String Landscape:
Status Report

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Abstract

Over the last few years, our picture for how string theory might make contact with the real world has significantly changed, with the advent of the "landscape." We explain these ideas, evidence for and against them, and implications for testing the theory

1. Background and overview

- String compactification leads to quasi-realistic models, and probably realistic models.
- Many new ideas have emerged, with potentially testable consequences: detailed models with low energy susy, new gauge groups and matter with exotic quantum numbers, nontrivial fixed point sectors, large extra dimensions with light KK or string modes, warping with light spin 2 modes, split supersymmetry, and so on.

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- We live in (at most) one vacuum of string theory. So to know which of these predictions to look for, we need to make some hypothesis about which vacuum we live in.

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- We live in (at most) one vacuum of string theory. So to know which of these predictions to look for, we need to make some hypothesis about which vacuum we live in.
- So far, we have only studied a tiny fraction of string compactifications (particular choice of CY for internal dimensions, etc.) and have no reason to think these are the preferred ones. We need to get a better sense for the possibilities.

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- Perhaps the most difficult problem in constructing a realistic vacuum is to reproduce the observed small positive dark energy. It has been argued that there are no self-tuning mechanisms in local field theory (Weinberg) or in string/M theory (Polchinski), and the non-zero value of the dark energy speaks against self-tuning anyways.

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- In 2000, Bousso and Polchinski argued that, because a typical CY has hundreds of homology cycles, there would be a large multiplicity of flux vacua, of order $10^{100's}$. These vacua should have widely distributed vacuum energies, thus enabling Weinberg's proposal for an anthropic solution to the cosmological constant problem.

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- In 2003, Kachru et al (KKLT) proposed a way to construct IIb flux vacua with all moduli stabilized. Explicit constructions of this type were realized by Denef, Florea and myself in 2004, and by many others since.
- Further study of this construction, as well as studies of the statistics of flux vacua (the distribution of vacuum energy and other parameters), appears to bear out Bousso and Polchinski's picture. (work of myself with Ashok and Denef, Kachru et al, Quevedo et al, ...)

- Even in very early work on string/M theory vacua, it was apparent that many choices were involved – of compactification manifold, and of additional structure such as bundles, branes, lattices, modular invariants, etc. However, without a theory of moduli stabilization, it was unclear how many of these choices actually led to vacua, *i.e.* long-lived metastable minima of the effective potential.

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  Thus there is at present no obvious way to rule out any of these vacua, other than to compare the detailed predictions of each one with observation.

- While 10^{500} vacua at first sounds terrible, actually it is not a disaster – we will discuss this in some detail later. But we would be happier if there were a few vacua and some other solution to the c.c. problem, or perhaps of order 10^{120} vacua.

  The analyses leading to 10^{500} are only a first cut and it is certainly possible that going further would lower the number (or drastically increase it). In addition, by thinking about early cosmology and the processes which create vacua, we might be able to find an *a priori* probability distribution on the set of vacua. This is usually called the "measure factor".

After reviewing these ideas, we will discuss the present status of arguments for and against low energy supersymmetry, large extra dimensions and warping, and give some other suggestions for general "predictions" of string/M theory.

2. Structure of the landscape

Let us grant for now that our present constructions of string/M theory vacua are valid (we discuss possible loopholes later) and ask: How can we get a sense of the totality of possibilities?

- Explicit constructions of vacua
- Statistical surveys of large classes of vacua
- Arguments from general principles that certain vacua cannot exist
- Arguments that the total number of quasi-realistic vacua is finite, ideally which give some simple way to estimate their number.
- Arguments using large number theorems and peaking of distributions

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2.1. Explicit constructions

Clearly everything else is based on this. It has been discussed by many speakers here and we will not go into details. Bert Schellekens' remark on Tuesday about the limits of present techniques is well taken, however progress (mostly mathematical and formal) on CY geometry, F theory, computing superpotentials, etc. should improve this situation.

Of course, we need to know that our explicit constructions actually lead to vacua, and this is not so easy to prove in a given example – one needs to check that no field is tachyonic, one needs metastability, etc.

