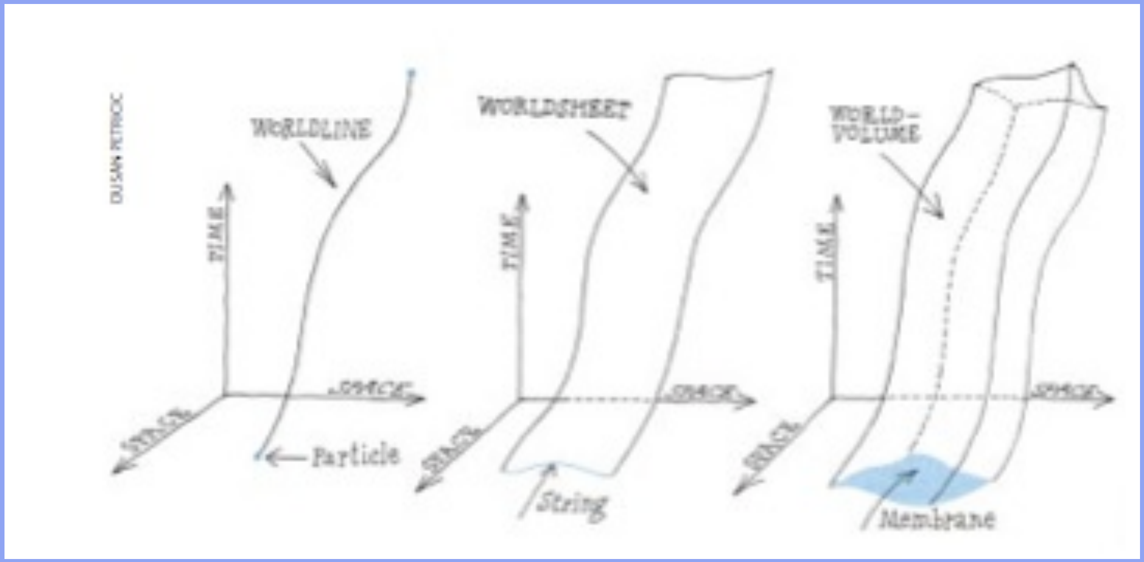
0-branes, 1-branes, 2-branes,...p-branes.



