

# **The Pursuit of Unification: Fulfilling Einstein's Dream**

**2004**

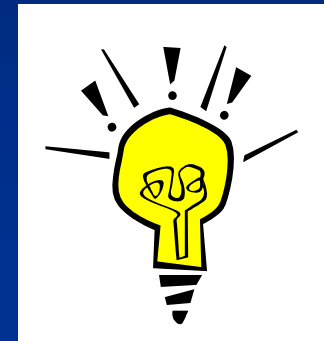
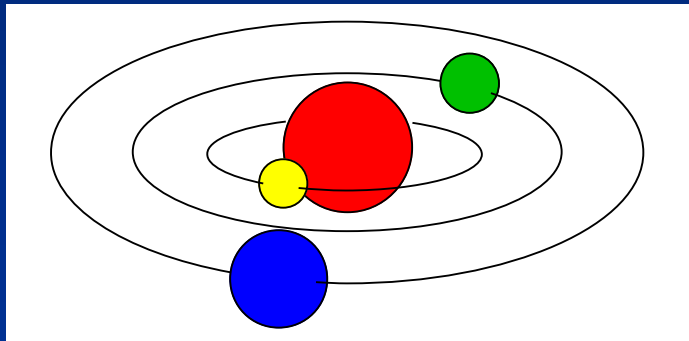
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# Pre-20th Century Physics

- **Space-time** is an arena
- **Forces:** gravity, electric, magnetic

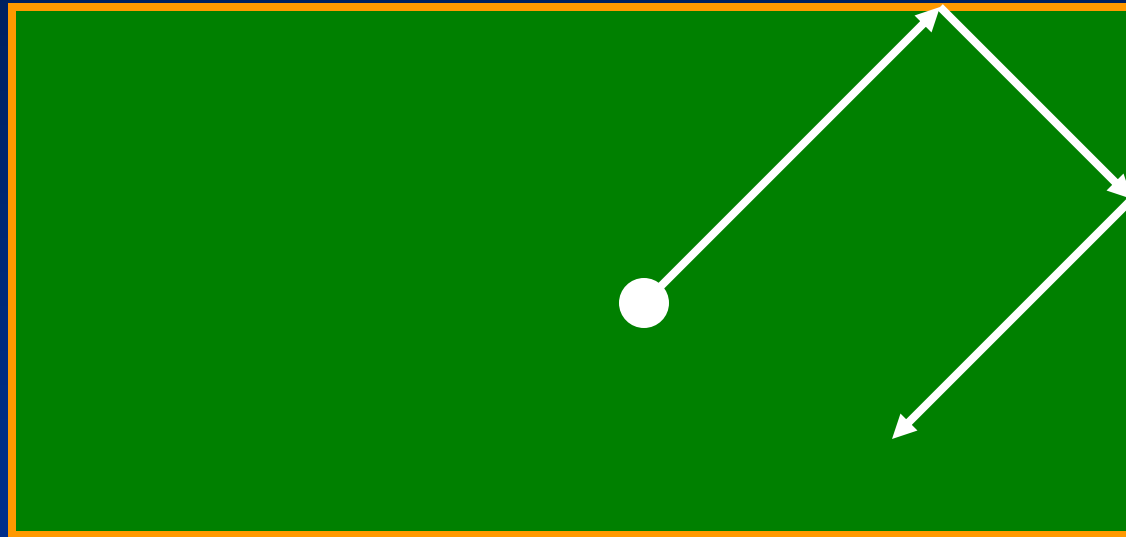


Unified



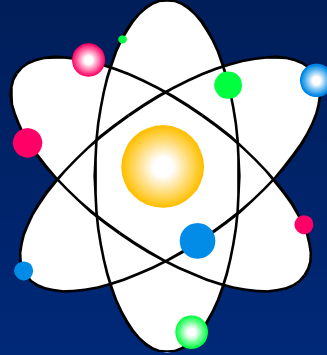
Explains almost all phenomena in everyday life.