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Of course, we need to know that our explicit constructions actually lead to vacua, and this is not so easy to prove in a given example – one needs to check that no field is tachyonic, one needs metastability, etc.

However, having looked at this issue extensively, in my opinion the known checks of this sort do not eliminate many vacua. For example, if one has a hierarchy $M_{susy} << M_{Planck}$, tachyons tend not to be present, by the broken susy relation

$$M_{boson}^2 \sim M_{fermion}(M_{fermion} - M_{susy}).$$

One just needs $M_{susy} < M_{Planck}/N_{fields}$, not low energy susy.

The remaining "loopholes" are more conceptual, we discuss these later.

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2.2. Statistical surveys

Again, well covered in many existing talks and reviews. Let us cite a few simple results:

- Λ is uniformly distributed and independent of other parameters, in particular M_{susy}.
- Couplings (when properly defined) are “often” uniformly distributed, consistent with ’traditional” naturalness.
- This can still lead to interesting distributions, for example dimensional transmutation

  $$M_{dynamical} \sim \exp -8\pi/g^2_{YM}N$$

  with uniform dg^2_{YM} (and correct N dist) leads to dM/M.

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  with uniform dg_{YM}^2 (and correct N dist) leads to dM/M.
- On the other hand, discrete symmetries appear to be unnatural (Dine and Sun 0506246), with some exceptions such as R-parity.
- In particular model classes, gauge groups and matter content satisfy approximate simple distributions, for example (Blumenhagen, Gmeiner et al 0411173):

  $$(\text{probability of having an } SU(M) \text{ factor}) \;\; \propto \;\; \exp -\alpha M$$

  for IIa brane constructions (here $\alpha \sim \sqrt{\frac{\log L}{L}}$).

2.3. Correlations and theory space

Although uniformity and independence simplify our study, it would be rather disappointing if this was the whole story. Rather, we are looking for interesting structure in the distribution of vacua: correlations, regions with many or few vacua, etc.

In principle, all of this information can be summarized in a vacuum counting distribution, giving the number of vacua with specified $SU(N_i)$ gauge groups, I_{ij} matter multiplets in the $(N_i, \bar{N}_j)$ representation, couplings g_i and λ_a, etc., as

$$N_{vac}[N_1, N_2, \ldots, I_{12}, I_{13}, \ldots, g_1, g_2, \ldots, \lambda_a, \Lambda, \ldots]$$

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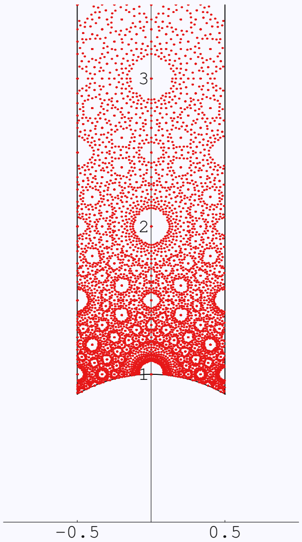
We can picture this multivariable distribution as a measure on "theory space," a sum of unit weight delta functions for each theory.



This is a set of flux vacua with stabilized moduli for IIb theory on a rigid Calabi-Yau, plotted as a function of the value of the dilaton (vertical axis) and axion (horizontal axis). Some points, such as the ones in the middle of the "holes," correspond to many vacua.

We can think of quasi-realistic models as points in an analogous 19-dimensional plot, with one axis for each Standard Model coupling.

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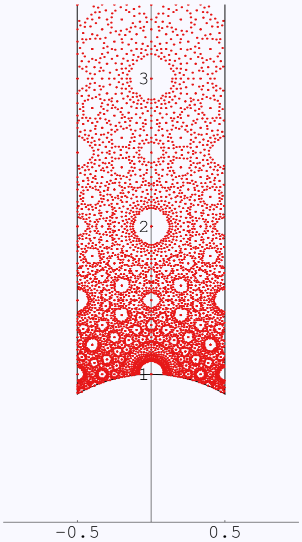

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More generally, we can ask: are there dense regions, or empty regions? Do vacua populate the filled regions fairly uniformly, or are there correlations between parameters? And so on...

