Strings, Exceptional Groups and Grand Unification

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Outline

- Grand Unification and
- global symmetries

play an important role in particle physics research

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- Where do they come from?
- The nature of “global” symmetries
- The need for an ultraviolet completion
- Strings and local grand unification
- Discrete (gauge) symmetries
- The fate of “local model building”

GUT groups

GUT motivation comes from bottom-up picture

- GUTs need SUSY
- SU(5) as the minimal extension
- SO(10) allows complete family in **16**

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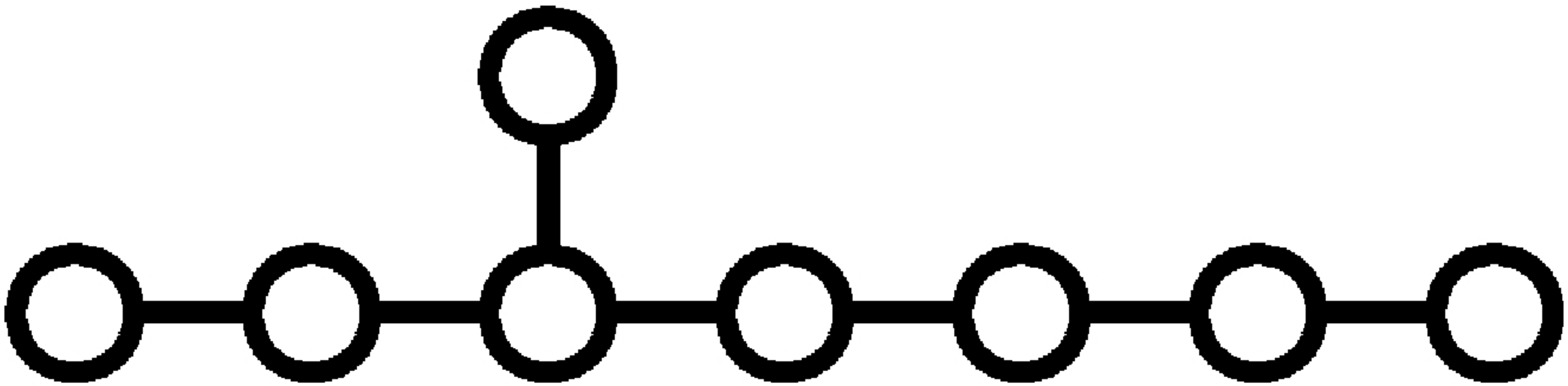
From the mathematical structure we would prefer exceptional groups

- There is a maximal group: E_8,
- but E_8 and E_7 do not allow chiral fermions in $d = 4$.
- How does this fit with SU(5) and SO(10)?

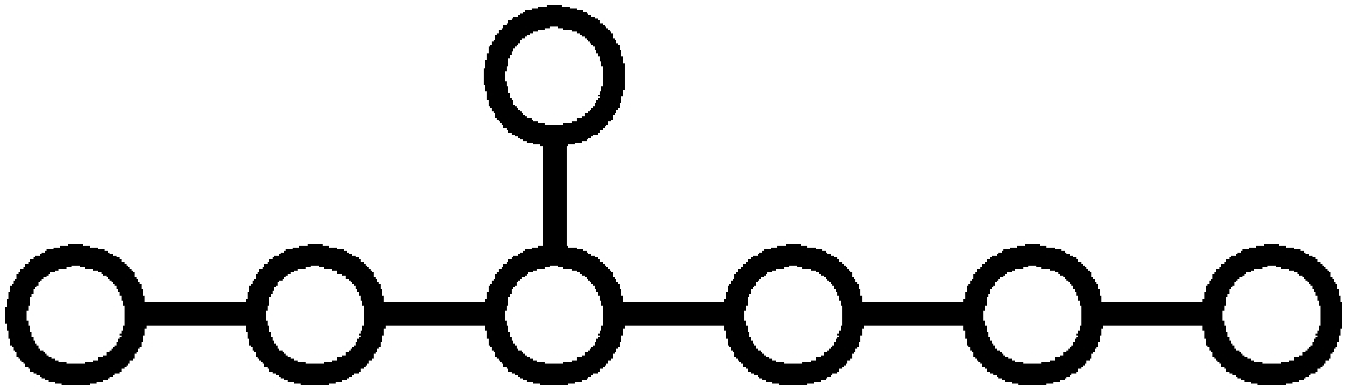
Maximal Group



E_8 is the maximal group.

There are, however, no chiral representations in $d = 4$.

