String Theory

Adil Belhaj
Sultan Moulay Slimane University, Beni Mellal, Morocco

07 June 2010

1. From zero to one dimensional objects

2. String Theory
   - Classical and quantum version of String Theory
   - Classification of superstring models
   - Higher dimensional theories
   - Compactification

3. Building models

4. Conclusion

Plan

Particle Physics

- Fundamental Interactions of Nature
  - Electromagnetic interaction :
  - Strong interaction :
  - Weak interaction :
  - Gravitation theory
- Gauge Theories
  - Grand Unified theory (GUT) :
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Electromagnetic interaction :
  - Strong interaction :
  - Weak interaction :
  - Gravitation theory
- Gauge Theories
  - Grand Unified theory (GUT) :
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Electromagnetic interaction :
  - Strong interaction :
  - Weak interaction :
  - Gravitation theory
- Gauge Theories
  - Grand Unified theory (GUT) :
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Electromagnetic interaction :
  - Strong interaction :
  - Weak interaction :
  - Gravitation theory
- Gauge Theories
  - Grand Unified theory (GUT) :
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Electromagnetic interaction :
  - Strong interaction :
  - Weak interaction :
  - Gravitation theory
- Gauge Theories
  - Grand Unified theory (GUT) :
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Electromagnetic interaction :
  - Strong interaction :
  - Weak interaction :
  - Gravitation theory
- Gauge Theories
  - Grand Unified theory (GUT) :
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Electromagnetic interaction :
  - Strong interaction :
  - Weak interaction :
  - Gravitation theory
- Gauge Theories
  - Grand Unified theory (GUT) :
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Electromagnetic interaction :
  - Strong interaction :
  - Weak interaction :
  - Gravitation theory
- Gauge Theories
  - Grand Unified theory (GUT) :
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Electromagnetic interaction :
  - Strong interaction :
  - Weak interaction :
  - Gravitation theory
- Gauge Theories
  - Grand Unified theory (GUT) :
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Strong interaction :
  - Weak interaction :
  - Electromagnetic interaction :
  - Gravitation theory :
- Gauge Theories
  - Grand Unified theory (GUT) :
    1. Electromagnetic interaction
    2. Strong interaction
    3. Weak interaction
  - Gauge Symmetries :

Particle Physics

- Fundamental Interactions of Nature
  - Strong interaction : su(3) Lie algebra
  - Weak interaction : su(2) Lie algebra
  - Electromagnetic interaction : u(1) Lie algebra
  - Gravitation theory : Geometric deformation of the univers
- Gauge Theories
  - Grand Unified theory (GUT) : E_6, so(10), su(5) Lie algebras
    1. Electromagnetic interaction
    2. Strong interaction
    3. Weak interaction
  - Gauge Symmetries : $A_n D_n E_{6,7,8}$ Lie algebras

Lie algebras in particle physics

- Lie structure
- Representation theory
- Coxter and Dynkin diagrams
- Cartan matrices

Secrets of Nature are hidden in Lie algebra structures

The main problem is the gravity theory

M. Green, J. Schwarz and E. Witten, *Superstring Theory*, 2 Vols., Cambridge U.P.1987.
A. Belhaj, *Introduction to String Theory*, arXiv:0808.2957.

Lie algebras in particle physics

- Lie structure
- Representation theory
- Coxter and Dynkin diagrams
- Cartan matrices

Secrets of Nature are hidden in Lie algebra structures

The main problem is the gravity theory

M. Green, J. Schwarz and E. Witten, *Superstring Theory*, 2 Vols., Cambridge U.P.1987.
A. Belhaj, *Introduction to String Theory*, arXiv:0808.2957.

Lie algebras in particle physics

- Lie structure
- Representation theory
- Coxter and Dynkin diagrams
- Cartan matrices

Secrets of Nature are hidden in Lie algebra structures

The main problem is the gravity theory

M. Green, J. Schwarz and E. Witten, *Superstring Theory*, 2 Vols., Cambridge U.P.1987.
A. Belhaj, *Introduction to String Theory*, arXiv:0808.2957.