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In many cases, the true vacuum counting distributions can be approximated reasonably well by simple continuous functions – this one is approximately

$$dN_{vac} \sim \frac{d^2\tau}{(\mathrm{Im}\ \tau)^2},$$

which is the natural measure associated to the metric on field space.

There is a general formula for the approximate distribution of IIb flux vacua (Ashok and Douglas 2003). It is determined by the number of three-cycles b_3, the "tadpole number" L, and the metric on field space:

$$\rho_I(z,\tau) = \frac{(2\pi L)^{b_3}}{b_3!\pi^{n+1}} \det(-R - \omega \cdot 1).$$

This justifies Bousso and Polchinski's $N^{\text{number of cycles}}$ estimate (though many details are different). It probably contains a lot of information about correlations between parameters of vacua, but this has only begun to be explored.

2.4. Non-existence or “swampland” arguments

Many arbitrary modifications of our effective theories lead to inconsistencies. For example, many sensible gauge theories (*e.g.* with matter in higher tensor representations), and many theories suggested by astrophysicists (MOND, TeVeS, $f(R)$ gravity, ...), can be argued not to come out of string/M theory.

There are interesting arguments that some sensible quantum field theories cannot be coupled to gravity. For example, Arkani-Hamed *et al* have argued that the coupling g for any $U(1)$ group must satisfy

$$g > \frac{M_{min}}{M_{Planck}}$$

where M_{min} is the mass of the lightest charged particle. Otherwise, charged black holes will not be able to radiate away charged particles.

While the Standard Model and its commonly proposed extensions are not near any known bounds of this type, we see that not all low energy theories are possible within string/M theory.

2.5. Finiteness arguments

Within the “filled regions” of theory space, we would like to know whether some regions are more densely filled than others. BUT – suppose there were an infinite number of quasi-realistic vacua: then this question might not make sense!

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In all well-understood examples the number turns out to be finite. Often it is controlled by topological numbers as in Bousso-Polchinski.

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However this is not always the case, as there are infinite sequences of vacua which run off to large volume. For example, consider $AdS_5 \times S^5$ with flux N. N can be any integer, and $\mathrm{Vol}\ (S^5) \sim N^{5/4}$.

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To make the number of quasi-realistic vacua finite, we define "quasi-realistic" to include an upper bound on the size of the compact dimensions, perhaps set by the validity of the gravitational inverse square law. Using this justification, the most natural bound is an upper bound on the diameter (the maximum distance between any pair of points) of M.

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One interesting choice which we do not know is finite is the choice of compactification manifold. Mathematicians do not know whether the number of topologically distinct 6d Calabi-Yau manifolds is finite.

Nevertheless, there is a mathematical theorem (Cheeger 1970) which states that, in any infinite series of manifolds (with bounded curvature), the diameter has to run off to infinity. With Bobby Acharya, we argued that, even if the number of Calabi-Yau manifolds were infinite, the number of quasi-realistic string vacua would still be finite.

2.6. Large number theorems and peaking

One might hope that the large number of vacua would lead to simplifications. In particular, systems with large numbers of degrees of freedom often show universality for statistical reasons: central limit theorem, matrix model and large N limits, etc.

Certainly, an observable which is the sum of many independent contributions, should be normally distributed. This is plausible for the c.c., and the width is so large that this is consistent with the uniform distribution claimed earlier. However most observables in string compactification (coupling constants, matter content) do not appear to be the sum of many indepndent contributions.

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A more plausible argument of this type is to model a mass matrix as a random matrix drawn from one of the standard distributions (after all it is a piece of a random Hamiltonian). From the structure of $N = 1$ supergravity, this should be the CI ensemble, *i.e.* $M^2 = ZZ^\dagger$ where Z is complex symmetric (Denef and Douglas 0411183). This should apply to stabilized moduli and leads to a universal level spacing

$$P \propto |M_i^2 - M_j^2|.$$

Given additional structure this could be modified, for example Easther and McAllister 0512102 argued that axionic moduli masses (which get masses from instanton corrections) should be governed by the Marcenko-Pastur distribution (like the above but with rectangular Z).