# Example: Billiards

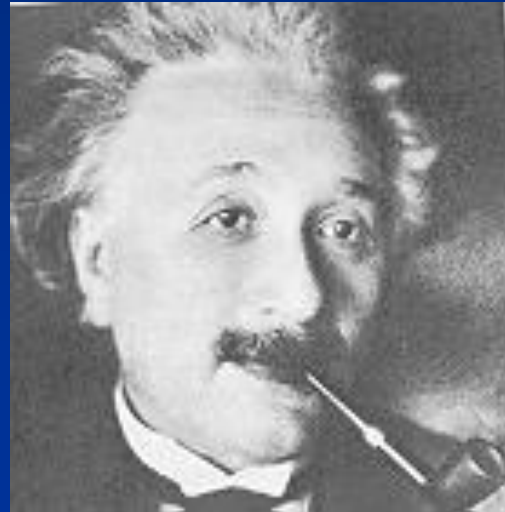


# 20th Century Physics

- Quantum Theory



- Special Relativity
- General Relativity



# Many intuitive notions changed

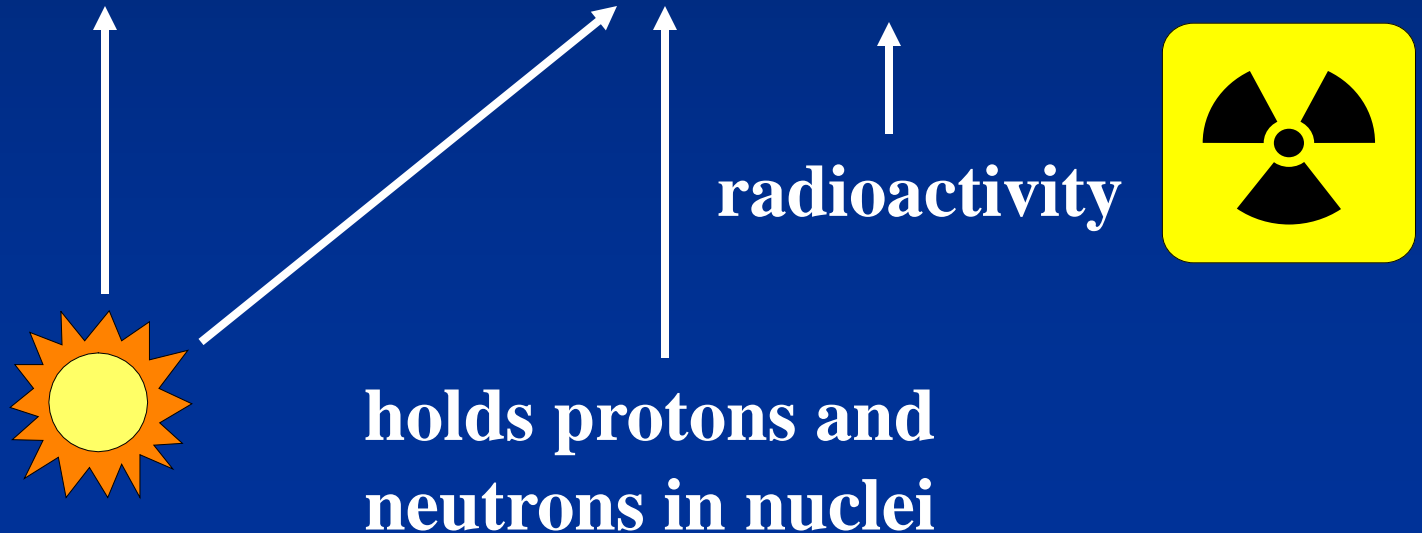
Not surprising:

- Our intuition is based on every day experience.
- Phenomena at very short distances, very long distances, fast velocities, etc. - **counter intuitive.**

# The Standard Model

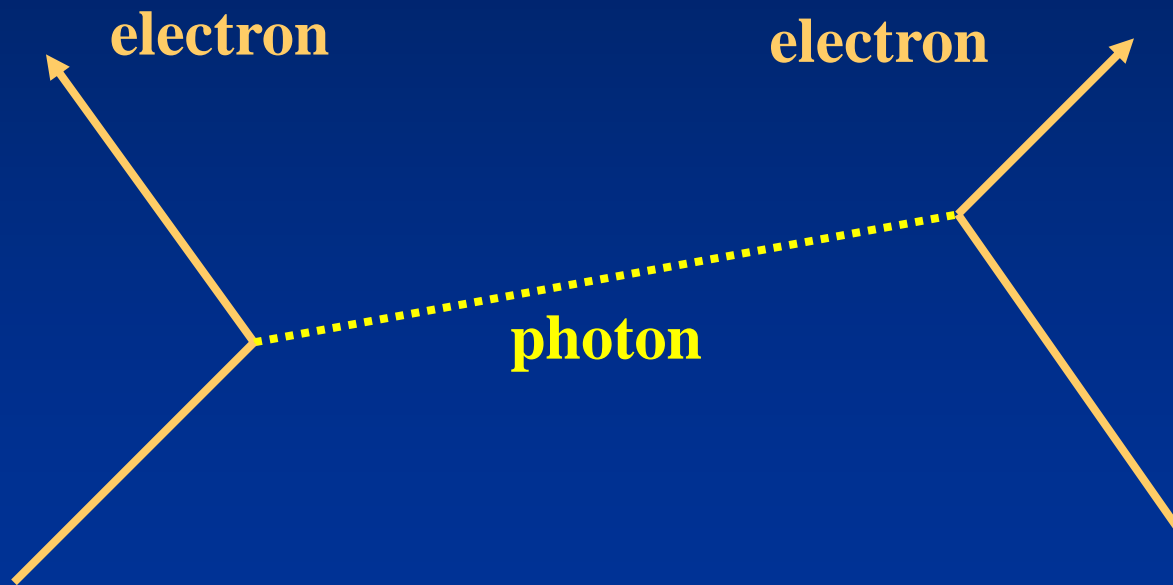
Using Quantum Theory and Special Relativity many phenomena can be described.