Lie algebras in particle physics

- Lie structure
- Representation theory
- Coxter and Dynkin diagrams
- Cartan matrices

Secrets of Nature are hidden in Lie algebra structures

The main problem is the gravity theory

M. Green, J. Schwarz and E. Witten, *Superstring Theory*, 2 Vols., Cambridge U.P.1987.
A. Belhaj, *Introduction to String Theory*, arXiv:0808.2957.

Lie algebras in particle physics

- Lie structure
- Representation theory
- Coxter and Dynkin diagrams
- Cartan matrices

Secrets of Nature are hidden in Lie algebra structures

The main problem is the gravity theory

M. Green, J. Schwarz and E. Witten, *Superstring Theory*, 2 Vols., Cambridge U.P.1987.
A. Belhaj, *Introduction to String Theory*, arXiv:0808.2957.

Lie algebras in particle physics

- Lie structure
- Representation theory
- Coxter and Dynkin diagrams
- Cartan matrices

Secrets of Nature are hidden in Lie algebra structures

The main problem is the gravity theory

M. Green, J. Schwarz and E. Witten, *Superstring Theory*, 2 Vols., Cambridge U.P.1987.
A. Belhaj, *Introduction to String Theory*, arXiv:0808.2957.

Lie algebras in particle physics

- Lie structure
- Representation theory
- Coxter and Dynkin diagrams
- Cartan matrices

Secrets of Nature are hidden in Lie algebra structures

The main problem is the gravity theory

M. Green, J. Schwarz and E. Witten, *Superstring Theory*, 2 Vols., Cambridge U.P.1987.
A. Belhaj, *Introduction to String Theory*, `arXiv:0808.2957`.

Plan

String theory

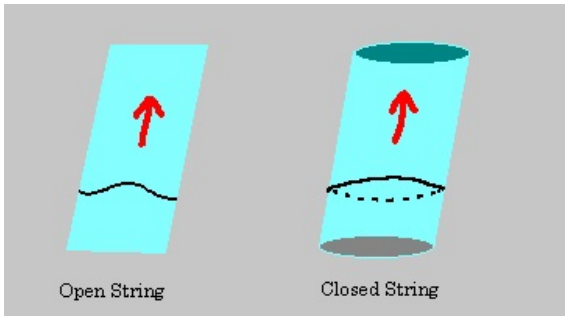
The motion of particles (zero dimensional objects) should be extended to the motion of one dimensional objects : strings

- Two configurations
  1. Open string theory
  2. Closed string theory

String theory

The motion of particles (zero dimensional objects) should be extended to the motion of one dimensional objects : strings

- Two configurations
  1. Open string theory
  2. Closed string theory



String theory

The motion of particles (zero dimensional objects) should be extended to the motion of one dimensional objects : strings

- Two configurations
  1. Open string theory
  2. Closed string theory

String theory

The motion of particles (zero dimensional objects) should be extended to the motion of one dimensional objects : strings

- Two configurations
  1. Open string theory
  2. Closed string theory

String theory

The motion of particles (zero dimensional objects) should be extended to the motion of one dimensional objects : strings

- Two configurations
  1. Open string theory
  2. Closed string theory

Classical string theory

The action of the classical theory

$$S = \frac{1}{2\pi\alpha'} \int d\tau d\sigma \left(\frac{\partial X^\mu}{\partial \tau}\frac{\partial X_\mu}{\partial \tau} - \frac{\partial X^\mu}{\partial \sigma}\frac{\partial X_\mu}{\partial \sigma}\right)$$

Quantum theory

- The quantization gives

$$(g_{\mu\nu}, B_{\mu\nu}, A_\mu, \phi, ...)$$

- Graviton, photons,.....