Particle	String	Membrane
p=0,d=1	p=1,d=2	p=2,d=3

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

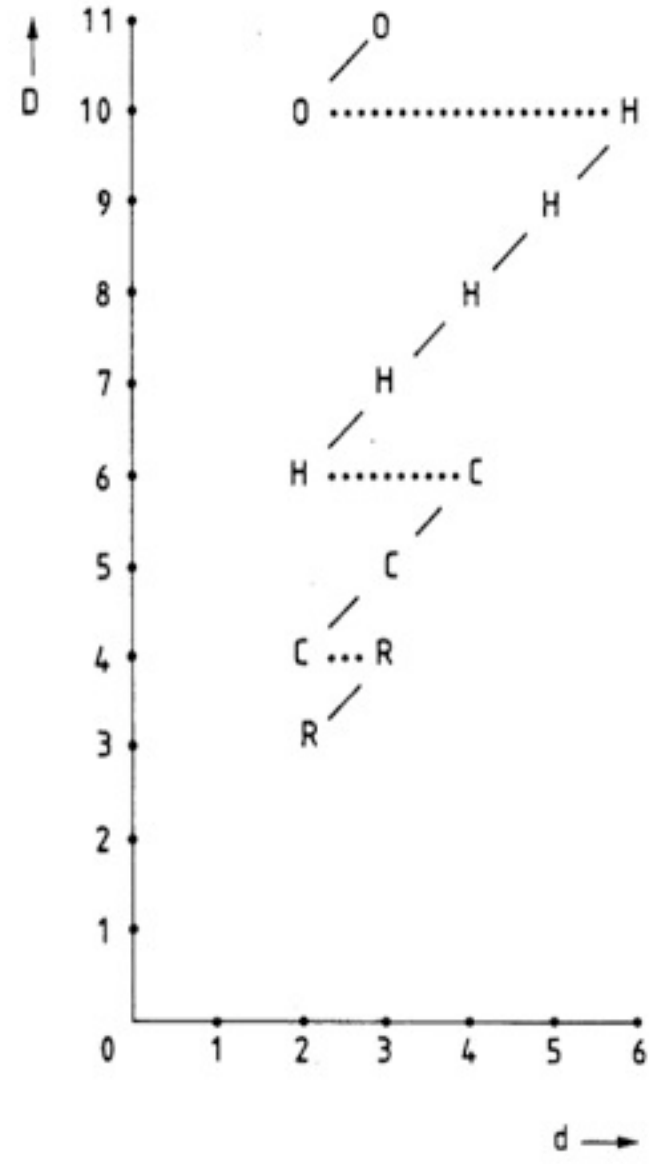
R=real

C=complex

H=quaternion

O=octonion

String in D=10 but Membrane in D=11



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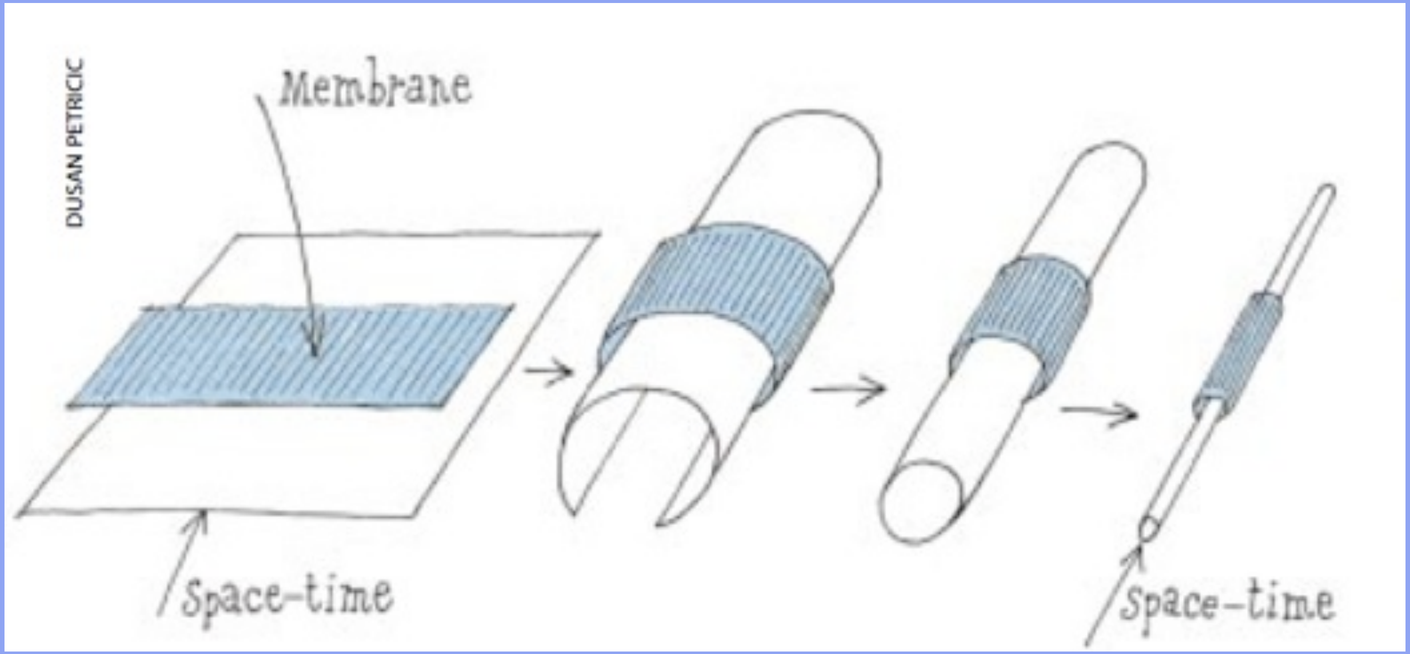
Strings in D=10 from membranes in D=11



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.

Branes

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

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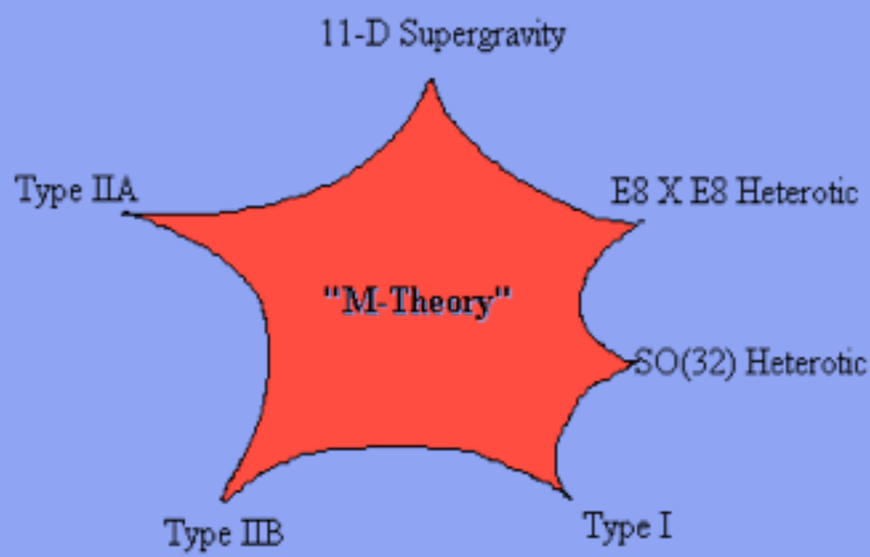
1995 M-theory revolution

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



Edward Witten, Fields Medalist

``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”

*

Story so far: Unification

Faraday	Glashow,Weinberg,Salam	Georgi,Glashow	Green,Schwarz	Witten
1831	1967	1974	1984	1995

Electricity }
}
} Electromagnetic force }
} }
Magnetism} } Electro-weak force }
} }
Weak nuclear force} } Grand unified force }
} } 5 Different } ?
Strong nuclear force} } D=10 String } M-theory
} Theories }
Gravitational force} +branes in D=11

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Repurposing string theory

1970s Strong interactions

1980s Quantum gravity; ``theory of everything''

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

2000s AdS/CFT: superconductors

2000s Cosmic strings

2010s Black hole/qubit correspondence: entanglement in Quantum Informatio

Falsifiable predictions:

Previous result 2006:

Stringy black holes imply 5 ways to entangle three qubits

Already known in QI; verified experimentally

New result 2010:

Stringy black holes imply 31 ways to entangle four qubits

Not already known in QI: in principle testable in the laboratory

Abstract

- Quantum entanglement lies at the heart of quantum information theory, with applications to quantum computing, teleportation, cryptography and communication. In the apparently separate world of quantum gravity, the Bekenstein-Hawking entropy of black holes has also occupied center stage.
- Here we describe a correspondence between the entanglement measures of qubits in quantum information theory and black hole entropy in string theory.
- Reviewed in Borsten, Dahanayake, Duff, Ebrahim, Rubens: "Black Holes, Qubits and Octonions" Phys. Rep. 471:113-219,2009 arXiv:0809.4685 [hep-th].