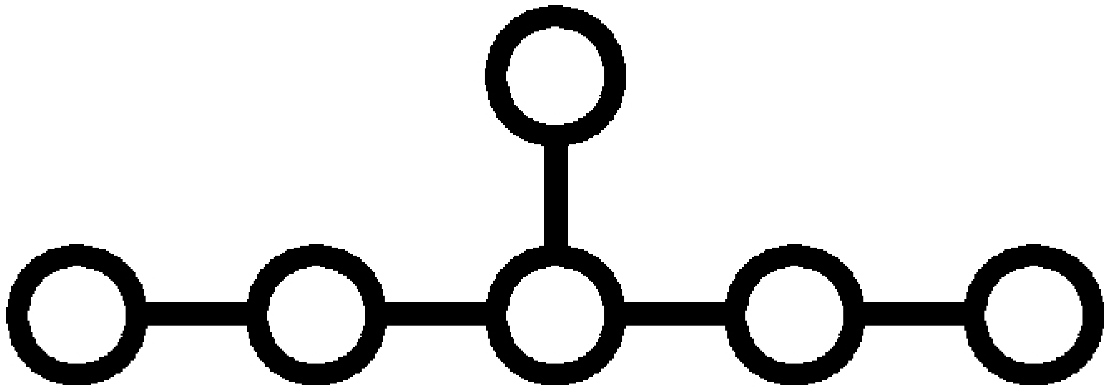
E_7



Next smaller is E_7.

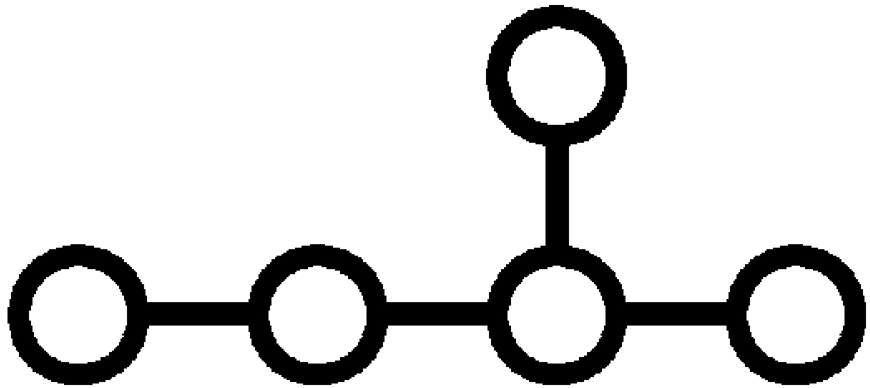
No chiral representations in $d = 4$ either

E_6



E_6 allows for chiral representations even in $d = 4$.

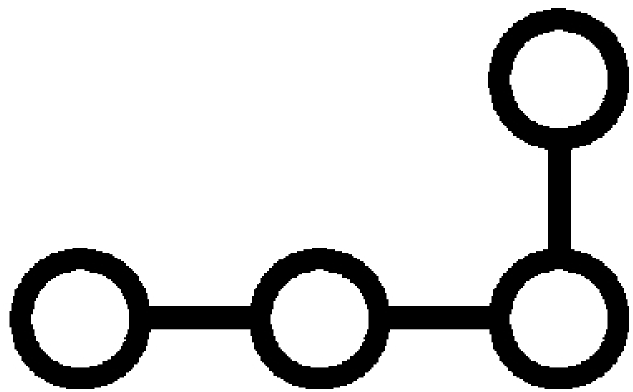
$E_5 = D_5$



E_5 is usually not called exceptional.

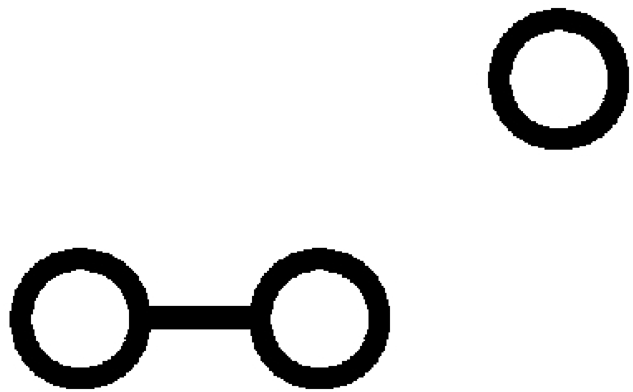
It coincides with $D_5 = SO(10)$.

$E_4 = A_4$



E_4 coincides with $A_4 = SU(5)$

E_3



E_3 coincides with $A_2 \times A_1$ which is $SU(3) \times SU(2)$.

Exceptional groups in string theory

String theory favours E_8

- $E_8 \times E_8$ heterotic string
- E_8 enhancement at a local point in F-theory

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Strings live in higher dimensions:

- chiral spectrum possible even with E_8
- E_8 broken in process of compactification
- provides source for more (discrete) symmetries
- from $E_8/SO(10)$ and $SO(6)$ of the higher dimensional Lorentz group

The use of additional symmetries

Symmetries are very useful for

- absence of FCNC (solve flavour problem)
- Yukawa textures à la Frogatt-Nielsen
- solutions to the μ problem
- creation of hierarchies
- proton stability

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But they might be destroyed by gravitational effects:

- we need a UV-completion of the theory
- with a consistent incorporation of gravity
- (discrete) gauge symmetries are safe

String theory as UV-completion

What do we get from string theory?