While moduli masses in flux compactification are too high to be directly observable, such results might be useful for cosmology.

A simpler claim of this type is that, given enough cycles, low dynamical scales and/or their dual gravity realization (conifold singularities) are generic. This follows from the uniform distribution dg^2_{YM} giving the log uniform dM/M discussed earlier.

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3. Effective potential hypothesis

In no case has the construction of an explicit supersymmetry breaking or even stabilized $N = 1$ vacuum been worked out to the end. All current claims about numbers of vacua include some statistical element, *i.e.* one estimates the probability p that a given field will be tachyonic, and includes a factor $(1 - p)$ in the estimated number of vacua.

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Furthermore, unless we use a nonperturbative formulation of string/M theory, one can hypothesize that some sort of missing correction or consistency condition would destabilize or eliminate the candidate vacuum. Obviously this would be important to understand.

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Furthermore, unless we use a nonperturbative formulation of string/M theory, one can hypothesize that some sort of missing correction or consistency condition would destabilize or eliminate the candidate vacuum. Obviously this would be important to understand.

However, whatever the hypothetical missing correction or consistency condition might be, it probably has some reinterpretation in terms of known physics. And, having considered these arguments in detail, at this point there do not seem to be candidates for it in known physics.

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Perhaps the main hope for finding a loophole in “unknown physics” is the implicit assumption in all current analyses that we can define and, at least approximately, compute an effective potential, a function of all of the scalar fields whose local minima are (metastable) vacua.

One reason to be suspicious of this claim, emphasized by Tom Banks, is that the effective potential is an off-shell quantity. On the other hand, it is often claimed that one cannot define off-shell quantities in string theory.

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Perhaps the most direct answer to this question would be to develop an off-shell formulation such as string field theory. While this is not yet sufficiently advanced to use directly, it does seem that for many vacua (including quasi-realistic ones), one can think of the effective potential as the sum of classical and perturbative terms (fluxes, supersymmetry breaking effects), with nonperturbative effects which are generated by field theory, *i.e.* strong gauge dynamics at low scale. The former are well described by string field theory, even in its present primitive state. And, we know that the latter can be described by an effective potential.

Finally, one needs to be able to add these contributions. Although there are some ambiguities in this procedure, one can consider vacua for which the various terms have different (parametrically controlled) magnitudes, so that order one uncertainties will not affect the existence of minima. For example, in the KKLT construction, the flux potential (stabilizing complex structure and dilaton moduli) is at a parametrically higher scale than the nonperturbatively generated potential (stabilizing Kahler moduli).

Clearly it would be valuable to have a nonperturbative construction of at least some vacua with stabilized moduli, to be sure there are no subtleties in the preceding claims. While this seems out of reach for nonsupersymmetric vacua and de Sitter vacua (positive c.c.), we expect that supersymmetric AdS vacua have gauge theory duals which are $d = 3, N = 2$ superconformal theories. Can we construct these duals?

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While a few attempts were made (Silverstein 0308175, Aharony et al 0801.3326), these were inconclusive. But it was observed that the expected gauge theory duals would have strange properties. In particular, if we want a "true compactification," *i.e.* with KK scale much above the c.c., the AdS/CFT duality map implies that the CFT must have a large gap in operator dimensions – a few operators with dimension around 3 (massless fields), and then no operators up to $\Delta \sim c$ for some large c. Is this possible? Of course, we are asking for it to happen in the strong coupling limit, so we have no very clear intuition, but one might be suspicious.

A sharper argument can be attempted for AdS_3/CFT_2 duality, as we can try to write modular invariant partition functions with this property. Some results of this type were obtained in Gaberdiel et al 0805.4216, but again no clear problem was seen, and partition functions with this gap seem possible.

Finally, another problem with finding interesting duals, is that in the vacua with small c.c. (much smaller than the KK scale), this is due to cancellations between many large contributions to the vacuum energy. This is going to be hard to reproduce without exact results, though perhaps we could statistically demonstrate that such duals exist.