  Duff: "Black Holes and Qubits" CERN COURIER May 2010

Bits and pieces

- **A bit in the classical sense is the basic unit of computer information and takes the value of either 0 or 1. A light switch provides a good analogy; it can either be off, denoted 0, or on, denoted 1.**

- **A quantum bit or "qubit" can also have two states but whereas a classical bit is either 0 or 1, a qubit can be both 0 and 1 until we make a measurement. In quantum mechanics, this is called a superposition of states.**

- **When we actually perform a measurement, we will find either 0 or 1 but we cannot predict with certainty what the outcome will be; the best we can do is to assign a probability to each outcome.**

ONE QUBIT

- A *qubit* is any two-state quantum system. For example: spin-up/spin-down electron or left/right polarized photon.
- The one qubit system Alice (where $A = 0, 1$) is described by the state

$$|\Psi\rangle = a_A|A\rangle = a_0|0\rangle + a_1|1\rangle$$

where a_0 and a_1 are complex numbers.

TWO QUBITS

The two qubit system Alice and Bob (where $A, B = 0, 1$) is described by the state

$$
\begin{aligned}
|\Psi\rangle &= a_{AB}|AB\rangle \\
&= a_{00}|00\rangle + a_{01}|01\rangle + a_{10}|10\rangle + a_{11}|11\rangle.
\end{aligned}
$$

ENTANGLEMENT

- Example, separable state:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|01\rangle = |0\rangle\left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right)$$

  Alice measures spin up, Bob can measure either spin up or spin down. This state is not *entangled*.

- Example, Bell state:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle$$

  If Alice measures spin up, Bob has to measure spin up too! This state is entangled.

Quantum entanglement

Einstein, Podolsky, Rosen: paradox 1935

John Bell : falsifiable prediction 1964

Alain Aspect: empirical confirmation 1982

ENTANGLEMENT MEASURE

- The measure of the bipartite entanglement of Alice and Bob is given by the "two-tangle"

$$\tau_{AB} = 4|\det a_{AB}|^2 = 4|a_{00}a_{11} - a_{01}a_{10}|^2$$

or equivalently

$$\tau_{AB} = 4|\det \rho_A| = 4|\det \rho_B|$$

where ρ_A and ρ_B are the reduced density matrices

$$\rho_A = Tr_B|\Psi\rangle\langle\Psi| \qquad \rho_B = Tr_A|\Psi\rangle\langle\Psi|$$

- For normalized states

$$0 \leq \tau_{AB} \leq 1$$

EXAMPLES

- Example, separable state:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|01\rangle$$

$$\tau_{AB} = 0$$

No entanglement.

- Example, Bell state:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle$$

$$\tau_{AB} = 1$$

Maximal entanglement.

SYMMETRIES OF τ_{AB}

- Under $SL(2)$ a_A transforms as a 2:

$$\begin{pmatrix} a_0 \\ a_1 \end{pmatrix} \to \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \end{pmatrix}$$

where

$$\alpha\delta - \beta\gamma = 1$$

- Under $SL(2)_A \times SL(2)_B$, a_{AB} transforms as a $(2, 2)$.
- τ_{AB} is invariant under $SL(2)_A \times SL(2)_B$ and under a discrete duality that interchanges A and B.

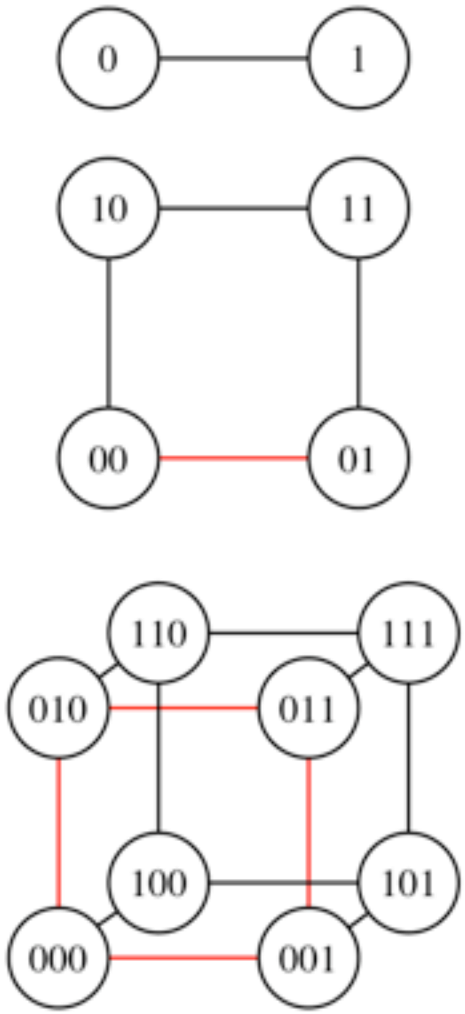
Three qubits

The three qubit system Alice, Bob and Charlie (where $A, B, C = 0, 1$) is described by the state

$$|\Psi\rangle = a_{ABC}|ABC\rangle$$
$$= a_{000}|000\rangle + a_{001}|001\rangle + a_{010}|010\rangle + a_{011}|011\rangle$$
$$+ a_{100}|100\rangle + a_{101}|101\rangle + a_{110}|110\rangle + a_{111}|111\rangle.$$

Hypermatrix

The 3-index quantity a_{ABC} is an example of what Cayley termed a *hypermatrix* in 1845. Its elements may be represented by the cube