- **Space-time:** 3 space + 1 time dimensions
- **Matter particles:** electrons, quarks, neutrinos...
- **Forces:** electromagnetic, strong, weak



# Forces are carried by other particles:

- **Electromagnetic** by photons
- **Weak** by W and Z
- **Strong** by gluons



Action at a distance becomes simpler.

# **Range of Force = 1/Mass of Carrier**

- **The photon has no mass - electric force has long range.**
- **The W and Z are heavy - weak force has short range.**

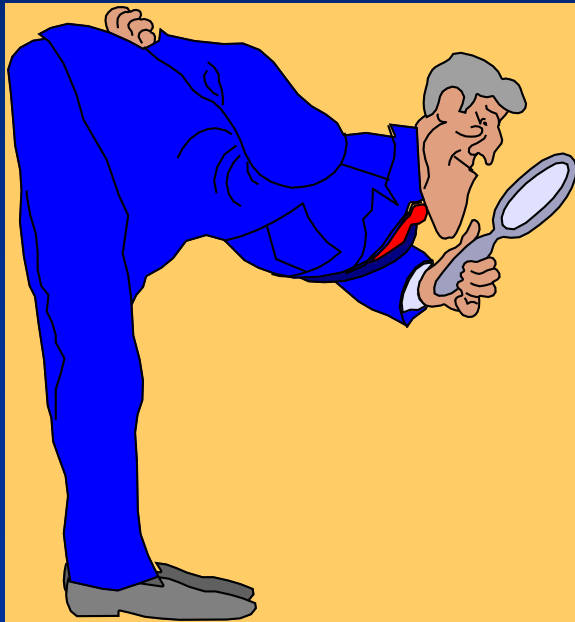


# The Standard Model

Gives a beautiful and consistent description of all known experiments up to  $1/1000000\dots000$  cm!