A related point is that, by varying any of the fluxes by one unit, one goes from a vacuum with small c.c. to a vacuum with order one c.c.. How can this come out of gauge theory dynamics?

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Finally, another problem with finding interesting duals, is that in the vacua with small c.c. (much smaller than the KK scale), this is due to cancellations between many large contributions to the vacuum energy. This is going to be hard to reproduce without exact results, though perhaps we could statistically demonstrate that such duals exist.

A related point is that, by varying any of the fluxes by one unit, one goes from a vacuum with small c.c. to a vacuum with order one c.c.. How can this come out of gauge theory dynamics?

Actually, this is not so unreasonable. The fluxes N_i are usually dual to ranks of gauge groups. The c.c. is dual to the central charge or effective number of degrees of freedom in the IR limit, *i.e.* after RG flow.

In the known examples, for example duality cascade theories, starting with the gauge group $\prod U(N_i)$, one flows to a gauge theory with rank $\mathrm{gcd}(N_i)$. Usually this is 1, and one needs all N_i to have a common factor to make it higher. So this feature does come out easily.

4. Measure Factor

If the number of string/M theory vacua were not too large, we could imagine making absolute predictions from the statistics of vacua. The standard example is to imagine that our theory has

- 10^{100} vacua which fit the data without low energy susy
- 10^{130} vacua which fit the data with susy.

Only the second class contains enough vacua to expect to find one with the observed small c.c., so the hypothesis that we live in a vacuum without low energy susy would be very unlikely in a theoretical (non-probabilistic) sense.

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However, if $N_{vac} \sim 10^{500}$, we cannot get very far with this logic. There are some observations which would rule out string theory, for example a time-varying fine structure constant (Banks, Dine, Douglas 0112059). But probably not many.

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Now, if we believed that there were some *a priori* probability $P(i)$ that we lived in a vacuum i, we would be much better off. We would estimate the probability that we observe X, as the sum of probabilities for all vacua in which X is true,

$$P(X) = \sum_{i|X} P(i).$$

Although the idea of probabilities for vacua is mind-boggling, cosmologists are very used to the idea and use it all the time in interpreting CMB and other data. Linde, Vilenkin and others have done a lot of work on trying to use the dynamics of early cosmology to get a rule which would allow us to compute the $P(i)$.

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For example, according to the theory of eternal inflation, in early (but still sub-Planckian) cosmology, causal regions are created and tunnel according to the laws of semiclassical gravity. Working this out leads to a master equation for the "time evolution" of $P(i)$,

$$\frac{d}{dt}P(i) = \sum_{j\neq i} \Gamma(j \rightarrow i)P(j) - \Gamma(i \rightarrow j)P(i).$$

One can then claim that the stationary distribution $dP(i)/dt = 0$ is the result of early cosmology.

Unfortunately, the study of measure factors has been remarkably inconclusive, even paradoxical. Every proposal which has been developed far enough to make a prediction, makes manifestly wrong predictions (the youngness paradox, the Boltzmann brain paradoxes, the supersymmetry paradox...).

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Of course, we can re-interpret a vacuum counting distribution as a probability distribution, by taking $P(i) = 1/N_{vac}$ for all vacuum, the uniform distribution. This does not seem obviously wrong (yet). How close could it be to the "true" distribution? Perhaps it is good enough.

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One standard argument for this is that Weinberg's anthropic solution to the c.c. problem requires that the vacua with small c.c. not be too improbable. If $P(i)$ is not correlated with Λ, which is plausible if early cosmology does not know about Λ, then this suggests that $P(i)$ cannot be too wildly varying.

We can generalize this to the observation that it is very plausible that $P(i)$ is uncorrelated from many quantities of interest to particle physicists, such as the low energy matter content and couplings.

The argument is that the early cosmology which determines $P(i)$ is above the scale of inflation, which is far above LHC energies. Thus the tunneling rates $\Gamma(i \to j)$ know nothing about LHC physics, rather they depend on barrier heights at high scales such as the scale of the flux potential (α'/R^3 in IIb theory), the scale of inflation, and so on.