Cayley's hyperdeterminant

- The tripartite entanglement of Alice, Bob and Charlie is given by the three-tangle

$$\tau_{ABC} = 4|\mathrm{Det}\ a_{ABC}|,$$

Coffman et al: arXiv:quant-ph/9907047

- Det a_{ABC} is Cayley's hyperdeterminant

$$\mathrm{Det}\ a_{ABC} = -\frac{1}{2}\, \varepsilon^{A_1A_2}\varepsilon^{B_1B_2}\varepsilon^{C_1C_4}\varepsilon^{C_2C_3}\varepsilon^{A_3A_4}\varepsilon^{B_3B_4} \cdot a_{A_1B_1C_1}a_{A_2B_2C_2}a_{A_3B_3C_3}a_{A_4B_4C_4}$$

Miyake, Wadati: arXiv:quant-ph/0212146

- It is invariant under $SL(2)_A \times SL(2)_B \times SL(2)_C$, with a_{ABC} transforming as a $(\mathbf{2},\mathbf{2},\mathbf{2})$, and under a discrete triality that interchanges A, B and C.

SLOCC

- In QIT the group $[SL(2)]^n$ is known as the n-qubit SLOCC equivalence group.
- SLOCC = Stochastic Local Operations and Classical Communication
- For one qubit SLOCC=$SL(2)_A$ and a_A transforms as a 2:

$$\begin{pmatrix} a_0 \\ a_1 \end{pmatrix} \rightarrow \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \end{pmatrix}$$

where

$$\alpha\delta - \beta\gamma = 1$$

- For three qubits SLOCC=$SL(2)_A \times SL(2)_B \times SL(2)_C$ and a_{ABC} transforms as a $(2, 2, 2)$.

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STU MODEL

- The STU supergravity model arises in string theory. Its bosonic sector consists of gravity coupled to 4 photons and three complex scalars, denoted S, T and U.
- The equations of motion display the symmetry $SL(2)_S \times SL(2)_T \times SL(2)_U$ and a discrete triality that interchanges S, T and U.
- Duff, Liu, Rahmfeld: arXiv:hep-th/9508094

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

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Event horizon

- Every object, such as a star, has a critical size that is determined by its mass, which is called the Schwarzschild radius. A black hole is any object smaller than this. Once something falls inside the Schwarzschild radius, it can never escape. This boundary in space–time is called the event horizon.

- So the classical picture of a black hole is that of a compact object whose gravitational field is so strong that nothing – not even light – can escape.

Hawking effect

- Yet in 1974 Stephen Hawking showed that quantum black holes are not entirely black but may radiate energy. In that case, they must possess the thermodynamic quantity called entropy. Entropy is a measure of how disorganized a system is and, according to the second law of thermodynamics, it can never decrease.

Bekenstein-Hawking entropy

Noting that the area of a black hole's event horizon can never decrease, Jacob Bekenstein had earlier suggested such a thermodynamic interpretation implying that black holes must have entropy. This Bekenstein–Hawking black-hole entropy is given by one quarter of the area of the event horizon:

$$S=A/4$$

STU BLACK HOLE ENTROPY

- A general static spherically symmetric STU black hole solution depends on 8 charges denoted $q_0, q_1, q_2, q_3, p^0, p^1, p^2, p^3$.
- Black hole entropy S given by the one quarter the area of the event horizon. Hawking: 1975
- The *extremal* STU black hole entropy is a complicated function of the 8 charges :

$$
\begin{aligned}
(S/\pi)^2 = -(p^0q_0 + p^1q_1 + p^2q_2 + p^3q_3)^2 \\
+4\Big[(p^1q_1)(p^2q_2) + (p^1q_1)(p^3q_3) + (p^3q_3)(p^2q_2) \\
+q_0p^1p^2p^2 - p^0q_1q_2q_3\Big]
\end{aligned}
$$

Behrndt et al: arXiv:hep-th/9608059

Extremal and BPS black holes

- *Extremal* black holes obey generalised mass=charge conditions.
- A black hole that preserves some unbroken supersymmetry (admitting one or more Killing spinors) is said to be *BPS* (after Bogomol'nyi-Prasad-Sommerfield) and non-BPS otherwise.
- All BPS black holes are extremal but extremal black holes can be BPS or non-BPS.

Black hole/qubit correspondence

Duff: arXiv:hep-th/0601134 Identify STU with ABC and the 8 black hole charges with the 8 components of the three-qubit hypermatrix a_{ABC},

$$\begin{bmatrix} p^0 \\ p^1 \\ p^2 \\ p^3 \\ q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} a_{000} \\ -a_{001} \\ -a_{010} \\ -a_{100} \\ a_{111} \\ a_{110} \\ a_{101} \\ a_{011} \end{bmatrix}$$

Find that the black hole entropy is related to the 3-tangle as in

$$S = \pi\sqrt{|\mathrm{Det}\ a_{ABC}|} = \frac{\pi}{2}\sqrt{\tau_{ABC}}$$

Turns out to be the tip of an iceberg.

FURTHER DEVELOPMENTS

- Further papers have written a more complete dictionary, which translates a variety of phenomena in one language to those in the other, for example:
- The *attractor mechanism* on the black hole side is related to *optimal local distillation protocols* on the QI side Levay: arXiv:0708.2799 [hep-th]
- Moreover, supersymmetric and non-supersymmetric black holes corresponding to the suppression or non-suppression of bit-flip errors Levay: arXiv:0708.2799 [hep-th]
- Classification of black holes matches classification of qubit entanglement
  Kallosh, Linde: hep-th/060206
  Borsten, Dahanayake, Duff, Ebrahim, Rubens: arXiv:0809.4685 [hep-th]

LOCAL ENTROPY

- Besides $\mathrm{Det}\, a$, another useful quantity is the local entropy S_A, which is a measure of how entangled A is with the pair BC:

$$S_A = 4\mathrm{det}\ \rho_A$$

where ρ_A is the reduced density matrix

$$\rho_A = \mathrm{Tr}_{BC}|\Psi\rangle\langle\Psi|,$$

and with similar formulae for B and C.

