Moduli, Fluxes & the Hierarchy Problem

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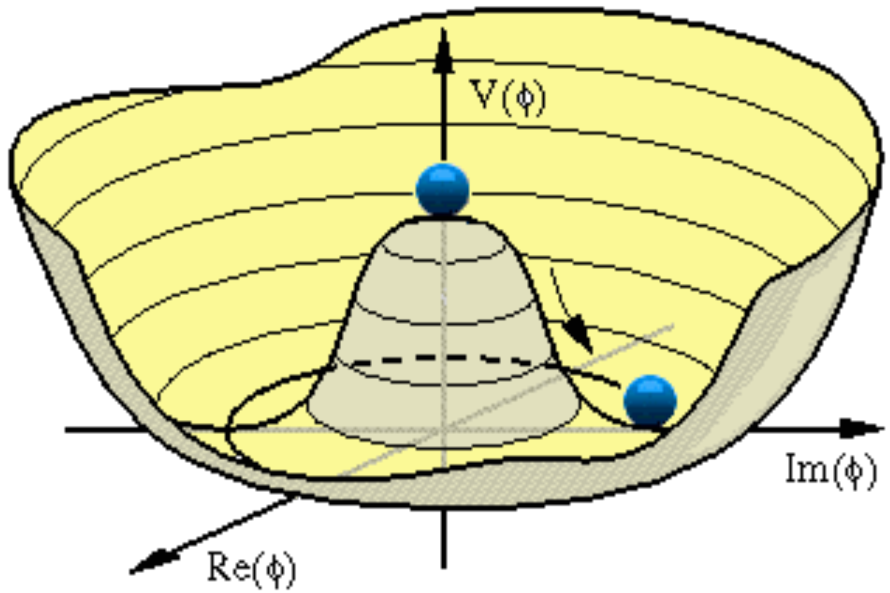
Outline

1. What are moduli?
2. Why are they important?
3. Why are they annoying?
4. What are fluxes?
5. Why are they useful?
6. What else do we need?
7. How to solve the hierarchy problem?

1. What are moduli?

Moduli $\longleftrightarrow$ 4d scalar fields with $m \approx 0$ & M_P^{-1} couplings

$\longleftrightarrow$ related to "degeneracy" of vacuum state



Geometric moduli $\longleftrightarrow$ fluctuations of metric along extradimensions

$\longleftrightarrow$ determine size and shape of compact space

Simplest example: compactify on circle S^1

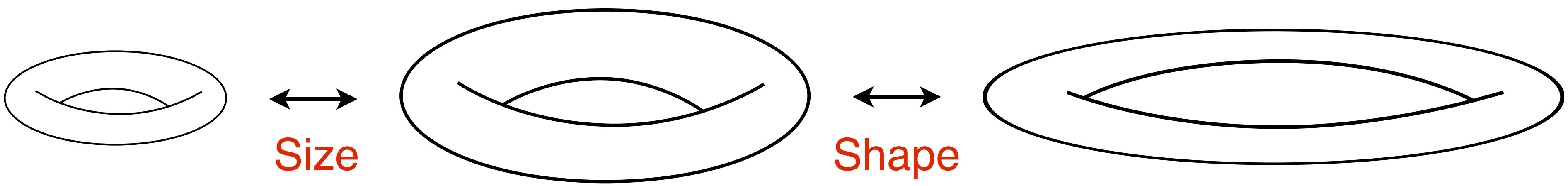
$\longleftrightarrow$ 1 modulus: fluctuation of radius $\longleftrightarrow$ $G_{55} \sim R$