- supersymmetry
- extra spatial dimensions
- (large unified) gauge groups
- consistent theory of gravity
- a plenitude of discrete symmetries
- no global continuous symmetries

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String theory serves as a UV-completion with a consistent incorporation of gravity, and thus able to provide reliable symmetries.

Grand Unification in String Theory

In fact string theory gives us a variant of GUTs

- complete (or split) multiplets for fermion families
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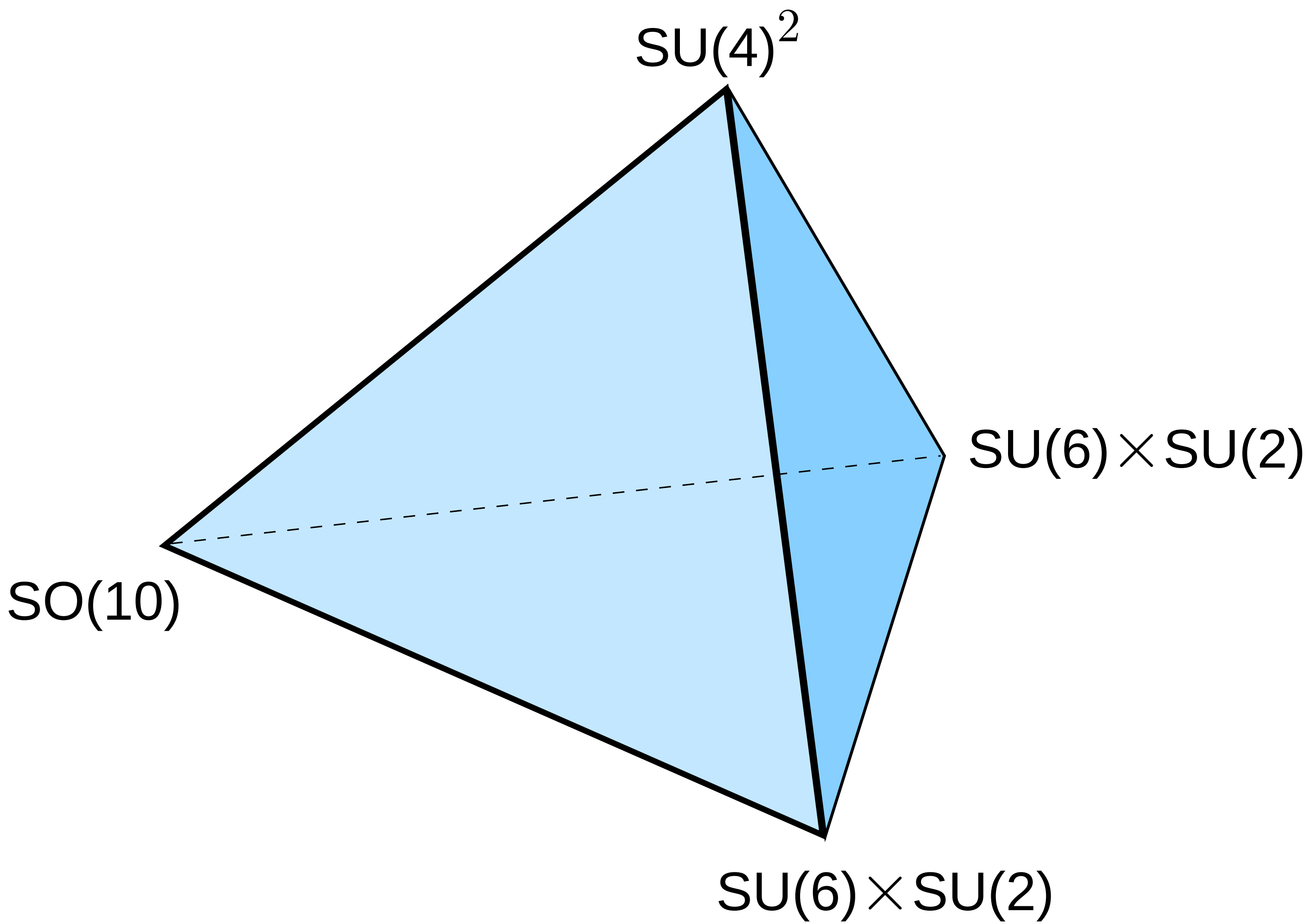
Key properties of the theory depend on the geography of the fields in extra dimensions.

This geometrical set-up called local grand unification, and can be realized in the framework of the
"heterotic braneworld".

