On Isolated Vacua and Background Independence

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Abstract: I argue that isolated vacua of M-theory, cannot in any conventional way
be said to live in the same theory as other disconnected parts of the moduli space.
The usual field theoretic mechanisms, which allow an observer in one disconnected
component of a moduli space to verify the existence of other components, fail. The
failure is a consequence of robust properties of black holes. When barriers between
components are much smaller than the Planck scale, the usual field theoretic picture is
approximately valid.

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1. Introduction - a vacuous diatribe

There has been much speculation about the topology of the space of asymptotically flat M-theory vacua, by which I mean quantum mechanical states of the system with some number of asymptotically flat dimensions with propagating gravitons and exact Poincare symmetry. In cases where eight or more supercharges are also included in the asymptotic symmetry group, the situation is, as I review briefly below, fairly well understood. There are continuous moduli spaces of such vacua, which can reasonably reliably be said to constitute states of “the same theory” in a sense that I will make more precise. The main purpose of this article is to investigate whether the same can be said of vacua with only four supercharges, which perforce have only four asymptotically flat dimensions. Our considerations will be more general, and actually apply to any two disconnected components of moduli space, but for the most part I will use the language of theories with four supercharges in four dimensions.

In this case, continuous moduli spaces are not generic. Indeed, given the absence of exact continuous global symmetries in string theory, one expects a superpotential of general form on the would be moduli space and this implies that SUSY vacua form a discrete set. Indeed, if we impose the extra restriction of vanishing cosmological constant, the equations are overdetermined and should only be satisfied at points of enhanced discrete complex R-symmetry. It is only if some of the (infinitesimal variations) of the moduli at such an enhanced symmetry point carry vanishing discrete R charge that we can expect a moduli space of nonvanishing dimension [2]. Within such
$N = 1$ moduli spaces, the arguments alluded to in the first paragraph go through and
the different vacua are states of the same theory. If these moduli spaces contain bound-
aries where space decompactifies and an enhanced SUSY algebra is restored, then these
vacua are likely to be in the same theory as the higher dimensional, extended SUSY
vacua referred to above.

Now however, consider an isolated vacuum with four supercharges$^1$. In local
quantum field theory we have no problem asserting that such a vacuum state might
be in the same theory as any other isolated SUSY vacuum, or the continuous moduli
spaces referred to above. Indeed, consider a field theory with two degenerate minima
of the potential. If we are willing to expend enough energy, we can easily construct an
excited state of the theory in one of these vacuum states, that contains an arbitrarily
large region which looks like the other. This is a bubble and its energy scales as
the square of its radius. For large radius it is unstable, and shrinks, but causality
guarantees that such a large bubble cannot dissipate for times much less than $R$. Thus,
an experimentalist with a large amount of energy at his disposal can create and study
such a vacuum bubble.

In this paper we will argue that the same is not true in a theory containing gravity.
At its crudest, the argument consists of the simple observation that if $\sigma$ is the surface
tension of the bubble, then the Schwarzchild radius of the large distance gravitational
field of the bubble is $\sigma(R/m_P)^2$. Thus, the bubble will be smaller than its Schwarzchild
radius if $R > m_P^2/\sigma$. Thus, unless $\sigma$ is very tiny in Planck units, an experimenter who
attempts to create a large bubble of an alternative universe will instead create a black
hole. This observation is closely related to previous studies of “creating a universe in the
laboratory”$^3$ and more particularly to the seminal work of Cvetic and collaborators
$^4$ on domain walls between SUSY vacua. We will give a more precise discussion of
this work in the next section.

For the moment however, let us return to exact moduli spaces of vacua. In this
context, the difficulty mentioned in the previous paragraph does not arise. There is no
potential energy on the space of vacua, and we can construct a configuration with a
large region of another vacuum at an arbitrarily small cost in energy if we are willing
to let the wall interpolating between the bubble and the outside world be very thick
(as we will see, this is not an option if we have a potential)$^2$. Thus, points at finite

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$^1$Our considerations apply equally well to any two disconnected components of moduli space with
vanishing cosmological constant.

$^2$Conversations with Barak Kol, L. Motl and C. Roemelsberger have shown that this discussion is
more intricate than one would have thought. In order to explore regions of moduli space which are of
order $NM_P$ apart (in four dimensional normalization for canonical fields) we must construct bubbles
which grow exponentially with $N$ and then have a series of small bubbles inside them. The step in
separation in exact moduli spaces should surely be thought of as being in the same
theory.