Classical string theory

The action of the classical theory

$$S = \frac{1}{2\pi\alpha'} \int d\tau d\sigma \left(\frac{\partial X^\mu}{\partial \tau}\frac{\partial X_\mu}{\partial \tau} - \frac{\partial X^\mu}{\partial \sigma}\frac{\partial X_\mu}{\partial \sigma}\right)$$

Quantum theory

- The quantization gives

$$(g_{\mu\nu}, B_{\mu\nu}, A_\mu, \phi, ...)$$

- Graviton, photons,.....

Classical string theory

The action of the classical theory

$$S = \frac{1}{2\pi\alpha'} \int d\tau d\sigma \left(\frac{\partial X^\mu}{\partial \tau}\frac{\partial X_\mu}{\partial \tau} - \frac{\partial X^\mu}{\partial \sigma}\frac{\partial X_\mu}{\partial \sigma}\right)$$

Quantum theory

- The quantization gives

$$(g_{\mu\nu}, B_{\mu\nu}, A_\mu, \phi, ...)$$

- Graviton, photons,.....

Classical string theory

The action of the classical theory

$$S = \frac{1}{2\pi\alpha'} \int d\tau d\sigma \left(\frac{\partial X^\mu}{\partial \tau}\frac{\partial X_\mu}{\partial \tau} - \frac{\partial X^\mu}{\partial \sigma}\frac{\partial X_\mu}{\partial \sigma}\right)$$

Quantum theory

- The quantization gives

$$(g_{\mu\nu}, B_{\mu\nu}, A_\mu, \phi, ...)$$

- Graviton, photons,.....

Classical string theory

The action of the classical theory

$$S = \frac{1}{2\pi\alpha'} \int d\tau d\sigma \left(\frac{\partial X^\mu}{\partial \tau}\frac{\partial X_\mu}{\partial \tau} - \frac{\partial X^\mu}{\partial \sigma}\frac{\partial X_\mu}{\partial \sigma}\right)$$

Quantum theory

- The quantization gives

$$(g_{\mu\nu}, B_{\mu\nu}, A_\mu, \phi, ...)$$

- Graviton, photons,.....

String theory

Motion of particles (zero dimensional objects)→ Motion of one dimensional objects : strings

- Possible unified theory of
  - Strong interaction,
  - Weak interaction,
  - Electromagnetic interaction,
  - Gravitation interaction
- Two configurations
  1. Open string theory (D-branes)→Gauge theories
  2. Closed string theory →Gravity theory

String theory

Motion of particles (zero dimensional objects)→ Motion of one dimensional objects : strings

- Possible unified theory of
  - Strong interaction,
  - Weak interaction,
  - Electromagnetic interaction,
  - Gravitation interaction
- Two configurations
  1. Open string theory (D-branes)→Gauge theories
  2. Closed string theory →Gravity theory

String theory

Motion of particles (zero dimensional objects)→ Motion of one dimensional objects : strings

- Possible unified theory of
  - Strong interaction,
  - Weak interaction,
  - Electromagnetic interaction,
  - Gravitation interaction
- Two configurations
  1. Open string theory (D-branes)→Gauge theories
  2. Closed string theory →Gravity theory

String theory

Motion of particles (zero dimensional objects)→ Motion of one dimensional objects : strings

- Possible unified theory of
  - Strong interaction,
  - Weak interaction,
  - Electromagnetic interaction,
  - Gravitation interaction
- Two configurations
  1. Open string theory (D-branes)→Gauge theories
  2. Closed string theory →Gravity theory

String theory

Motion of particles (zero dimensional objects)→ Motion of one dimensional objects : strings

- Possible unified theory of
  - Strong interaction,
  - Weak interaction,
  - Electromagnetic interaction,
  - Gravitation interaction
- Two configurations
  1. Open string theory (D-branes)→Gauge theories
  2. Closed string theory →Gravity theory

String theory

Motion of particles (zero dimensional objects)→ Motion of one dimensional objects : strings

- Possible unified theory of
  - Strong interaction,
  - Weak interaction,
  - Electromagnetic interaction,
  - Gravitation interaction
- Two configurations
  1. Open string theory (D-branes)→Gauge theories
  2. Closed string theory →Gravity theory