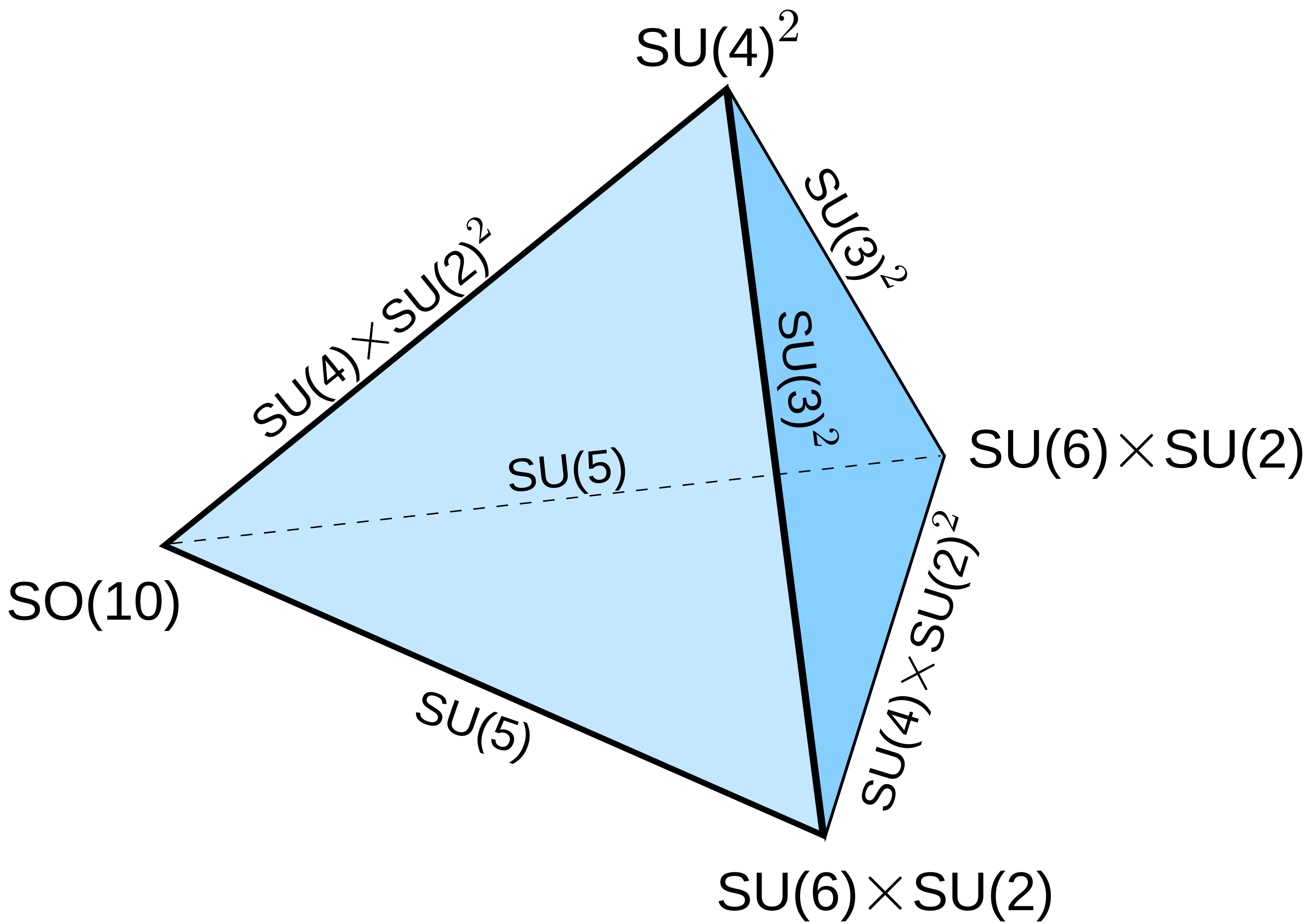
(Förste, HPN, Vaudrevange, Wingerter, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)

Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



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Do not trust the predictions of "Local Models" unless they are confirmed by a global completion!

Symmetries

String theory gives us

- gauge symmetries
- discrete symmetries from geometry and stringy selection rules (Kobayashi, HPN, Plöger, Raby, Ratz, 2006)
- accidental global $U(1)$ symmetries in the low energy effective action