Entanglement classes

Class	Condition				
	$\|\psi\|^2$	S_A	S_B	S_C	Det a
Zero	0	0	0	0	0
A-B-C	>0	0	0	0	0
A-BC	>0	0	>0	>0	0
B-CA	>0	>0	0	>0	0
C-AB	>0	>0	>0	0	0
W	>0	>0	>0	>0	0
GHZ	>0	>0	>0	>0	$\neq 0$

- Dur, Vidal, Cirac: arXiv:quant-ph/0005115

Representatives

- Null class: 0
- Separable class A-B-C (product states): $q_0|111\rangle$
- Biseparable class (bipartite entanglement):

$$A\text{-}BC : q_0|111\rangle - p^1|100\rangle$$
$$B\text{-}CA : q_0|111\rangle - p^2|010\rangle$$
$$C\text{-}AB : q_0|111\rangle - p^3|001\rangle$$

- Class W (maximizes bipartite entanglement):

$$-p^1|100\rangle - p^2|010\rangle - p^3|001\rangle$$

- Class GHZ (genuine tripartite entanglement):

$$q_0|111\rangle - p^1|100\rangle - p^2|010\rangle - p^3|001\rangle$$

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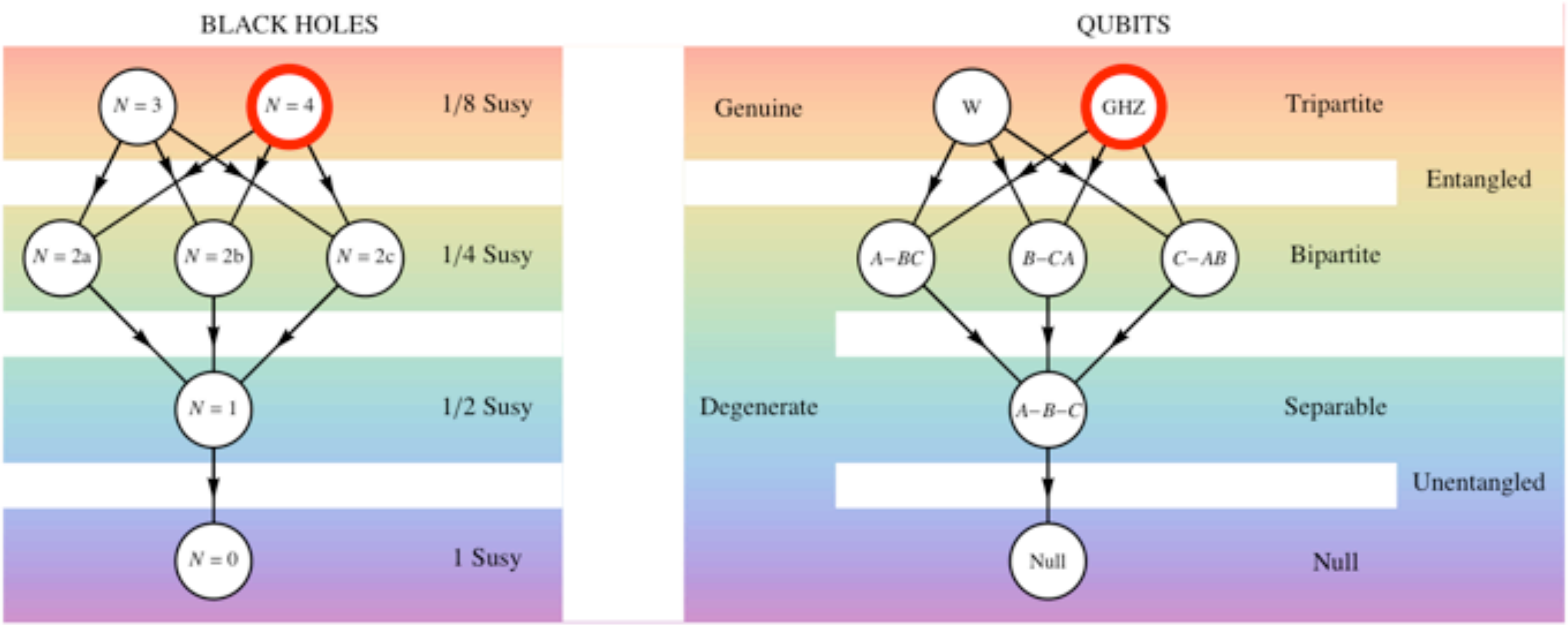
Wrapped branes and qubits

Table 1

x^0	x^1	x^2	x^3	x^4	x^5	x^6	x^7	x^8	x^9	brane	ABC
X	O	O	O	X	O	X	O	X	O	D3	000
X	O	O	O	X	O	O	X	O	X	D3	011
X	O	O	O	O	X	X	O	O	X	D3	101
X	O	O	O	O	X	O	X	X	O	D3	110



- N= number of charges / number of kets

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No force condition

- The 4-charge solution with just q_0, p^1, p^2, p^3 switched on obeys the no-force condition and may be regarded as a bound state of four individual black holes with charges q_0, p^1, p^2, p^3, with zero binding energy.
- This translates into the special GHZ (or Mermin) state

$$|\Psi\rangle = -p^3|001\rangle - p^2|010\rangle - p^1|100\rangle + q_0|111\rangle.$$

- Flipping the sign of q_0 flips the sign of $\mathrm{Det}\, a_{ABC}$ and corresponds to going from $1/8$ susy (BPS) to 0 susy (non-BPS) black hole.
- Similarly GHZ state

$$|\Psi\rangle = p^0|000\rangle + q_0|111\rangle.$$

corresponds to non-BPS black hole.