First revolution

Superstring models

- Models beyond particle physics
- 5 models
  1. Type IIA
  2. Type IIB
  3. Heterotic superstring theory with $SO(32) = D_{16}$ gauge symmetry
  4. Heterotic superstring theory with $E_8 \times E_8$ gauge group
  5. Type I with $SO(32) = D_{16}$. gauge symmetry.
- Dimension of the space-time : $D = 10$
- Gauge symmetries (Lie algebras) :
  1. $E_8 \times E_8$
  2. $SO(32) = D_{16}$

First revolution

Superstring models

- Models beyond particle physics
- 5 models
  1. Type IIA
  2. Type IIB
  3. Heterotic superstring theory with $SO(32) = D_{16}$ gauge symmetry
  4. Heterotic superstring theory with $E_8 \times E_8$ gauge group
  5. Type I with $SO(32) = D_{16}$. gauge symmetry.
- Dimension of the space-time : $D = 10$
- Gauge symmetries (Lie algebras) :
  1. $E_8 \times E_8$
  2. $SO(32) = D_{16}$

First revolution

Superstring models

- Models beyond particle physics
- 5 models
  1. Type IIA
  2. Type IIB
  3. Heterotic superstring theory with $SO(32) = D_{16}$ gauge symmetry
  4. Heterotic superstring theory with $E_8 \times E_8$ gauge group
  5. Type I with $SO(32) = D_{16}$. gauge symmetry.
- Dimension of the space-time : $D = 10$
- Gauge symmetries (Lie algebras) :
  1. $E_8 \times E_8$
  2. $SO(32) = D_{16}$

First revolution

Superstring models

- Models beyond particle physics
- 5 models
  1. Type IIA
  2. Type IIB
  3. Heterotic superstring theory with $SO(32) = D_{16}$ gauge symmetry
  4. Heterotic superstring theory with $E_8 \times E_8$ gauge group
  5. Type I with $SO(32) = D_{16}$. gauge symmetry.
- Dimension of the space-time : $D = 10$
- Gauge symmetries (Lie algebras) :
  1. $E_8 \times E_8$
  2. $SO(32) = D_{16}$

First revolution

Superstring models

- Models beyond particle physics
- 5 models
  1. Type IIA
  2. Type IIB
  3. Heterotic superstring theory with $SO(32) = D_{16}$ gauge symmetry
  4. Heterotic superstring theory with $E_8 \times E_8$ gauge group
  5. Type I with $SO(32) = D_{16}$. gauge symmetry.
- Dimension of the space-time : $D = 10$
- Gauge symmetries (Lie algebras) :
  1. $E_8 \times E_8$
  2. $SO(32) = D_{16}$

First revolution

Superstring models

- Models beyond particle physics
- 5 models
  1. Type IIA
  2. Type IIB
  3. Heterotic superstring theory with $SO(32) = D_{16}$ gauge symmetry
  4. Heterotic superstring theory with $E_8 \times E_8$ gauge group
  5. Type I with $SO(32) = D_{16}$. gauge symmetry.
- Dimension of the space-time : $D = 10$
- Gauge symmetries (Lie algebras) :
  1. $E_8 \times E_8$
  2. $SO(32) = D_{16}$

First revolution

Superstring models

- Models beyond particle physics
- 5 models
  1. Type IIA
  2. Type IIB
  3. Heterotic superstring theory with $SO(32) = D_{16}$ gauge symmetry
  4. Heterotic superstring theory with $E_8 \times E_8$ gauge group
  5. Type I with $SO(32) = D_{16}$. gauge symmetry.
- Dimension of the space-time : $D = 10$
- Gauge symmetries (Lie algebras) :
  1. $E_8 \times E_8$
  2. $SO(32) = D_{16}$