1. What are moduli?

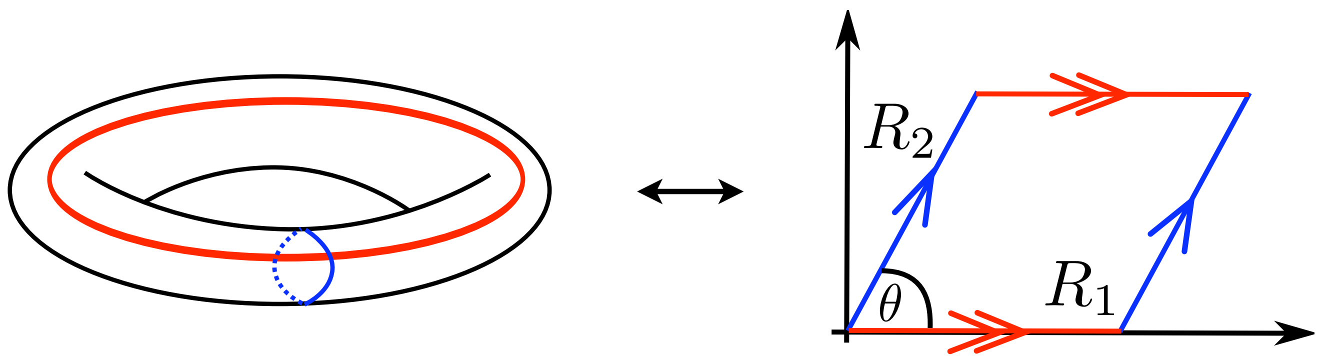
Next simplest example: compactify on 2 circles

$\longleftrightarrow$ compactify on torus T^2

Size & shape is difference between



How to quantify these differences? Consider 2 “base” circles



Define 2 complex moduli fields:

$$T \sim R_1 R_2 \sin\theta + iB_{12} \;\&\; U \sim \frac{R_2}{R_1}\sin\theta + i\frac{R_2}{R_1}\cos\theta$$

2. Why are they important?

ANY parameter of 4d low-energy effective field theory, e.g.

a) gauge couplings,

b) or Yukawa couplings,

in string theory compactifications is of the generic form

$$g = \#(\text{computable number}) \cdot f(\text{moduli})$$

Example: 4d effective gauge coupling of 5d gauge boson on a circle

$$\boxed{\frac{1}{g_{4d}^2} = \frac{R}{g_{5d}^2}}$$

Main challenge for today: "Moduli stabilisation"

Values of all couplings in the vacuum? $\longleftrightarrow$ What is $\langle R \rangle$ etc.?

What is effective 4d scalar potential for moduli? What minima exist?

Minima $\longleftrightarrow$ Moduli acquire mass & expectation values

3. Why are they annoying?

Just compactification manifold: moduli either have

a) (approx.) no potential at all, i.e. moduli unfixed

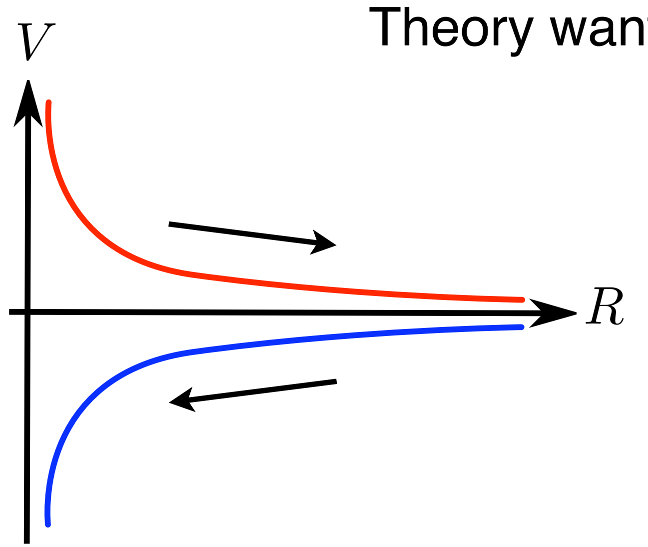
b) or a “runaway” potential towards decompactification!

Well, that sucks... But why does it happen all the time?

Intuitive reason: think of compact (sub-)manifolds as “bubbles”

Bubbles have surface tension, i.e. curvature ⟷ Surface tension or curvature cost potential energy to maintain

Theory wants to live in 10d & must be “forced” to 4d!