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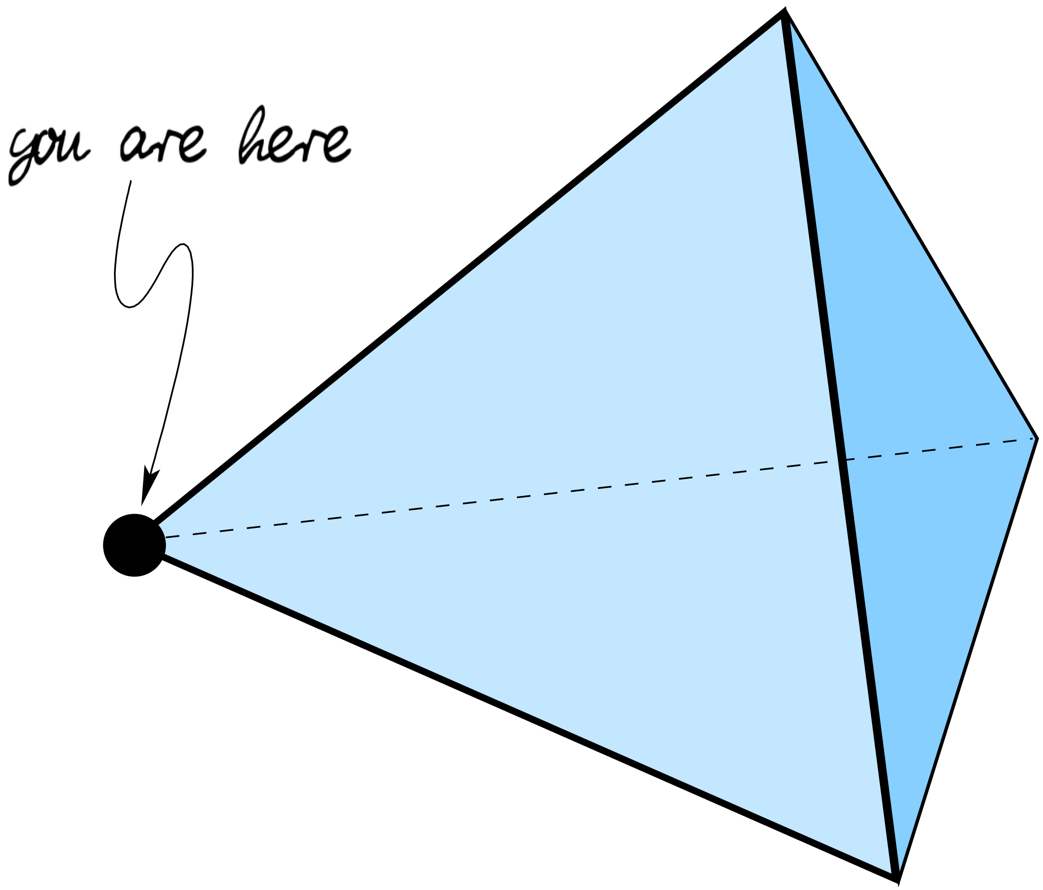
Location matters



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These symmetries can be trusted as we are working within a consistent theory of gravity (global model)!.

Applications of global symmetries

Applications of discrete and accidental global symmetries:

- (nonabelian) family symmetries (and FCNC)

  (Ko, Kobayashi, Park, Raby, 2007)

- Yukawa textures (via Frogatt-Nielsen mechanism)
- a solution to the μ-problem

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)

- creation of hierarchies

  (Kappl, HPN, Ramos-Sanchez, Ratz, Schmidt-Hoberg, Vaudrevange, 2008)

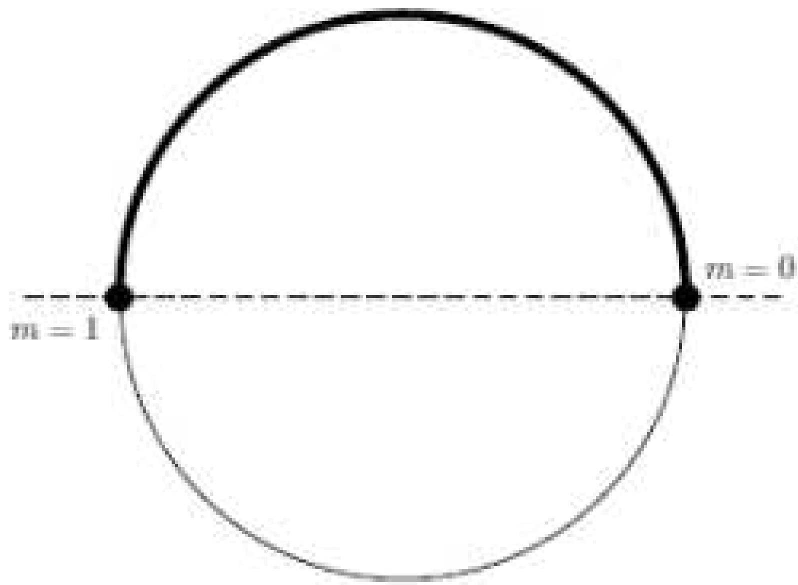
- proton stability via “Proton Hexality” or Z_4^R

  (Förste et al. 2010; Lee et al. 2011)

- approximate global $U(1)$ for a QCD accion

  (Choi, Kim, Kim, 2006; Choi, HPN, Ramos-Sanchez, Vaudrevange, 2008)

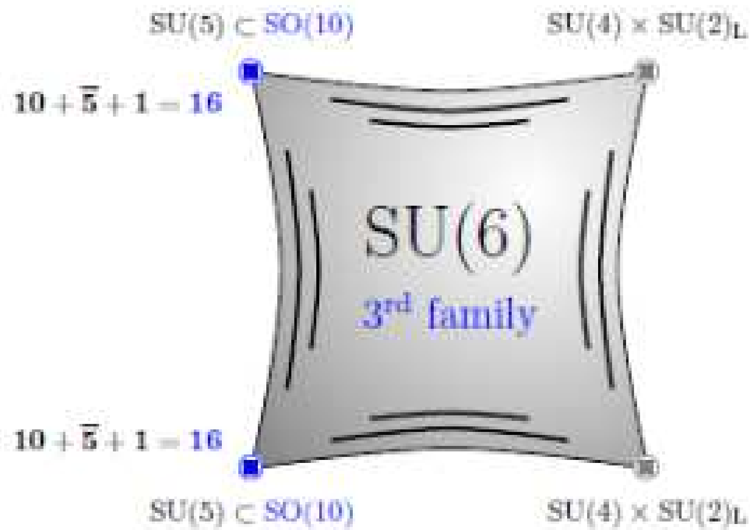
Origin of discrete symmetries



The semidirect product of $Z_2 \times Z_2$ and S_2

leads to the nonabelian group D_4

Local GUT picture



Family symmetries in local GUT models

The μ problem

In general we have to worry about

- doublet-triplet splitting
- mass term for additional doublets
- the appearance of "naturally" light doublets