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Second revolution

Problems and partial solutions

- Many problems !
  1. Space-time dimension : $D = 10 > 4$
  2. Five models
  3. Large gauge symmetries : $SO(32) = D_{16}$, $E_8 \times E_8$
  4. .....
- Partial solutions
  - Compactification
    - $D = 10 \rightarrow D = 4$
  - String dualities
    - Connection between string models in lower dimensions
  - New theories
    1. M-theory in $D = 11$, Witten, 1995
    2. F-theory in $D = 12$, Vafa, 1996

Compactification of higher dimensional theories

Compactification

- Four dimensional models

$$R^{1,D-1} \rightarrow R^{1,3} \times X^{D-4}$$

X^{D-4}=$(D-4)$-dimensional compact manifolds.

1. String theory lives in $D = 10$
   - 10= 4+6
2. M-theory lives in $D = 11$
   - 11=4+7
3. F-theory lives in $D = 12$
   - 12=4+8

Compactification of higher dimensional theories

Compactification

- Four dimensional models

$$R^{1,D-1} \rightarrow R^{1,3} \times X^{D-4}$$

X^{D-4}=$(D-4)$-dimensional compact manifolds.

1. String theory lives in $D = 10$
   - 10= 4+6
2. M-theory lives in $D = 11$
   - 11=4+7
3. F-theory lives in $D = 12$
   - 12=4+8

Compactification of higher dimensional theories

Compactification

- Four dimensional models

$$R^{1,D-1} \rightarrow R^{1,3} \times X^{D-4}$$

X^{D-4}=$(D-4)$-dimensional compact manifolds.

1. String theory lives in $D = 10$
   - 10= 4+6
2. M-theory lives in $D = 11$
   - 11=4+7
3. F-theory lives in $D = 12$
   - 12=4+8

Compactification of higher dimensional theories

Compactification

- Four dimensional models

$$R^{1,D-1} \rightarrow R^{1,3} \times X^{D-4}$$

X^{D-4}=$(D-4)$-dimensional compact manifolds.

1. String theory lives in $D = 10$
   - 10= 4+6
2. M-theory lives in $D = 11$
   - 11=4+7
3. F-theory lives in $D = 12$
   - 12=4+8

Compactification of higher dimensional theories

Compactification

- Four dimensional models

$$R^{1,D-1} \rightarrow R^{1,3} \times X^{D-4}$$

X^{D-4}=$(D-4)$-dimensional compact manifolds.

1. String theory lives in $D = 10$
   - 10= 4+6
2. M-theory lives in $D = 11$
   - 11=4+7
3. F-theory lives in $D = 12$
   - 12=4+8

Toroidal Compactification of superstring theory

String theory

- Compactification

$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6=6-dimensional compact manifolds.

- $X^6 = T^2 \times T^2 \times T^2$.

Toroidal Compactification of superstring theory

String theory

- Compactification

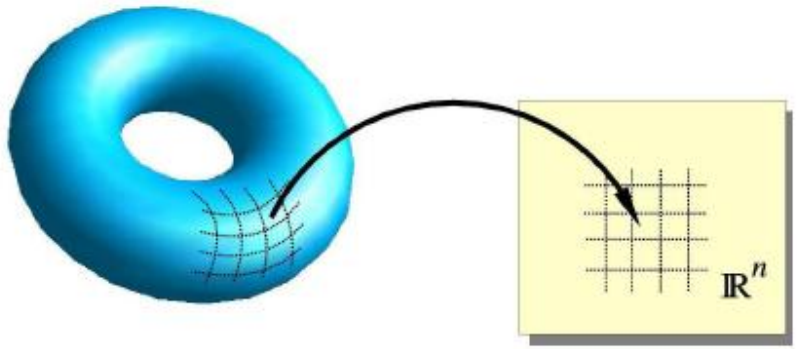
$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6=6-dimensional compact manifolds.

- $X^6 = T^2 \times T^2 \times T^2$.

Toroidal compactification of superstring theory

Toroidal compactification of superstring theory



Connection with particle physics

Calabi-Yau manifolds

- Calabi-Yau compactification

$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6= 3- dimensional Calabi-Yau manifolds.

