The Swamp Surrounding the Landscape

Cumrun Vafa

The main difficulty in describing nature using string theory comes from the multiplicity of string vacua. The low energy effective theories in supersymmetric compactifications typically have a moduli space parametrized by scalar fields, and there is no dynamical principle which can select a prefered vacuum. In particular it has been clear for a long time that specially if one preserves supersymmetry, there are many choices of consistent string vacua. In the 80's it was hoped by some that breaking susy would solve the problem, but we now are confident that this is not the case. This embarasse de richesse implies a partial failure of string theory in describing the real world.

A possible way out would be to suspend the whole string project, and start with a consistent effective (susy) theory of gravity and matter, hoping that eventually string theory (or another theory of quantum gravity) will provide us with a consistent "quantum completion".

But this evasion of string theory might prove dangerous, since *not any consistent looking effective theory can emerge as a string vacuum.* Even though we do not have a closed set of rules to decide whether a given field theory can come or not from string theory, we have enough evidence accumulated that suggests that such a set of rules is expected to exist. To illustrate these ideas, let us look at the following four examples.

1) The non-anomalous N=1 susy field theories in 10D have the following gauge groups:

1. $E_8 \times E_8$
2. $SO(32)$
3. $U(1)^{496}$
4. $U(1)^{248} \times E_8$

The first two cases are realized in string theory, but *it does not seem possible to realize in string/M theory the last two cases, which are perfectly sensible from a field theory point of view.* How does string theory select some gauge groups out of the set of consistent possibilities? Similar issues arise when we take the theory with 16 supercharges in lower dimensions (such as the CHL strings). Again there are far fewer gauge groups realized in the context of string theory than allowed by effective field theory arguments.

2) In 4D, the bosonic part of the low energy effective action of a generic string compactificaction looks like

$$S_{eff} = M_P^2 \int d^4x\sqrt{g}R + \int d^4x\sqrt{g}\partial\phi^\alpha\partial\phi^\beta m_{\alpha\beta}(\phi) \tag{1}$$

Here M_P^2 is the square of the Planck mass, which is proportional to the volume of the compactified space, and $m_{\alpha\beta}(\phi)$ is the metric of the moduli space of vacua. We are ignoring possible potential terms for ϕ^α. Also, string theory tells us what is the range $\mathcal{M}$ of values that ϕ^α take. Integrating $\sqrt{|m_{\alpha\beta}(\phi)|}$ over $\mathcal{M}$ we get the volume of the moduli space of vacua.

In all known string compactifications in which the compactified space is finite (so that G is finite also), the volume of $\mathcal{M}$ is finite or diverges logarithmically.

This result seems to be a string theory requirement, unjustified from a purely field theoretic perspective and is generally related the dualities of string/M-theory.

A simple example of this phenomenon is obtained by compactifying from $\mathbb{R}^{1,9}$ to $\mathbb{R}^{1,7} \times T^2$. The moduli space is parametrized by the T^2 parameter τ, and its volume is

$$Vol(\mathcal{M}) = \int \frac{d\tau^2}{\tau_2^2} \tag{2}$$

This could be infinite for a noncompact range of τ, but S-duality instructs us to integrate over the fundamental region of the $SL(2,\mathbb{Z})$ group, thus rendering the result finite. In the context of type IIB in 10 dimensions, the coupling constant has the same properties as the moduli of a complex torus. In that context, had we known that the volume of $\mathcal{M}$ should be finite, we could have deduced some form of S-duality for type IIB strings!

3) In 4D N=2 supergravity, we can have a consistent theory with the multiplet

$$g_{\mu\nu}, A_\mu, \psi_{\mu\alpha} \tag{3}$$

and no scalars. But in any compactification of M/string theory down to 4D, we get extra scalars. In string theory we have at least the dilaton as a scalar, and in M theory the size of the compact space.

*Either there is something bad in the multiplet (**??**) or some ingredient is missing in our theories of quantum gravity.*

4) In the above example, string/M theory provided us with "too many " fields. Let us see now an example of the inverse situation, where the "too many" fields come from the field theory side.

In 4D N=2 supergravity, we can have vector and hypermultiplets. Considering a theory with only vector multiplets, any number of them is possible from a field-theoretic perspective. But obtaining such a vacua form a CY compactification, the number of vector multiplets is

$$\frac{1}{2} dim H^{even}(CY) - 1 \tag{4}$$

and it is not clear if there exist CY spaces with arbitrarily high even cohomologies.

So we have seen four examples which point to the features of what we might call ”the universality class” of quantum gravity. Understanding how this universality class is defined will certainly teach us a lot about the connections we seek between string theory and the real world.

It would be useful to tabulate more examples of what cannot be obtained from string theory, but is allowed from consistent looking field theories. We need to come up with refinements of the notion of consistency of effective field theories which makes it compatible with possibilities allowed in string theory. In other words we aim to define what string theory is by identifying the boundary of what is allowed. Or, on the less positive side, if we cannot find anything wrong with these effective theories, we should search for its quantum completion. This would be showing us how limited our current tools are in understanding string theory, and how we can extend it.