In the heterotic braneworld we find models

- with only 2 doublets
- which are neutral under all selection rules
- if $M(s_i)$ allowed in superpotential
- then $M(s_i)H_uH_d$ is allowed as well

The μ problem II

We have verified that (up to order 8 in the superpotential)

- $F_i = 0$ implies automatically
- $M(s_i) = 0$ for all allowed terms $M(s_i)$ in the superpotential W

Therefore

- $W = 0$ in the supersymmetric (Minkowski) vacuum
- as well as $\mu = \partial^2 W / \partial H_u \partial H_d = 0$, while all the vectorlike exotics decouple
- with broken supersymmetry $\mu \sim m_{3/2} \sim < W >$

This solves the μ-problem (Casas, Munoz, 1993)

The creation of the hierarchy

Is there an explanation for a vanishing μ:

- string miracle or an underlying symmetry?

The μ-term is in fact forbidden by an R-smmetry.

For a continuous R-symmetry we would have

- a supersymmetric ground state with $W = 0$ and $\mathrm{U}(1)_R$ spontaneously broken
- a problematic R-Goldstone-Boson

However, the above R-symmetry appears as an accidental continous symmetry resulting from an exact discrete symmetry of (high) order N

Hierarchy

Such accidental symmetries lead to

- creation of a small constant in the superpotential
- explanation of a small μ term

(Kappl, HPN, Ramos-Sanchez, Ratz, Schmidt-Hoberg, Vaudrevange, 2008)

Even with a moderate hierarchy like $\phi/M_P \sim 10^{-2}$ one can generate small values for μ and $< W >$

$$m_{3/2} \sim W_{\text{eff}} = c + A\,\mathrm{e}^{-a\,S}$$

The second term in W_{eff} could be protected by an anomalous R-symmetry like e.g. Z_4^R

(Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange; 2010)

Proton stability

In the standard model Baryon number $U(1)_B$ is not a good symmetry

- Baryon and lepton number are anomalous
- cannot be gauged in a consistent way
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Baryon number violation is needed for baryogenesis.

- Grand unification addresses these questions
- proton decay via dimension-6 operators
- GUT scale has to be sufficiently high

GUTs need SUSY

Grand unification most natural in the framework of SUSY

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But there is a problem

- dimension-4 and -5 operators
- more symmetries needed
- matter parity (or R-parity)
- baryon triality, proton hexality

(Ibanez, Ross, 1991; Dreiner, Luhn, Thormeier, 2005)

MSSM

The minimal particle content of the susy extension of the standard model includes chiral superfields

- Q, $\bar{U}$, $\bar{D}$ for quarks and partners
- L, $\bar{E}$ for leptons and partners
- H_d, H_u Higgs supermultiplets

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with superpotential

$$W = QH_d\bar{D} + QH_u\bar{U} + LH_d\bar{E} + \mu H_u H_d.$$

Also allowed (but problematic) are dimension-4 operators

$$\bar{U}\bar{D}\bar{D} + QL\bar{D} + LL\bar{E}.$$

The question of proton stability

These dimension-4 operators could be forbidden by some symmetry

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Where does this symmetry come from?

- it could be a subgroup of $SO(10)$
- in consistent heterotic constructions it comes from $(E_8 \times E_8)/SO(10)$
- in local F-theory construction from $E_8/SO(10)$

Proton Hexality

But there are in addition dimension-5 operators that might mediate too fast proton decay $QQQL + \bar{U}\bar{U}\bar{D}\bar{E}$

	Q	$\bar{U}$	$\bar{D}$	L	$\bar{E}$	H_u	H_d	$\bar{\nu}$
$6\,Y$	1	-4	2	-3	6	3	-3	0
$\mathbb{Z}_2^{\text{matter}}$	1	1	1	1	1	0	0	1
B_3	0	-1	1	-1	2	1	-1	0
P_6	0	1	-1	-2	1	-1	1	3

Proton hexality is exactly what we need:

- dangerous dimension 4 and 5 operators forbidden
- neutrino Majorana masses allowed (LLH_uH_u)

(Dreiner, Luhn, Thormeier, 2005)