1. Kahler manifolds
2. SU(3) holonomy group
3. $\Omega = dz_1 dz_2 dz_3$,

- Constructions of Calabi-Yau manifolds
  1. Orbifolds : T^6/G, $G \subset SU(3)$
  2. Hypersurfaces in $CP^4(z_1, z_2, z_3, z_4, z_5)$ projective space

$$P_5(z_1, z_2, z_3, z_4, z_5) = 0$$

  3. Hypersurfaces in toric varieties, using toric geometry method.

Connection with particle physics

Calabi-Yau manifolds

- Calabi-Yau compactification

$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6= 3- dimensional Calabi-Yau manifolds.

1. Kahler manifolds
2. SU(3) holonomy group
3. $\Omega = dz_1 dz_2 dz_3$,

- Constructions of Calabi-Yau manifolds
  1. Orbifolds : T^6/G, $G \subset SU(3)$
  2. Hypersurfaces in $CP^4(z_1, z_2, z_3, z_4, z_5)$ projective space

$$P_5(z_1, z_2, z_3, z_4, z_5) = 0$$

  3. Hypersurfaces in toric varieties, using toric geometry method.

Connection with particle physics

Calabi-Yau manifolds

- Calabi-Yau compactification

$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6= 3- dimensional Calabi-Yau manifolds.

1. Kahler manifolds
2. $SU(3)$ holonomy group
3. $\Omega = dz_1 dz_2 dz_3$,

- Constructions of Calabi-Yau manifolds
  1. Orbifolds : T^6/G, $G \subset SU(3)$
  2. Hypersurfaces in $CP^4(z_1, z_2, z_3, z_4, z_5)$ projective space

$$P_5(z_1, z_2, z_3, z_4, z_5) = 0$$

  3. Hypersurfaces in toric varieties, using toric geometry method.

Connection with particle physics

Calabi-Yau manifolds

- Calabi-Yau compactification

$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6= 3- dimensional Calabi-Yau manifolds.

1. Kahler manifolds
2. SU(3) holonomy group
3. $\Omega = dz_1 dz_2 dz_3$,

- Constructions of Calabi-Yau manifolds
  1. Orbifolds : T^6/G, $G \subset SU(3)$
  2. Hypersurfaces in $CP^4(z_1, z_2, z_3, z_4, z_5)$ projective space

$$P_5(z_1, z_2, z_3, z_4, z_5) = 0$$

  3. Hypersurfaces in toric varieties, using toric geometry method.

Connection with particle physics

Calabi-Yau manifolds

- Calabi-Yau compactification

$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6= 3- dimensional Calabi-Yau manifolds.

1. Kahler manifolds
2. SU(3) holonomy group
3. $\Omega = dz_1 dz_2 dz_3$,

- Constructions of Calabi-Yau manifolds
  1. Orbifolds : T^6/G, $G \subset SU(3)$
  2. Hypersurfaces in $CP^4(z_1, z_2, z_3, z_4, z_5)$ projective space

$$P_5(z_1, z_2, z_3, z_4, z_5) = 0$$

  3. Hypersurfaces in toric varieties, using toric geometry method.

Connection with particle physics

Calabi-Yau manifolds

- Calabi-Yau compactification

$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6= 3- dimensional Calabi-Yau manifolds.

1. Kahler manifolds
2. SU(3) holonomy group
3. $\Omega = dz_1 dz_2 dz_3$,

- Constructions of Calabi-Yau manifolds
  1. Orbifolds : T^6/G, $G \subset SU(3)$
  2. Hypersurfaces in $CP^4(z_1, z_2, z_3, z_4, z_5)$ projective space

$$P_5(z_1, z_2, z_3, z_4, z_5) = 0$$

  3. Hypersurfaces in toric varieties, using toric geometry method.

Connection with particle physics

Calabi-Yau manifolds

- Calabi-Yau compactification

$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6= 3- dimensional Calabi-Yau manifolds.