16 PARAMETERS

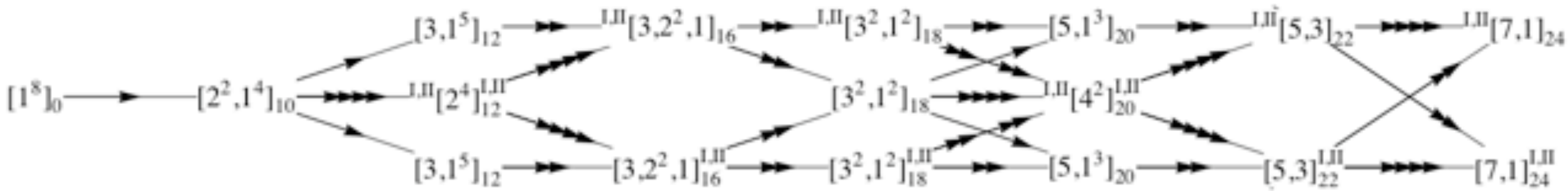
- In addition to the 4 electric and 4 magnetic charges, an STU black hole is also specified by its mass, its NUT charge (gravity analog of magnetic charge) and the values of the 6 real scalars at infinity, making 16 parameters in all.
- Suggests a correspondence with 4 qubits

$$|\Psi\rangle = a_{ABCD}|ABCD\rangle$$

- Levay: arXiv:1004.3639 [hep-th]

FAMILIES/CLASSES

- Under this finer classification there are 31 families of black hole



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- Bergshoeff et al: arXiv:0902.4438 [hep-th]
  Bossard, Michel, Pioline: arXiv:0902.4438 [hep-th]
- Suggests a way to classify 4 qubit entanglement
  Borsten, Dahanayake, Duff, Marrani, Rubens
  Phys. Rev. Lett. 105:100507,2010 arXiv:1002.4223 [hep-th]

Wednesday, January 19, 2011

Families/Classes

- Four-qubit literature is confusing
- Classes: vanishing or not of SLOCC covariants/invariants
- Families: normal forms parameterized by SLOCC invariants e.g.

$$\begin{aligned} G_{abcd} = &\frac{a+d}{2}(|0000\rangle + |1111\rangle) + \frac{a-d}{2}(|0011\rangle + |1100\rangle) \\ &+\frac{b+c}{2}(|0101\rangle + |1010\rangle) + \frac{b-c}{2}(|1001\rangle + |0110\rangle). \end{aligned} \tag{1}$$

- Example of difference: the separable EPR-EPR state $(|00\rangle + |11\rangle) \otimes (|00\rangle + |11\rangle)$, obtained by setting $b = c = d = 0$, belongs to the G_{abcd} family, whereas in the covariant approach it forms its own class.

- Four-qubit literature is contradictory

Paradigm	Author	Year	result mod perms		result incl. perms	
classes	Wallach	2005	?		90	
	Lamata et al,	2006	8 genuine,	5 degenerate	16 genuine,	18 degenerate
	Cao et al	2007	8 genuine,	4 degenerate	8 genuine,	15 degenerate
	Li et al	2007	?		$\geq$ 31 genuine,	18 degenerate
	Akhtarshenas et al	2010	?		11 genuine,	6 degenerate
families	Verstraete et al	2002	9		?	
	Chretrentahl et al	2007	9		?	
	String theory	2010	9		31	

- String theory lends itself to the families approach

Extremal black hole / 4 qubit correspondence

Extremal black holes classification of STU model

$\updownarrow$

31 real nilpotent orbits of $SO(4,4)$ acting on the $\mathbf{28}$

$\updownarrow$

Kostant-Sekiguchi Correspondence

$\updownarrow$

31 complex nilpotent orbits of $SL(2)^4$ acting on the $(\mathbf{2},\mathbf{2},\mathbf{2},\mathbf{2})$

$\updownarrow$

4 qubits entanglement classification

Borsten, Dahanayake, Duff, Marrani, Rubens

Phys. Rev. Lett. 105:100507,2010 arXiv:1002.4223 [hep-th]

STU black holes	perms	nilpotent rep		family
trivial	1	0	$\in$	G_{abcd}
doubly-critical $\frac{1}{2}$BPS	6	$\|0110\rangle$	$\in$	L_{abc_2}
critical, $\frac{1}{2}$BPS and non-BPS	4	$\|0110\rangle + \|0011\rangle$	$\in$	$L_{a_2b_2}$
lightlike $\frac{1}{2}$BPS and non-BPS	1	$\|0110\rangle + \|0101\rangle + \|0011\rangle$	$\in$	$L_{a_2 0_{3\oplus\bar{1}}}$
large non-BPS $z_H \neq 0$	1	$\frac{i}{\sqrt{2}}(\|0001\rangle + \|0010\rangle - \|0111\rangle - \|1011\rangle)$	$\in$	L_{ab_3}
"extremal"	6	$i\|0001\rangle + \|0110\rangle - i\|1011\rangle$	$\in$	L_{a_4}