If $P(i)$ is not too highly peaked, we are interested in a property X which decorrelates from $P(i)$, and there are many vacua, then to a good approximation

$$P(X) = \sum_{i|X} P(i) \sim \sum_{i|X} \frac{1}{N_{vac}}$$

since the fluctuations in $P(i)$ will be averaged out.

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On the other hand, there are clearly other observables which affect $P(i)$, such as the ones of direct interest to cosmologists – the scale of inflation, $\delta\rho/\rho$, etc.

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Another example of such a quantity is the size of the extra dimensions. Clearly this is important in cosmology.

It is a long-standing question how 10 or 11-dimensional string/M theory, produced our apparently 4-dimensional universe. Suppose we consider a set of vacua with different volumes $V(i)$ for the extra dimensions, then we can sharpen this question to: what is the probability $P(V)$?

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There is a good reason to think that it falls off rapidly with V. Namely, the number of flux vacua in certain models (IIa and M theory), grows as a power of the volume,

$$N(V) \propto V^{b/3}$$

where $b \sim 100's$ is a Betti number. This would heavily favor large extra dimensions, so much so that we should have seen them already!

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A simple way out is if

$$P(i) \propto \exp -V$$

so that

$$P(V) \sim \sum_{V} V^{b/3} e^{-V}$$

This would not only favor small dimensions, it predicts

$$\langle V \rangle \sim \frac{b}{3} \sim 100$$

which is interesting as in many models, this is a factor in M_{GUT}/M_{Planck}.

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The upshot is that there are good reasons to think that the measure factor is not uniform. However, it could have a simple dependence on a few parameters relevant for early cosmology, while being decorrelated with many observables in particle physics, such as Yukawa and probably gauge couplings, and numbers of generations. For predicting the latter observables, we can compute as if it were uniform.

It would be very important to know whether such a decorrelation is true for the scale of supersymmetry breaking. Since this scale might be involved in the structure of the potential which is seen by inflation or reheating, there could be a correlation. There are also proposals for measure factors which would lead to such correlations (*e.g.* the "descendants of the longest lived vacuum" proposal).

Thus we cannot make statistical predictions for the scale of supersymmetry breaking, until this point is clarified.

5. Low energy Supersymmetry

Let us ignore the previous remark, and imagine that we can take $P(i)$ uniform for estimating the probability of low energy supersymmetry.

In Susskind 0405189, Douglas 0405279 it was argued that string theory might then favor high scale supersymmetry. The first point is that the advantage of low scale susy models over fine tuning the Higgs mass to solve the hierarchy problem can be quantified: it is about

$$\frac{M_{EW}^2}{M_{fund}^2} \sim \frac{(100\ \mathrm{GeV})^2}{(10^{17}\ \mathrm{GeV})^2} \sim 10^{-30}.$$

So, if the number of vacua which would work if they are fine tuned, is more than 10^{30} the number of low energy susy vacua, then the statistics favor fine tuning.

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How many such vacua are there? The (rather naive) argument was that the supersymmetry breaking scale is a sum of squares,

$$M_{susy}^4 = \sum_i |F_i|^2 + \sum_a |D_a|^2.$$

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$$M^4_{susy} = \sum_i |F_i|^2 + \sum_a |D_a|^2.$$

If each of these is independent and uniformly distributed, then we have

$$dN_{vac}[M^2_{susy}] \sim d(M^{n_F+n_D}_{susy}),$$

a rapid power law growth.

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a rapid power law growth.

The flaw in this argument is that the different F_i and D_a are not independently distributed: as explained in Denef and Douglas 0411183; the equation $V' = 0$ forces a relation between one of the F_i and the goldstino mass, while the level repulsion of the CI ensemble makes the different F_i non-degenerate so that only one of them can vary.

The upshot is that one can reduce to the single field problem. For this case, there is a simple argument (Dine, O'Neil and Sun 0501214) that gives

$$dN_{vac}[M^2_{susy}] \sim d(M^{12}_{susy}).$$

It is that, writing the Taylor series expansion

$$W \sim W_0 + W_1\phi + W_2\phi^2 + W_3\phi^3 + \ldots,$$

one finds that one needs to tune all of W_1, W_2, W_3 small to get a stable low scale susy vacuum. In flux vacua, all of these parameters are independent, leading to this result.

