Systematic Investigations of the Free Fermionic Heterotic String Landscape

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Outline

- General outline of free fermionic heterotic string model (FFHS) construction.
- Systematic gauge group searches and optimizations.
- Systematic NAHE and NAHE variation extension investigations and the FF Framework.

FFHS Inputs

- Two inputs:
- A set of 64 component basis vectors.
- An $L \times L$ GSO coefficient matrix, where L is the number of basis vectors.
- Basis vector elements represent phases that fermion modes gain when parallel transported around non-contractible loops of space-time.
- The GSO coefficient matrix represents the degrees of freedom present in choosing a modular invariant model.

FFHS Degrees of Freedom

- Left moving supersymmetric vibrations and right moving bosonic vibrations make up the string.
- Left moving vibrations around the 6 compactified directions consist of three degrees of freedom: 1 fermion mode and a boson mode written as two real fermions.
- In addition there are four large space time modes, two of which are eliminated in light cone gauge.
- Left moving modes have 20 degrees of freedom.

FFHS Degrees of Freedom

- Right moving modes are only bosonic, and vibrate in 26 dimensions.
- We ignore the large dimensions here because the only massless mode in which they appear is the graviton.
- (26 - 4) = 22 modes in a complex fermion basis, or 44 in a real basis.
- Total number of basis vector components is 64.

FFHS Construction - Constraints

- **Order** - The allowed phases of the vibration modes, or a limit on basis vector component values.
- **Layer** - The number of basis vectors in a model.
- Modular invariance constrains the allowed basis vectors for a model.
- Modular invariance is crucial to producing actual Lie algebras in the model.

Systematic Gauge Group Searches

- A recent paper by G. Cleaver, M. Robinson, M. Hunziker (MPLA 24 (2009) p.2703) showed a new way of expressing basis vectors and the modular invariance constraints for models which contain only gauge groups.
- Substantial time improvement over a brute force approach.
- Comprehensive statistics for models of layer 1 and order 1-15 have been collected for these simple gauge group models.
- This approach is currently being generalized to include matter content.
- Higher layer gauge searches are currently underway.

Gauge Group Search Results

Order	Number of Solutions	Unique Gauge Group Products
1	1	1
2	5	5
3	39	8
4	271	18
5	1,505	22
6	6,699	38
7	26,967	40
8	96,630	40
9	326,842	65
10	1,005,097	67
11	2,932,573	67
12	8,065,302	67
13	20,941,804	69
14	52,672,916	70
15	126,723,711	70
16	≈300,000,000	71

Breakdown of Gauge Group Product Content

Group	No.	Group	No.	Group	No.
SU(2)	32	SU(16)	3	SO(8)	12
SU(3)	4	SU(17)	0	SO(10)	9
SU(4)	12	SU(18)	1	SO(12)	14
SU(5)	4	SU(19)	0	SO(14)	5
SU(6)	10	SU(20)	0	SO(16)	6
SU(7)	4	SU(21)	1	SO(18)	1
SU(8)	8	SU(22)	0	SO(20)	4
SU(9)	3	SU(23)	0	SO(24)	3
SU(10)	7			SO(28)	2
SU(11)	2	E_6	7	SO(32)	1
SU(12)	6	E_7	7	SO(40)	1
SU(13)	2	E_8	4	SO(44)	1
SU(14)	2				
SU(15)	0				

Non Standard E_8 Embedding

- One interesting result on this study was a non-standard embedding of E_8, reported in G. Cleaver, R. Obousy, M. Robinson (MPLA 24 (2009) p.1577).
- A basis vector of order 3 with 18 real twists of $\frac{2}{3}$ produced a gauge group of $E_8 \otimes SO(28)$.
- The E_8 appears by combining the 80 adjoint representation of SU(9) with an 84 and an $\overline{84}$, which give a 248, the adjoint of E_8.

The NAHE Set

- Serves as a nice starting basis for "realistic" FFHS models.
- N=1 ST SUSY.
- SO(10) observable GUT gauge group.
- Three generations of particles (each with 16 copies, however).

NAHE Variation

- A variation of the NAHE set reported in G. Cleaver, T. Ali, K. Pechan, J. Greenwald, T.R. (arXiv:0912.5207) provides an alternative to the NAHE set.
- N=1 ST SUSY is preserved.
- Gauge groups are $E_6 \otimes SO(28)$.
- Range of mirror models - models with identical observable and hidden sector gauge groups (and matter states) - possible.

Systematic NAHE Extensions

- NAHE set will be extended by adding any number of basis vectors of any order.
- Statistics will be collected on these models.
- Attention paid to SO(6)$\otimes$SO(4) models, flipped SU(5) models, and (N)MSSM-like models.
- Gauge groups and matter representations will be generated.

NAHE Variation Extensions

- NAHE variation will also be systematically extended.
- Special emphasis placed on mirror models.

Statistics

Probabilities of :

- Anomalous U(1).
- Hidden sector gauge groups.
- Hidden sector matter.
- Number of observable (chiral) generations.
- Number of Higgs scalars.

Challenges to Systematic Searches

- Lots of computing time needed - optimized software is necessary.
- Core logic changes may invalidate results.
- Several graduate careers.

FF Framework

- A collection of C++ classes.
- Designed to optimize and generalize computer construction of FFHS models.
- Intended to balance speed with usability by other graduate students.

Speed Improvements

- Redundancy reduction.
- Combinatoric basis vector generation allows far less file I/O.
- "Smart" loop nesting is used when applicable, greatly improved over brute force nesting.

Usability Improvements

- Current software in FORTRAN 77, contains hundreds of thousands of lines of code.
- FF Framework has under 5,000 lines, and is in a modern language.

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- Object oriented.
- Many features may be added or removed without compromising core logic.

Further Usability Improvements

- Core logic adjusts to layer and order.
- Uses C++ STL containers.
- Ideal not only for the NAHE extensions, but also for almost any kind of individual FFHS model as well.

Future Plans

- Framework is nearly complete.
- Preparations are being made to generate data and collect statistics over the summer.
- NAHE extension and the extension of the NAHE variation will be examined systematically.
- Continued improvements of speed will be implemented (i.e. threading, multi-node processing, etc.).
- Additional features will be added as more detailed analyses are desired.

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References

- *Free Fermionic Heterotic Model Building and Root Systems* - M. Robinson, G. Cleaver, M. Hunziker MPLA 24 (2009) p 2703
- *A Non-Standard Embedding of E_8* - R. Obousy, M. Robinson, G. Cleaver MPLA 24 (2009) p 1577
- *Note on a NAHE Variation* - J. Greenwald, K. Pechan, T.R., T. Ali, G. Cleaver (arXiv:0912.5207)
- *Systematic Investigation of Free Fermionic Heterotic String Gauge Group Statistics: Layer 1 Results* - C. Buescher, J. Greenwald, M. Janas, G. Miller, K. Pechan, T.R., S. Ruhnau,G. Cleaver. (in progress)
- *Systematic Investigation of NAHE and NAHE Variation Extensions* -T.R., J. Greenwald, D. Moore, G. Cleaver (in progress)
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