Typical potential energy:

$$V \sim \pm \frac{\#}{R^n}$$

$$R \to \infty \text{ or } 0$$

4. What are fluxes?

Fluxes are “generalized” electromagnetic fields, just with more indices

Basic reason why they appear in string theory:

a) point particle: worldline couples to electromagnetic field (“1-form”)

$$X_\mu(\tau) \rightarrow \oint d\Sigma_\mu A^\mu$$

b) string: worldsheet couples to “2-form” (2 antisymmetric indices)

$$X_\mu(\tau, \sigma) \rightarrow \oint d\Sigma_{\mu\nu} B^{\mu\nu}$$

c) Dp-brane: (p+1)-dim. worldvolume couples to “(p+1)-form”

$$X_\mu(\xi_0, \ldots, \xi_p) \rightarrow \oint d\Sigma_{\mu_0 \ldots \mu_p} C^{\mu_0 \ldots \mu_p}$$

Field Strength: $A_\mu \rightarrow F_{\mu\nu} = \partial_{[\mu} A_{\nu]}, B_{\mu\nu} \rightarrow H_{\mu\nu\rho} = \partial_{[\mu} B_{\nu\rho]}$ etc.

5. Why are they useful?

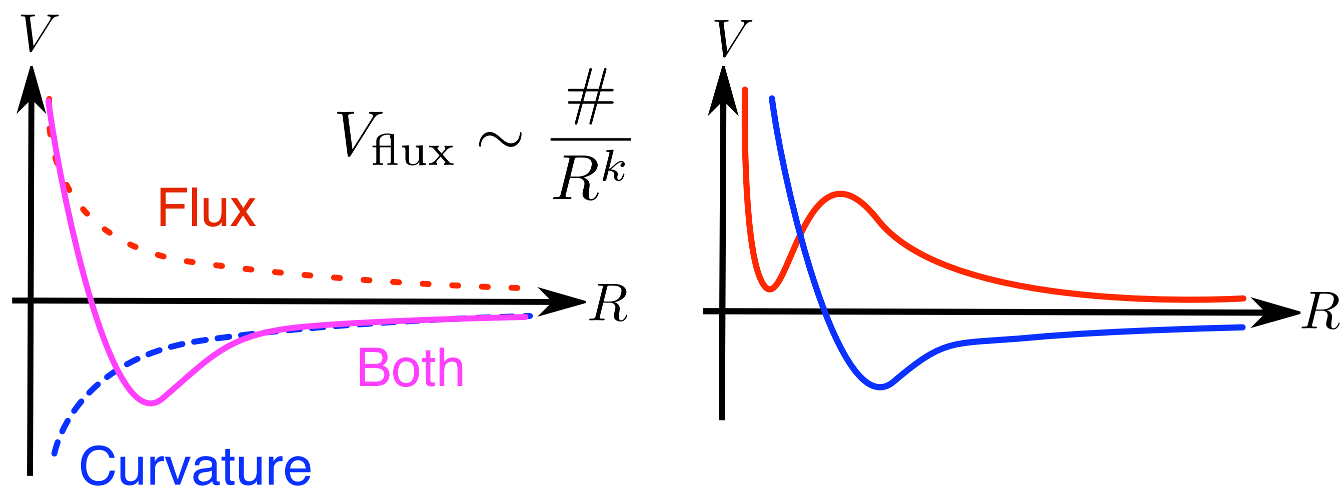
Need: additional energy source to balance surface tension

Fluxes: turn on "magnetic fields" in internal compact space

a) (p+1)-dim. manifold can support flux of p-form

e.g. magnetic field $F_{\mu\nu}$ on sphere S^2

b) "Magnetic" field energy density depends on R !



$$V_{\text{flux}} \sim \frac{\#}{R^k}$$

Remarks:

a) Moduli can be fixed with or without breaking supersymmetry

b) Fluxes are quantized $\oint d\Sigma_{\mu_0\ldots\mu_p} F^{\mu_0\ldots\mu_p} = \# \cdot N, \; N \in \mathbb{Z}$

6. What else do we need?

Typically: fluxes stabilize most but not all moduli...

In particular: overall volume $\mathcal{V}_6$ can be still free... What else can we do?