Thus, there probably still are a lot of flux vacua with high scale breaking, which might still dominate the low scale susy vacua. Dine et al referred to these as “branch 1” vacua, as opposed to others in which susy breaking is caused by low scale dynamics which correlates the parameters W_i above (thue evading the argument). It is very plausible that such theories exist, although all the string theoretic ones I have studied in detail still require fine tuning to work (for example, the ISS model requires a small fermion mass).

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One can further distinguish “branch 2” (low scale breaking but without R symmetry) and “branch 3” (low scale breaking of both susy and R symmetry). In the latter case, dynamical susy breaking even helps solve the c.c. problem (since $|W|$ is small), which would turn the 10^{30} advantage into more like 10^{90}.

However, Dine and Sun went on to argue that R symmetry is also highly nongeneric in flux vacua. The argument is that we can think of the multiplicity of flux vacua as coming from the ability to tune fluxes on each of b cycles,

$$N_{vac} \sim L^b \sim 10^{500}.$$

But, for many of these cycles, turning on a flux will break R symmetry. In examples, one finds these are an order one fraction, say half, then

$$N_{R\,symmetric\,vacua} \sim L^{b/2} \sim 10^{250},$$

a huge penalty.

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Ultimately the question of which class of models is favored, even granting that $P(i)$ is uniform, depends on how easy it is to make string vacua which dynamically break susy. It seems to me that the jury is still out on this; following ISS there are many, many more candidate models than before, but when one gets into the details one still needs unnatural ingredients like discrete symmetries to get them to work.

Still, it is reasonable to suspect there is some class of stringy models which is natural in this sense, and then it will be fair to say that they are the preferred prediction of string theory.

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6. LED and Warping

Large extra dimensions turn out to be easy to realize in string theory, indeed too easy as I commented earlier, with $N_{vac} \sim V^{b/3}$. There must be some cosmological mechanism which suppresses them, so I regard them as disfavored by the evidence to date.

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Large extra dimensions turn out to be easy to realize in string theory, indeed too easy as I commented earlier, with $N_{vac} \sim V^{b/3}$. There must be some cosmological mechanism which suppresses them, so I regard them as disfavored by the evidence to date.

Warping turns out also to be easy to realize in string theory, with the basic example being the Klebanov-Strassler solution, *i.e.* the warped deformed conifold. This is dual to a relatively simple $N = 1$ gauge theory and thus there is a fairly satisfying reason to believe in it.

Compared to field theory explanations of the hierarchy problem, the novelty of warping seems to be that one can "communicate the low scale" in a very novel way. As pointed out by Randall and Sundrum, given a warped metric

$$ds^2 = f(y)dx_4^2 + g_{ij}dy^i dy^j,$$

and a brane theory localized at some y_0 with small $f(y_0)$, the effective strength of gravitational sources on the brane is warped down. Working this out for compactification on a manifold M, one finds something like

$$M^2_{Planck\,effective} = \frac{\int_M \sqrt{g}\;\, f(y)^\alpha}{f(y_0)}$$

where the numerator is the "warped volume." In particular, the KS solution has $f(y) \sim (1 - gN/r^4)^{-1/2}$ large in the throat, and can lead to a realistic hierarchy.

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This effect is not easily understandable in 4d effective field theory terms. Indeed, this is probably not the right language for many physical questions. For example, perhaps the simplest general prediction of RS is that warping leads to a localized light spin 2 mode in the warped region, hard to describe in EFT.

On the other hand, for some questions it is worth trying. In particular, to analyze vacuum stability one wants an effective potential. Among other applications, this would enable us to count warped models and decide if they are statistically preferred.

We can also imagine models in which the scale of supersymmetry breaking is warped down, and then communicated to a Standard Model sector elsewhere; the SM sector should be describable in terms of 4d EFT with explicit breaking terms.