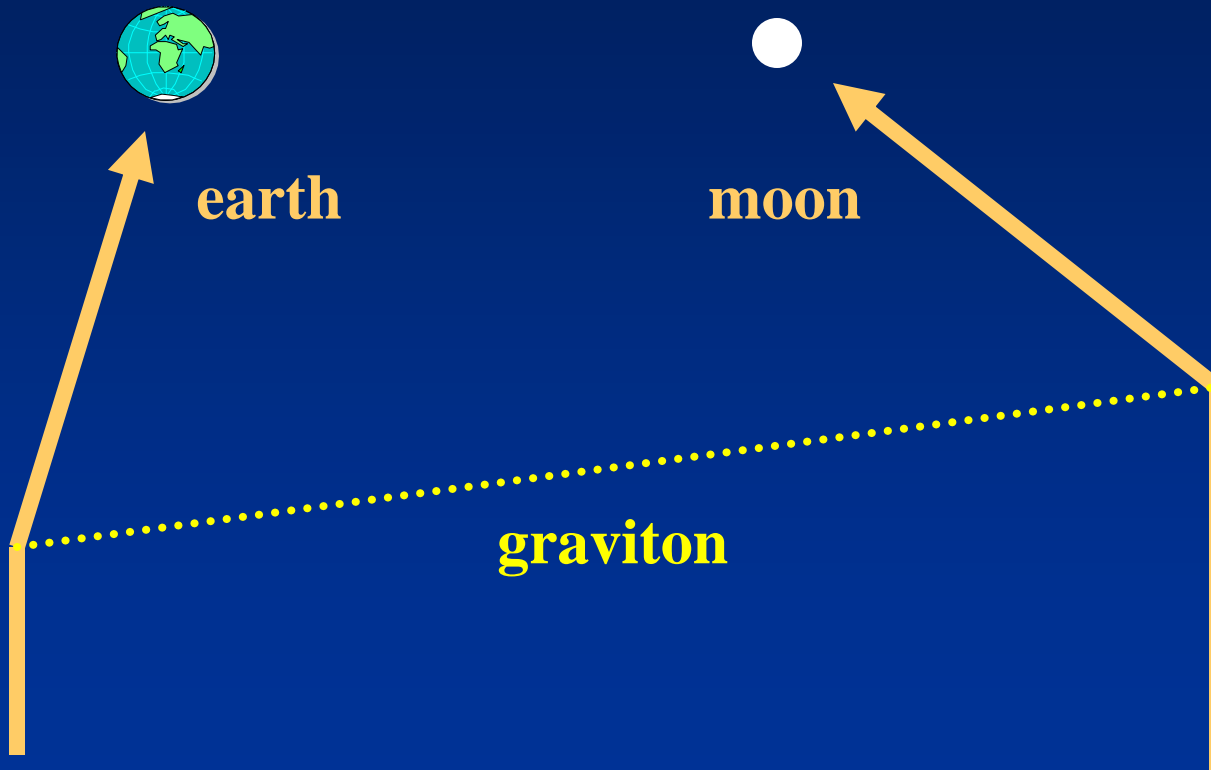


16 zeros



# Adding Gravity

Add another particle, graviton, to mediate the force.



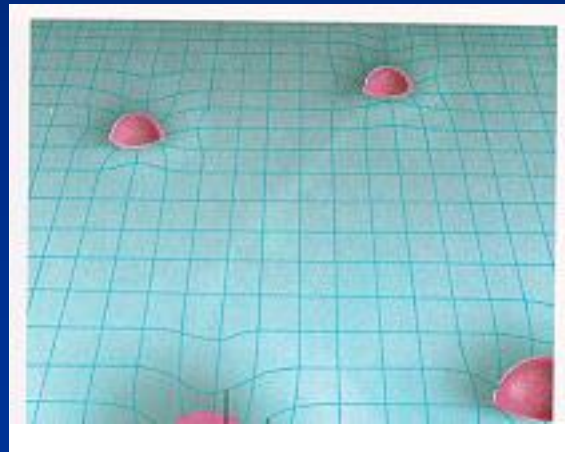
Gravity has long range; graviton has no mass.

**Adding the graviton leads to nonsense  
(infinite answers) in the equations!**

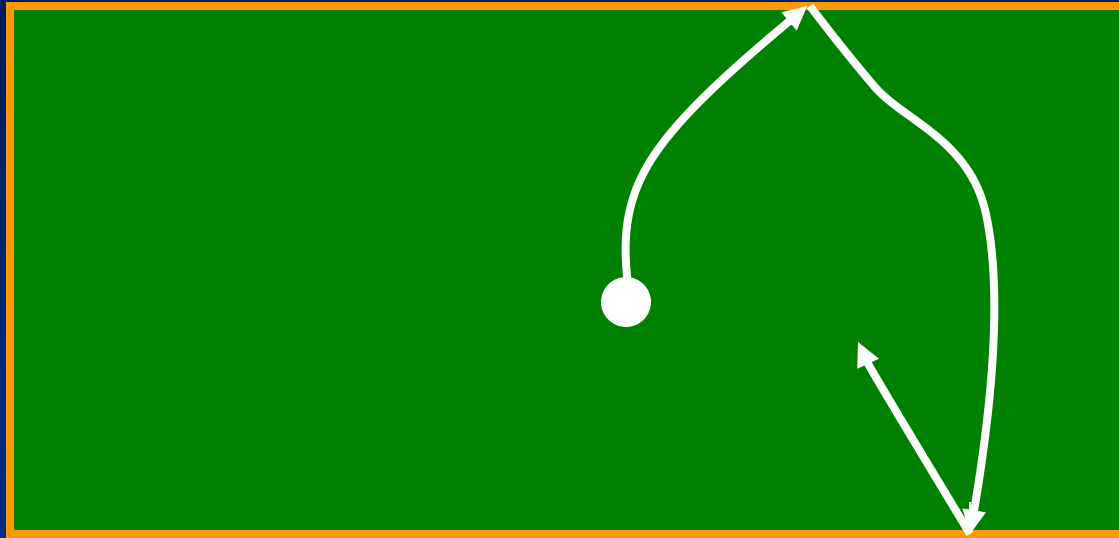
# Gravity = General Relativity = Modification of Space and Time