1. Kahler manifolds
2. SU(3) holonomy group
3. $\Omega = dz_1 dz_2 dz_3$,

- Constructions of Calabi-Yau manifolds
  1. Orbifolds : T^6/G, $G \subset SU(3)$
  2. Hypersurfaces in $CP^4(z_1, z_2, z_3, z_4, z_5)$ projective space

$$P_5(z_1, z_2, z_3, z_4, z_5) = 0$$

3. Hypersurfaces in toric varieties, using toric geometry method.

Connection with particle physics

Calabi-Yau manifolds

- Calabi-Yau compactification

$$R^{1,9} \rightarrow R^{1,3} \times X^6$$

X^6= 3- dimensional Calabi-Yau manifolds.

1. Kahler manifolds
2. SU(3) holonomy group
3. $\Omega = dz_1 dz_2 dz_3$,

- Constructions of Calabi-Yau manifolds
  1. Orbifolds : T^6/G, $G \subset SU(3)$
  2. Hypersurfaces in $CP^4(z_1, z_2, z_3, z_4, z_5)$ projective space

$$P_5(z_1, z_2, z_3, z_4, z_5) = 0$$

  3. Hypersurfaces in toric varieties, using toric geometry method.

Compactification of M-theory

M-theory

- Compactification

$$R^{1,10} \rightarrow R^{1,3} \times X^7$$

X^7=7-dimensional compact manifolds.

1. T^7, ...
2. G_2 manifolds (Standard model)

- G_2 manifolds

1. 7-dimensional real manifolds
2. G_2 holonomy group
3. Special 3-form

$$w = f_{ijk} dx_i dx_j dx_k$$

- Octonian algebra

$$t_i t_j = -\delta_{ij} + f_{ijk} t_k$$

Compactification of M-theory

M-theory

- Compactification

$$R^{1,10} \rightarrow R^{1,3} \times X^7$$

X^7=7-dimensional compact manifolds.

1. T^7, ...
2. G_2 manifolds (Standard model)

- G_2 manifolds
  1. 7-dimensional real manifolds
  2. G_2 holonomy group
  3. Special 3-form

$$w = f_{ijk} dx_i dx_j dx_k$$

  - Octonian algebra

$$t_i t_j = -\delta_{ij} + f_{ijk} t_k$$

Compactification of M-theory

M-theory

- Compactification

$$R^{1,10} \rightarrow R^{1,3} \times X^7$$

X^7=7-dimensional compact manifolds.

1. T^7, ...
2. G_2 manifolds (Standard model)

- G_2 manifolds
  1. 7-dimensional real manifolds
  2. G_2 holonomy group
  3. Special 3-form

$$w = f_{ijk} dx_i dx_j dx_k$$

  - Octonian algebra

$$t_i t_j = -\delta_{ij} + f_{ijk} t_k$$

Compactification of M-theory

M-theory

- Compactification

$$R^{1,10} \rightarrow R^{1,3} \times X^7$$

X^7=7-dimensional compact manifolds.

1. T^7, ...
2. G_2 manifolds (Standard model)

- G_2 manifolds

1. 7-dimensional real manifolds
2. G_2 holonomy group
3. Special 3-form

$$w = f_{ijk} dx_i dx_j dx_k$$

- Octonian algebra

$$t_i t_j = -\delta_{ij} + f_{ijk} t_k$$

Compactification of M-theory

M-theory

- Compactification

$$R^{1,10} \rightarrow R^{1,3} \times X^7$$

X^7=7-dimensional compact manifolds.

1. T^7, ...
2. G_2 manifolds (Standard model)

- G_2 manifolds

1. 7-dimensional real manifolds
2. G_2 holonomy group
3. Special 3-form

$$w = f_{ijk} dx_i dx_j dx_k$$

- Octonian algebra

$$t_i t_j = -\delta_{ij} + f_{ijk} t_k$$

Compactification of M-theory

M-theory

- Compactification

$$R^{1,10} \rightarrow R^{1,3} \times X^7$$

X^7=7-dimensional compact manifolds.