STU black holes	perms	nilpotent rep		family
large $\frac{1}{2}$BPS and non-BPS $z_H = 0$	4	$\lvert 0000\rangle + \lvert 0111\rangle$	$\in$	$L_{0_{3\oplus\bar{1}}0_{3\oplus\bar{1}}}$
"extremal"	4	$\lvert 0000\rangle + \lvert 0101\rangle + \lvert 1000\rangle + \lvert 1110\rangle$	$\in$	$L_{0_{5\oplus\bar{3}}}$
"extremal"	4	$\lvert 0000\rangle + \lvert 1011\rangle + \lvert 1101\rangle + \lvert 1110\rangle$	$\in$	$L_{0_{7\oplus\bar{1}}}$

- Total number of families without permutations = 9
- Total number of families including permutations = 31
- NB Trivially permuting the 9 yields many more than 31; still need to check equivalence

FALSIFIABLE PREDICTIONS

- Previous result 2006:
  STU black holes imply 5 ways to entangle three qubits
  Already known in QI; verified experimentally
- New result 2010:
  STU black holes imply 31 ways to entangle four qubits
  Not already known in QI: in principle testable in the laboratory

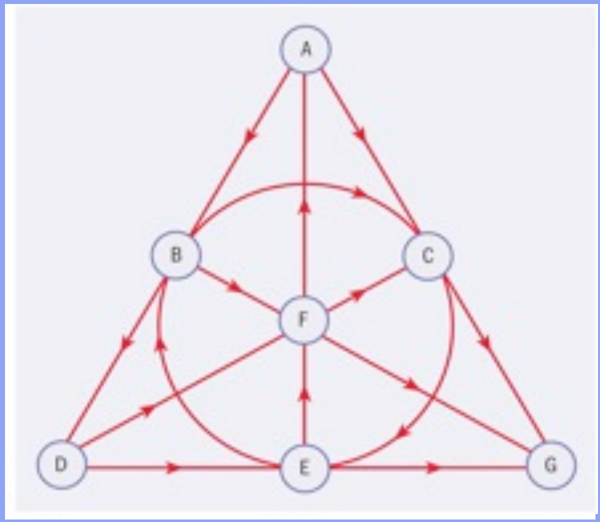
Black holes, qubits and octonions

M-theory black holes involve the mathematics of octonions
(discovered in 1845 by Cayley, but regarded as a 'lost cause' in physics).

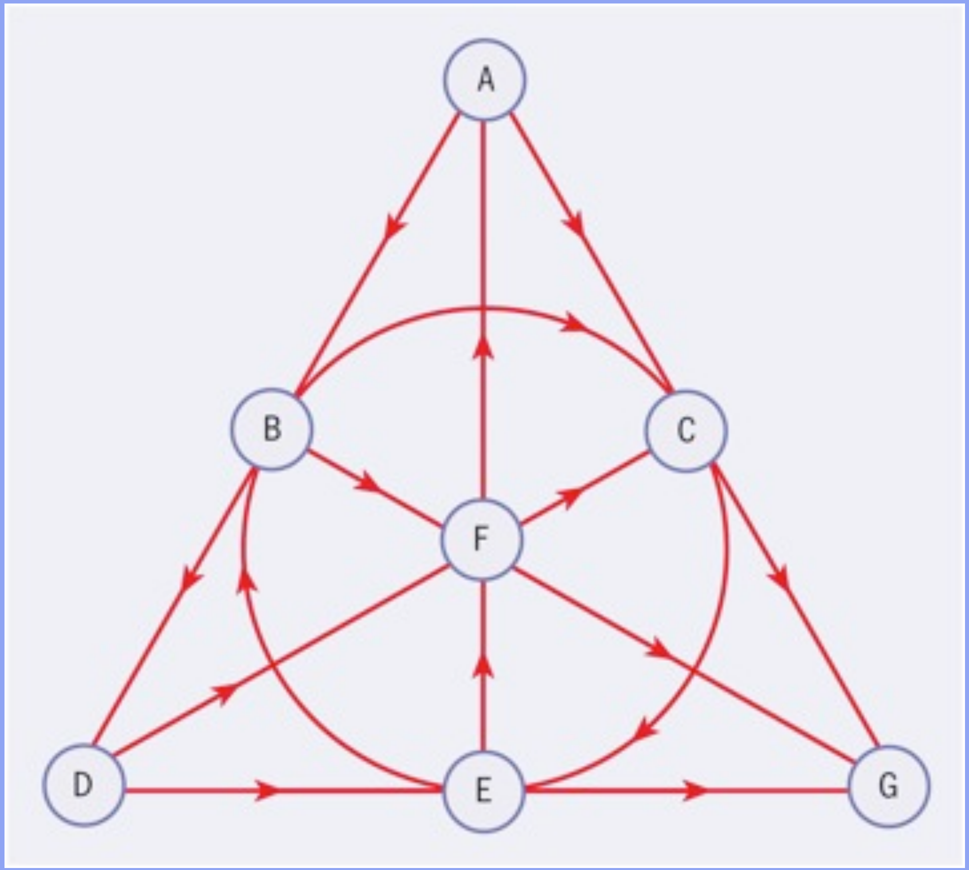
Can apply same mathematics
to quantum information theory:
7 qubits: Alice, Bob, Charlie,Daisy,
Emma, Fred and George.

Hawking black hole entropy provides
measure of quantum entanglement.