**Space and time** are no longer a rigid background, a static arena for particles to interact.

**Space and time** become dynamical and curved.



**Our billiard table is no longer flat but bumpy.**



**The ball moves on a curved line.**

**Curved space = Gravity**

## **Challenge:**

**Combine General Relativity with the Standard Model.**

**Find a Quantum Theory of curved and dynamical space and time.**

# String Theory

- **Invented in the late 60's as a theory of the strong force.**
- **Had some successes but was replaced by the standard model and was abandoned.**

**One of its problems was the existence of a particle without mass.**

**But no such particle participates in the strong force.**

# **Mid 70's: String theory is a theory of gravity!**

**The unwanted particle without mass is now interpreted as the graviton - the particle carrying the gravitational force.**

**Gravity is not an option in string theory.  
It is a logical consequence of it!**



**Main idea: the fundamental building blocks are not point-like particles but strings**



**Their small size ( $1/1000000\dots000$  cm) makes them look point-like.**



**33 zeros**

**Different shapes of the string  
(like different notes of a violin string),  
are different particles.**



**electron**



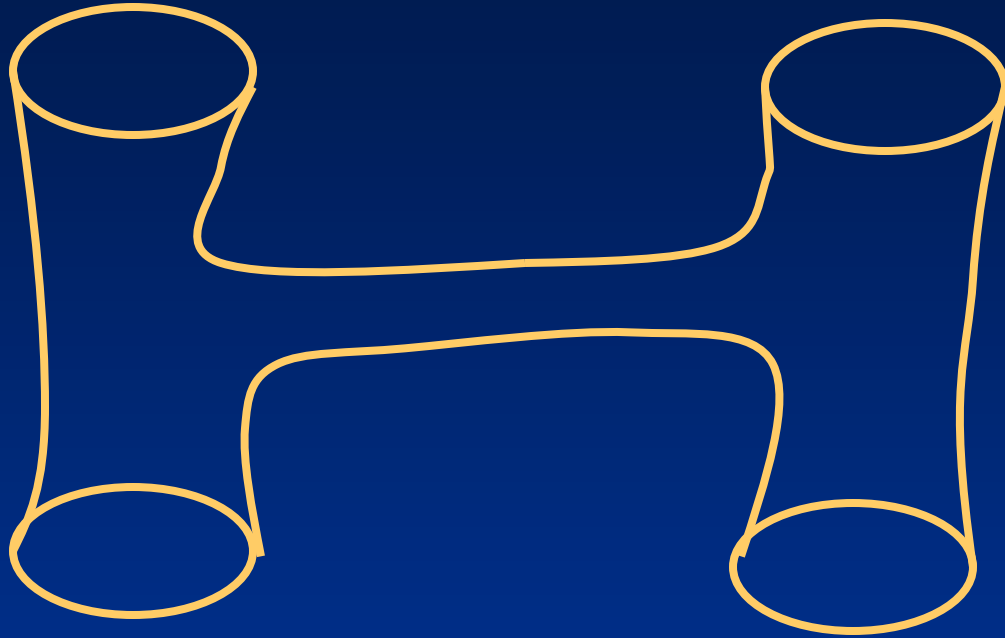
**quark**

**Very economical!**

# Strings can split and join



# Forces are mediated by exchanging strings



Looks from far away



Reproduces the old diagrams.

# Not easy to verify in experiment

In order to see stringy phenomena we need a microscope with resolution of  $1/1000000\dots000$  cm.



33 zeros

Resolution of best available accelerators is “only”

$1/1000000\dots000$  cm.



16 zeros

**Need indirect experimental confirmation.**

**During the past several years there has been tremendous, exciting progress toward understanding the fundamental principles of the theory.**