1. T^7, ...
2. G_2 manifolds (Standard model)

- G_2 manifolds

1. 7-dimensional real manifolds
2. G_2 holonomy group
3. Special 3-form

$$w = f_{ijk} dx_i dx_j dx_k$$

- Octonian algebra

$$t_i t_j = -\delta_{ij} + f_{ijk} t_k$$

Compactification of M-theory

M-theory

- Compactification

$$R^{1,10} \rightarrow R^{1,3} \times X^7$$

X^7=7-dimensional compact manifolds.

1. T^7, ...
2. G_2 manifolds (Standard model)

- G_2 manifolds
  1. 7-dimensional real manifolds
  2. G_2 holonomy group
  3. Special 3-form

$$w = f_{ijk} dx_i dx_j dx_k$$

  - Octonian algebra

$$t_i t_j = -\delta_{ij} + f_{ijk} t_k$$

Plan

Semi-realistic models in four dimensions :

- 1996 : Geometric engineering method : Vafa group
  1. Singularities of Calabi-Yau Manifolds
  2. Lie algebras
  3. D-brane physics
- 2001 : Intersecting branes : Madrid group
  1. Intersection theory
  2. D-brane physics
- 2008 : New method based on F-theory : Vafa group
  1. F-theory
  2. Varieties with elliptic fibrations.

D. Joyce, *Compact Manifolds with Special Holonomy*, Oxford U.P. 2000.

Semi-realistic models in four dimensions :

- 1996 : Geometric engineering method : Vafa group
  1. Singularities of Calabi-Yau Manifolds
  2. Lie algebras
  3. D-brane physics
- 2001 : Intersecting branes : Madrid group
  1. Intersection theory
  2. D-brane physics
- 2008 : New method based on F-theory : Vafa group
  1. F-theory
  2. Varieties with elliptic fibrations.

D. Joyce, *Compact Manifolds with Special Holonomy*, Oxford U.P. 2000.

Semi-realistic models in four dimensions :

- 1996 : Geometric engineering method : Vafa group
  1. Singularities of Calabi-Yau Manifolds
  2. Lie algebras
  3. D-brane physics
- 2001 : Intersecting branes : Madrid group
  1. Intersection theory
  2. D-brane physics
- 2008 : New method based on F-theory : Vafa group
  1. F-theory
  2. Varieties with elliptic fibrations.

D. Joyce, *Compact Manifolds with Special Holonomy*, Oxford U.P. 2000.

Semi-realistic models in four dimensions :

- 1996 : Geometric engineering method : Vafa group
  1. Singularities of Calabi-Yau Manifolds
  2. Lie algebras
  3. D-brane physics
- 2001 : Intersecting branes : Madrid group
  1. Intersection theory
  2. D-brane physics
- 2008 : New method based on F-theory : Vafa group
  1. F-theory
  2. Varieties with elliptic fibrations.

D. Joyce, *Compact Manifolds with Special Holonomy*, Oxford U.P. 2000.

Semi-realistic models in four dimensions :

- 1996 : Geometric engineering method : Vafa group
  1. Singularities of Calabi-Yau Manifolds
  2. Lie algebras
  3. D-brane physics
- 2001 : Intersecting branes : Madrid group
  1. Intersection theory
  2. D-brane physics
- 2008 : New method based on F-theory : Vafa group
  1. F-theory
  2. Varieties with elliptic fibrations.

D. Joyce, *Compact Manifolds with Special Holonomy*, Oxford U.P. 2000.

Plan

- There are many things.....
- String theory needs : Third revolution.

Thank you

- There are many things.....
- String theory needs : Third revolution.

Thank you

- There are many things.....
- String theory needs : Third revolution.

Thank you

- There are many things.....
- String theory needs : Third revolution.

Thank you

- There are many things.....
- String theory needs : Third revolution.

Thank you