Use "non-perturbative" effect: D7-brane wrapping a 4-dim. submanifold

a) 4d & 8d gauge coupling related by $g_{4d}^{-2} = g_{8d}^{-2} \cdot R^4$

b) Non-perturbative contributions to potential $\propto e^{-\#/g_{4d}^2}$

crucial: not visible in perturbative limit $g_{4d} \to 0$

c) Strong coupling phenomenon: "gaugino" condensation $\langle \lambda \bar{\lambda} \rangle \neq 0$

Similar to other fermion condensates, e.g.

a) Chiral symmetry breaking in QCD $\langle q \bar{q} \rangle \neq 0$

b) Technicolor EWSB $\langle \psi \bar{\psi} \rangle \neq 0$

All geometric moduli can be stabilised in principle...

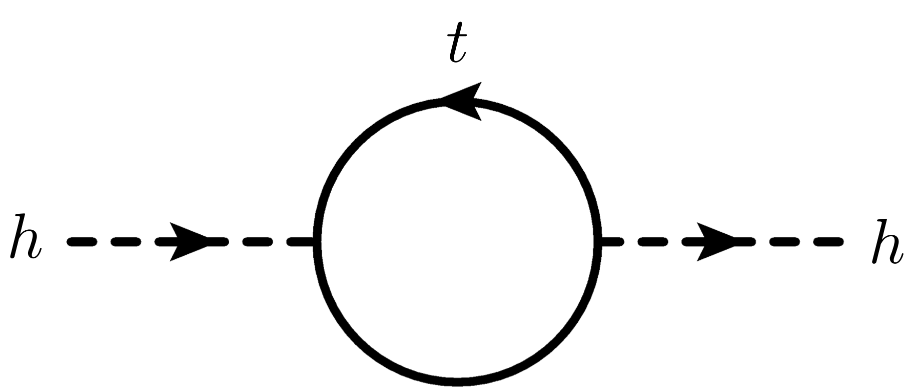
7. How to solve the hierarchy problem?

What is the hierarchy problem?

It is not about why $m_h^2 \ll M_P^2$

It is about the "radiative instability" of this hierarchy!

Quantum corrections induce large mass: $m_h^2 \sim \Lambda^2 + m_{h,0}^2$



Rough classification of solutions:

a) Eliminate quantum corrections above $\Lambda \sim \mathrm{TeV}$ (SUSY)

b) Explain why $\Lambda \sim \mathrm{TeV}$ instead of $\Lambda \sim M_P$ (everything else)

7. How to solve the hierarchy problem?

Moduli can solve it in both ways:

a) Act as hidden sector for spontaneous SUSY breaking

b) Make gravity strongly coupled at $\sim \mathrm{TeV}$

How to make gravity strongly coupled?

a) Experimentally only M_P is fixed

b) String theory relates M_P and string scale $M_s \sim \ell_s^{-1}$ by

$$M_P^2 \sim M_s^2 \cdot (\mathcal{V}_6 \ell_s^{-6})$$

c) Gravity becomes strongly coupled at $\sim \mathrm{TeV}$ if

$$M_s \sim \mathrm{TeV} \ \& \ \mathcal{V}_6 \sim 10^{30} \ell_s^6$$

d) LARGE Volume Scenario (or ADD scenario)

$\longleftrightarrow$ gravity diluted in extradimensions

Summary

Moduli are generic to string theory compactifications:

Geometric moduli characterize size & shape of extradimensions

Moduli determine couplings of 4d effective field theory

Decompactification problem:

Surface tension: moduli have "runaway" potentials $V \sim \pm \frac{\#}{R^n}$

Fluxes are also generic to string theory compactifications

Internal magnetic fields: balance surface tension $V_{\text{flux}} \sim \frac{\#}{R^k}$

Non-perturbative effects: corrections to potential $\propto e^{-\#/g_{4d}^2}$

$$g_{4d}^{-2} = g_{8d}^{-2} \cdot R^4$$

Hierarchy problem: make gravity strongly coupled at $\sim \text{TeV}$

LARGE Volume / ADD scenario $M_s \sim \text{TeV} \ \& \ \mathcal{V}_6 \sim 10^{30} \ell_s^6$