In a series of papers with Gonzalo Torroba, Jessie Shelton, Gary Shiu and Bret Underwood, we have made some progress in developing this theory. For example, there is a generalization of the usual $N = 2$ formula for the metric on complex structure moduli space in IIb on Calabi-Yau,

$$g_{i\bar{j}} = \log \int_M \chi_i \wedge \bar{\chi}_j,$$

to

$$K = \log \int_M e^{-4A} \chi_i \wedge \bar{\chi}_j,$$

where χ_i is a basis of $(2,1)$ forms and e^{-4A} is the warp factor.

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This formula appears in DeWolfe and Giddings 0208123, but as used there (and in our work with Shelton and Torroba) it is not correct (as already observed by Giddings and Maharana 0507158).

The subtlety (Douglas and Torroba 0805.3700) is that one cannot take the usual definition in which χ_i are harmonic forms $d\chi = d{*}\chi = 0$. Rather, one must use a warped harmonic condition $d * (e^{-4A}\chi) = 0$.

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Using this, we have shown that the effect of warping on the kinetic term of the complex structure modulus in the throat can be understood in EFT terms, as coming from the kinetic term. One has the superpotential

$$W = NS \log S + M\tau S$$

as in the unwarped case, but

$$G_{S\bar{S}} = \log|S| + c|S|^{-4/3} + \text{small corrections}$$

The new term arises from warping and produces $V \sim |S|^{4/3}$ which is warped down as expected.

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The new term arises from warping and produces $V \sim |S|^{4/3}$ which is warped down as expected.

While it is not too clear how far one can take a 4d EFT analysis, it does appear that putting SM branes in a KS throat could be another generic solution to the hierarchy problem.

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7. Other wild speculations

There are many more generic features of string compactification which perhaps have not received the attention they deserve. One is that string compactifications typically have additional factors in the gauge group, as well as hidden or “hidden valley” sectors, starting with the original $E_8 \times E_8$ string. This is almost universal, and models that avoid it probably have too few vacua to solve the c.c. problem.

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We could quantify both observations by computing $N_{vac}[n]$, where n is the number of factors in the gauge group. Presumably, this will be well approximated by some simple function of the topological numbers of the compactification manifold.

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We could quantify both observations by computing $N_{vac}[n]$, where n is the number of factors in the gauge group. Presumably, this will be well approximated by some simple function of the topological numbers of the compactification manifold.

I don't know of any claims about this, but one's first guess would be that N_{vac} is peaked at an n determined (for IIb orientifolds) only by b_2 and the numbers entering the tadpole cancellation condition. Given that these are (very roughly) of the same order, one might guess that

$$\langle n \rangle \sim b_2^{\alpha}$$

with the power $\alpha \sim 1/2$ guessed at by looking at existing orientifold and Gepner model results.

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This typically leads to 10–20 factors in the gauge group, far more than model builders usually postulate. Suppose this were true, then why don't we see these other gauge groups?

- Perhaps they only couple to the SM through gravity. Could they be part of the dark matter? Is this matter produced in reheating?
- Perhaps they get strong at higher energies.

Recall our generic distribution

$$dN_{vac} \sim dM/M$$

following from $M \sim \exp -1/g^2 N$ and a uniform distribution for g^2.

This suggests that, if we look at the log energy scale, we will find roughly the same number of new gauge sectors for each order of magnitude of energy. As we have seen $SU(2) \times SU(3)$ in the range $100\ \mathrm{MeV} - 100\ \mathrm{GeV}$, we might predict two new factors for each factor of 1000 in energy, giving 10 or so new factors to discover before we reach the GUT (compactification?) scale.

We might call this the "jungle" scenario. It certainly looks far more favorable for particle physics than the desert scenario.

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8. No conclusions

This is clearly an evolving story. Although theory is making steady progress, at this point it seems likely that we will not have definite conclusions or predictions before LHC data comes in.

Still, granting the assumptions we discussed, and if no "preferred" vacuum is discovered, the landscape framework will probably be an inevitable component of contact between string theory and the "real world".

Let us hope that discoveries here at Cern will reveal enough about the real world to make contact possible.