# We used to know of several distinct string theories:

- Closed strings



- Open strings



- Others

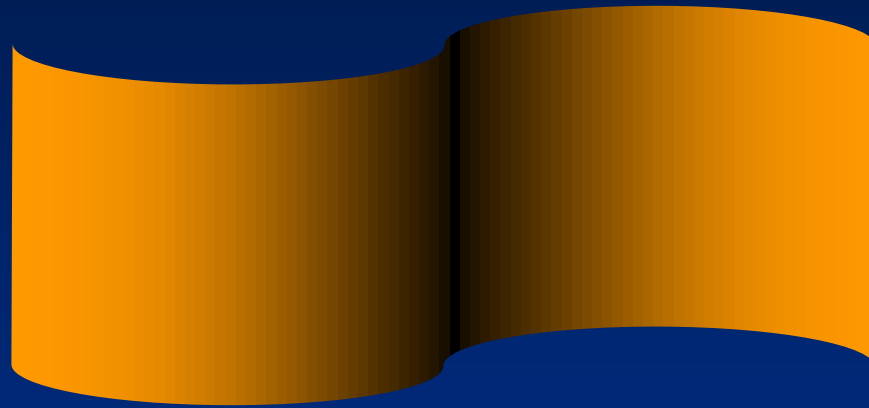
**All these theories are now understood as different descriptions of the same theory.**

**Telling the same story in different languages.**

**The theory is unique!**



# The theory has extended objects like membranes



## **p-branes:**

**0-brane = particle**

**1-brane = string**

**2-brane = membrane**

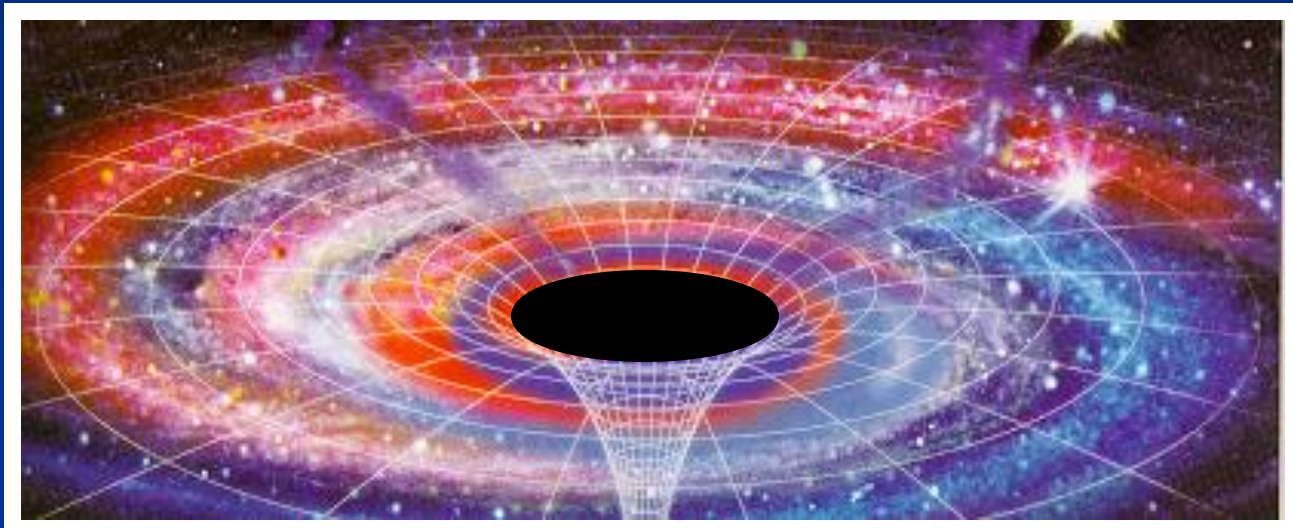
**etc.**

**All p-branes are equally fundamental.**

**String theory is not a theory of strings!**

# Black Holes and Information

- **Black holes are a dense form of matter.**
- **The gravitational force is so strong that even light cannot escape.**
- **No communication between the interior of a black hole and its exterior is possible.**



**This leads to various puzzles.**

**Suggestion: All the information about the interior of a black hole is summarized by the state of its surface.**



**String theory is the only known theory which can solve puzzles associated with black holes!**



**Recent developments show that in string theory (at least in certain situations) the state of the system is completely characterized by the behavior of its boundary.**

# Extra Dimensions

In addition to the three space dimensions there can be more “invisible dimensions”

- Small “invisible dimensions”
- Large “invisible dimensions”

# Small “invisible dimensions”

The world is like a garden hose.



Our three space dimensions

Not easy to detect features around the hose.

# Large “invisible dimensions”



Extra  
dimensions

Our three space dimensions

We are trapped in a brane and cannot  
“see” the other dimensions.



# Summary

- **String theory is the only candidate for a complete theory of nature.**
- **Ultimate confirmation of the theory will require verification by experiment.**
- **Its fundamental principles are not yet understood - but the past few years have seen tremendous progress.**