GUTs and Hexality

Combination of GUTs and proton hexality is perfect

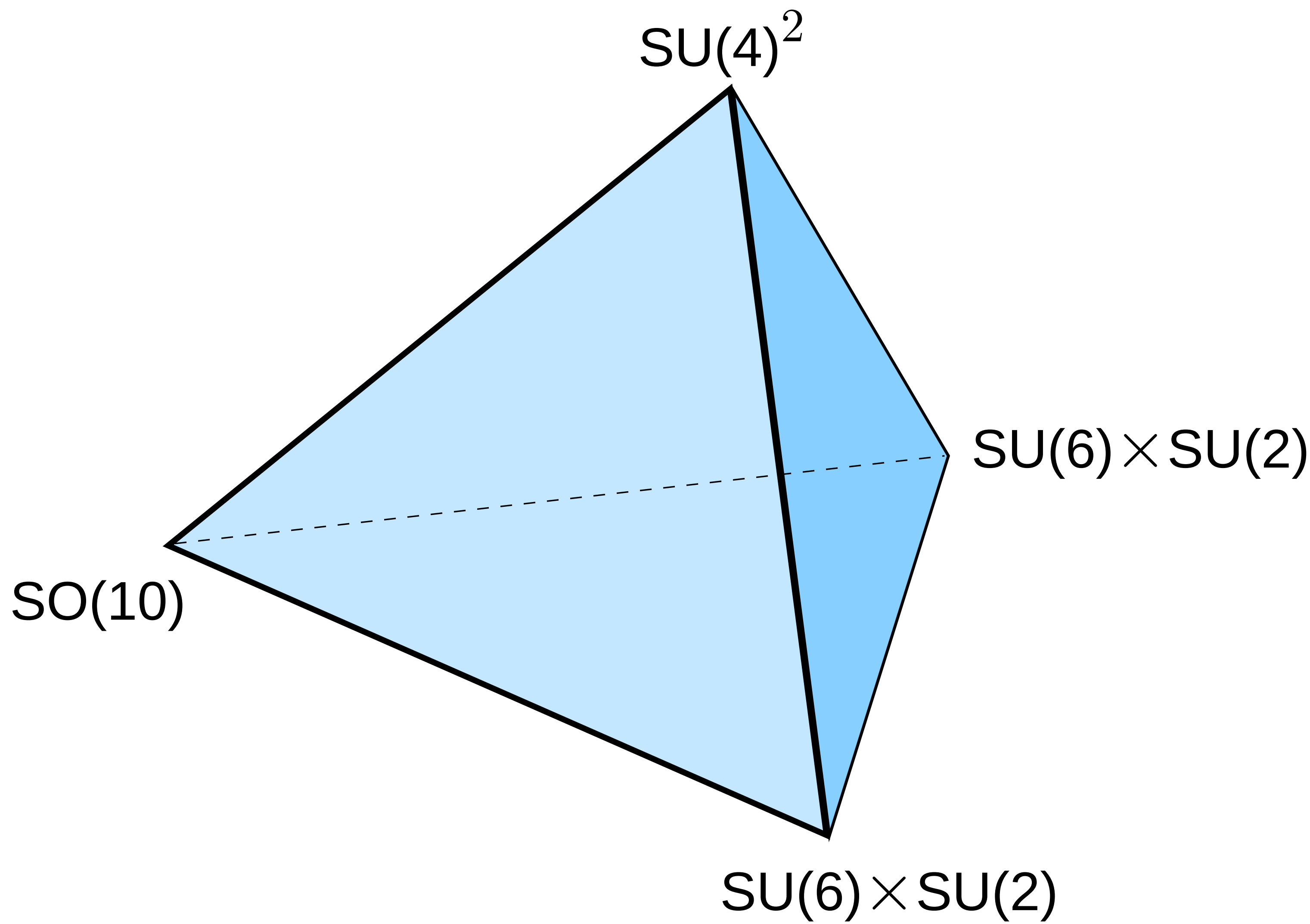
But GUTs and Hexality are incompatible (Luhn, Thormeier, 2007)

Example:
the 10-dimensional representation of SU(5) includes $\bar{U}$, Q and $\bar{E}$ and they cannot all have the same charge under hexality.

The problem is solved in

- Local Grand Unification
- need split multiplets for matter fields
- nonlocal structure of matter fields in compactified dimensions