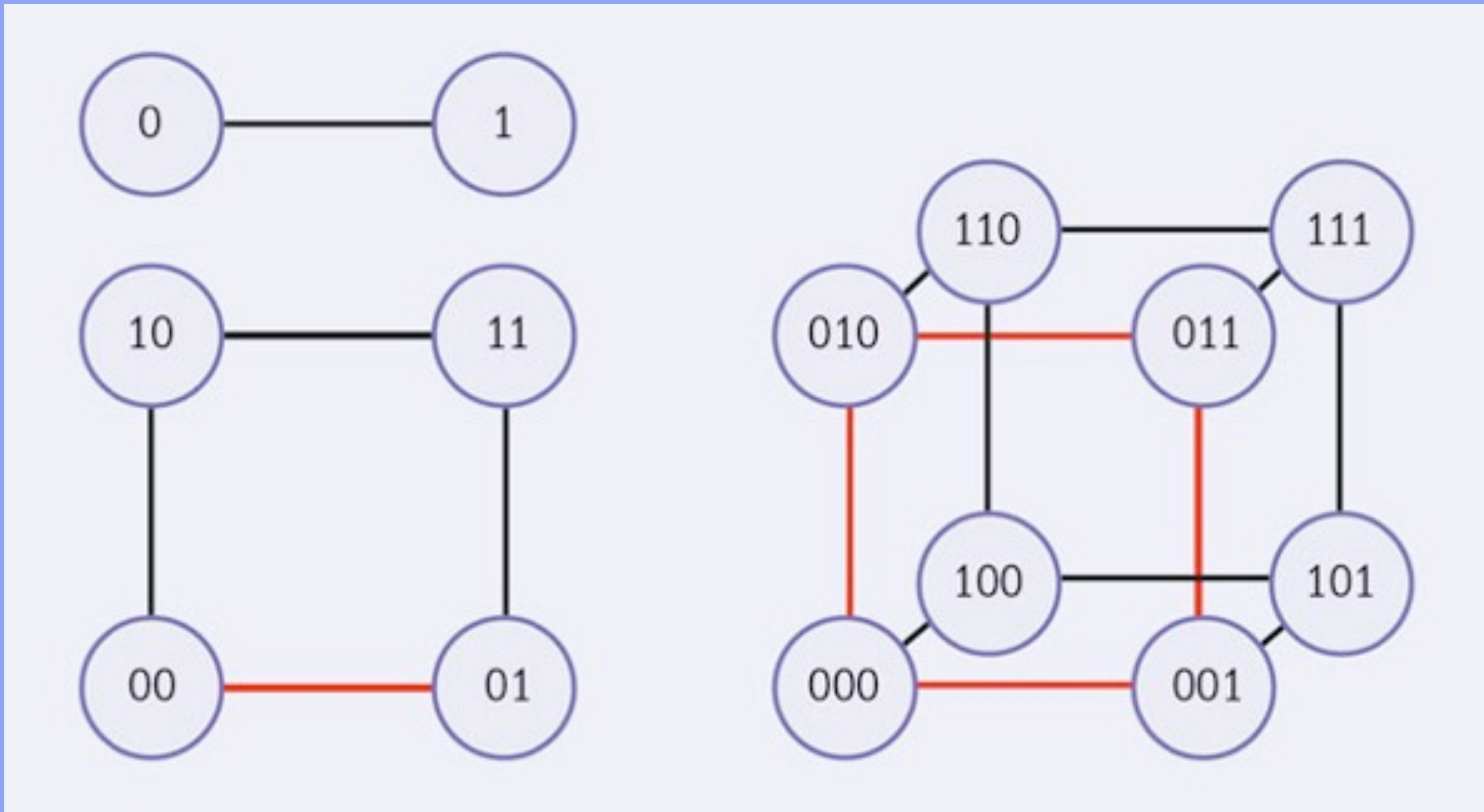
Can we now detect octonions in the lab?



Fano Plane


A
B
C
F
D
E
G

One, two and three qubits



Time-lags between Theory and Experiment

Examples:

- Black holes: predicted 1784, confirmed 1970s
- Bose-Einstein condensate: predicted 1925, confirmed 1995
- Yang-Mills bosons: predicted 1954, discovered 1982
- Quantum entanglement: predicted1935, discovered 1982

Predicted but not yet confirmed:

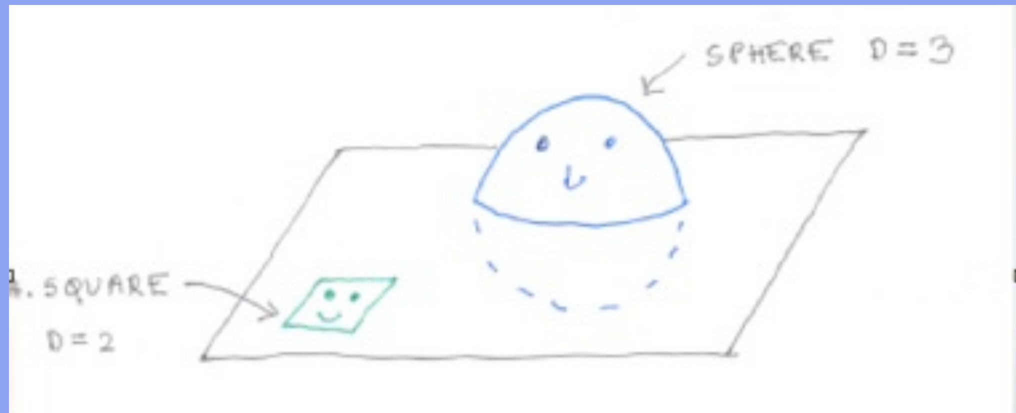
- Gravitational waves (1916)
- The cosmological constant (1917)
- Extra dimensions (1926)
- The Higgs boson (1964)
- Supersymmetry (1971)
- M-theory (1995)

Hawking effect

- Yet in 1974 Stephen Hawking showed that quantum black holes are not entirely black but may radiate energy. In that case, they must possess the thermodynamic quantity called entropy. Entropy is a measure of how disorganized a system is and, according to the second law of thermodynamics, it can never decrease.

EDWIN ABBOTT:

FLATLAND 1884



STRINGLAND 1987