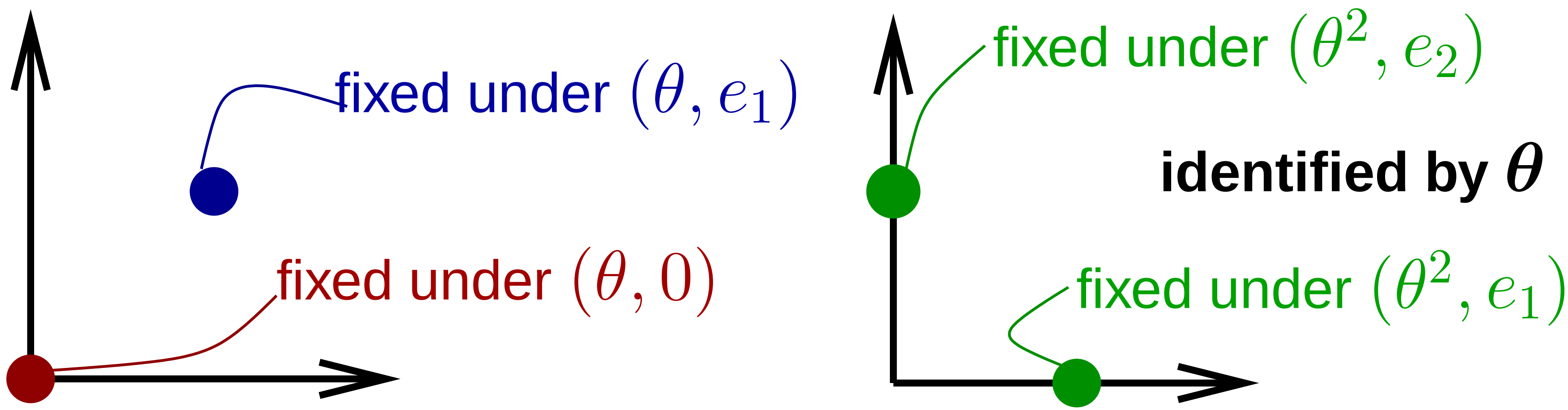
Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

A T_2/Z_4 toy example

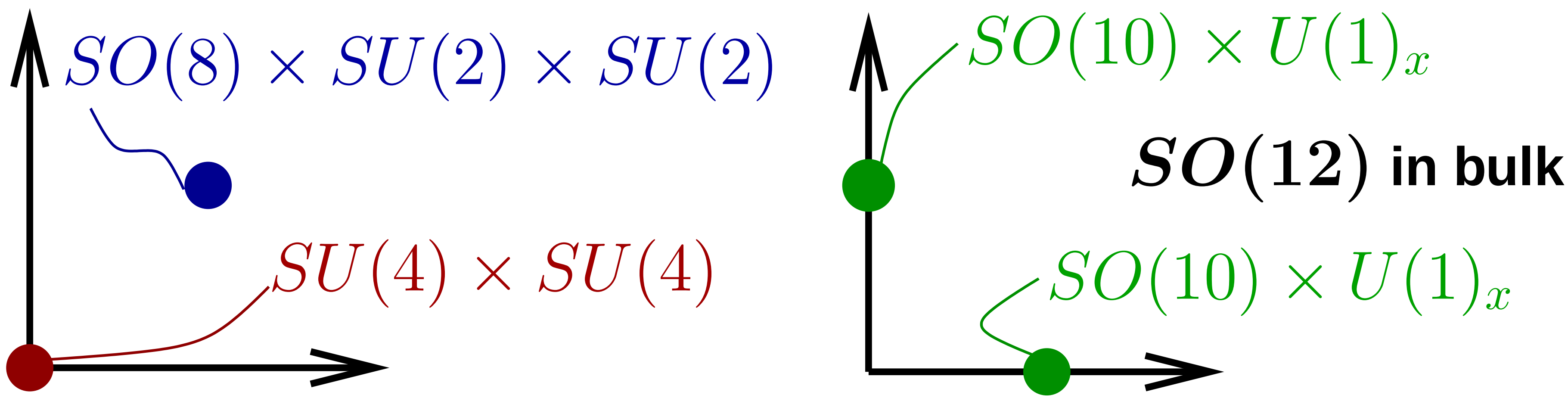
Consider the T_2/Z_4 orbifold, where we have two different types of fixed points



under rotation of $\theta = \pi/2$ and shift of the lattice vectors.

A T_2/Z_4 toy example

For a suitable embedding of twist and shift in the gauge group $SO(12)$ we have the following local gauge group structure



This allows split representations compatible with P_6 and does not require huge representations for the breakdown of $SO(12)$.

Lessons from the heterotic braneworld

The concept of local GUTs leads to a nontrivial structure of matter distribution in extra dimensions

- R-symmetries as subroup of SO(6) to solve the μ problem
- split multiplets for proton hexality
- Z_4^R consistent with 4d-GUTs

(Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange; 2010)

- discrete symmetries as subroups of $E_8 \times E_8 \times SO(6)$

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Note that we have consistent string models in a global construction. There is a plenitude of (discrete) gauge symmetries, both abelian and nonabelian.

(Kobayashi et al.,2006; Araki et al., 2008)

The fate of local model building

F-theory constructions are currently relying on "local models"

- decoupling of gravity
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Symmetries there all originate from

- a single gauge group like E_8
- matter parity as a subgroup of E_8
- but there is no global completion, the symmetry is inconsistent in the presence of gravity.

(Lüdeling, HPN, Stephan, 2011)

Predictions of "Local Models" are not reliable.

Conclusion

String theory might provide us with a consistent UV-completion of the MSSM including

- Local Grand Unification as a result of a consistent global construction,
- a plenitude of discrete symmetries,
- originating from some non-localities of matter distribution in extra dimensions.

Geography of extra dimensions plays a crucial role.

Local Grand Unification is the right way to proceed.

Discrete symmetries as subgroups of $E_8 \times E_8 \times SO(6)$ as a crucial prediction of string theory!

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