Nonetheless, the situation is, even in this case, not quite what SUSY field theory
intuition would lead us to believe. The problem is again associated with black holes,
though in a superficially different manner. In non-gravitational quantum mechanical
models there are two related notions of what it means for two states to be in the same
theory. The first comes from classical dynamics, and conditions most of our thinking
about these problems. One envisages a classical system with dynamical variables \( q^i(t) \)
and considers two static solutions to be in the same theory because they correspond to
different solutions of the same equations of motion. When the system is a field theory
in infinite volume, one observes that if the two solutions are also constant in space, then
the solution space breaks up into classes which can be viewed as local perturbations of
one or the other classical vacuum.

More abstractly, and more generally, one recalls that quantum field theories are
defined by (perhaps marginally) relevant perturbations of a fixed point conformal field
theory. By studying correlation functions at small Euclidean separations we find the
physics dominated by the fixed point and the relevant perturbations of it. In this way,
we can determine that two different vacua of the same theory are really in the same
theory. The superselection rule that prevents us from putting both vacua in the same
Hilbert space has a purely infrared character, and depends on the notion of locality.
The Hilbert space obtained by applying local fields to one vacuum state is orthogonal
to that obtained by applying them to the other. By studying short distance correlation
functions, we can identify the theory underlying each vacuum and verify that they both
belong to the same field theory (the same fixed point perturbed by the same relevant
operators).

It is worth pointing out that the classical notion of when two vacua come from
the same theory is a special case in which the fixed point theory is Gaussian. Indeed,
Feynman’s derivation of the path integral formalism proceeds by concatenating prop-
agation over infinitely short time intervals. The Lagrangian formalism emerges when
one makes the assumption that the short time behavior is dominated by a quadratic
theory. Thus, in the quantum theories we understand, the way to test whether two
ground states are states of the same theory is to examine short time, or high energy
behavior.

In Asymptotically Flat M (AFM) Theory\(^3\) it was pointed out in [6] and [7] that the
field space between a consecutive pair of bubbles is bounded by something of order the Planck scale.
The wall of each bubble is about as thick as its radius.

\(^3\)As always, I insist on using the term M-theory to describe the unified theory from which weakly
coupled string and SUGRA perturbation expansions are derived as limits. It is, at the very least,
physics of asymptotically high energies is dominated by black holes. This is an example of the UV-IR \cite{10} connection in M-theory. High energy states are associated with large objects with low curvatures and large degeneracies. Some aspects of the physics of these objects is consequently accessible to long wavelength SUGRA analysis. The black hole density of states is unlike anything in quantum field theory. It implies that operators which cannot resolve the black hole degeneracy cannot have well defined correlation functions. More precisely (cf. \cite{9}) generic Heisenberg operators $O(t)$ in such a theory are operator valued distributions on a space of test functions which cannot be localized in time (their Fourier transforms must fall off so rapidly that they cannot vanish outside compact intervals in time).

For our present purposes, what is most important is that the black hole density of states is dimension dependent. Thus, \textit{two AFM vacua with different numbers of AF dimensions are not vacua of the same theory in the sense with which we are familiar in Quantum Field Theory.} The relation between them is more subtle. The maximum growth of the density of states occurs for four noncompact spacetime dimensions. If one has a moduli space of such four dimensional compactifications, one can find boundaries of moduli space in which more noncompact dimensions appear.

As we take this decompactification limit, states of extended objects wrapped around cycles of the compact manifold will go off to infinite energy. It is no surprise to an M-theorist then (but would be to a quantum field theorist) that if we take the high energy limit after decompactification, we get a different behavior of the density of states than we did before. The relationship between moduli spaces of AFM theory with different numbers of noncompact spacetime dimensions but the same number of SUSYs can then be understood in this limiting fashion. All compactifications to four dimensions with a fixed number of SUSY generators, which lie on the same continuous moduli space, are plausibly states of the same theory. States with more noncompact dimensions can be obtained as limits of these. The limiting process is singular and does not commute with the high energy limit. A question left unanswered by this analysis is the relation between moduli spaces of vacua with the same number of AF dimensions, but different numbers of SUSYs.

The case of only four supercharges deserves a separate discussion. Here, general effective field theory arguments \cite{2} suggest that most SUSY vacua will have negative cosmological constant. Points with enhanced complex R-symmetry can naturally have vanishing cosmological constant but will generically be isolated. Only if there are chiral superfields with vanishing R-charge can one expect continuous moduli spaces. uneconomical to reserve this term for the region of moduli space near the 11 dimensional SUGRA limit.
The moduli space thus splits into disconnected components, most isolated points, but perhaps some of nonzero dimension. The aim of the rest of this paper is to study the extent to which we can consider these disconnected components as part of the same theory.

2. Walls of evidence

The first clue that isolated vacua cannot generically communicate with each other, comes from an examination of hypothetical domain walls separating two such vacua. In field theory, the solutions in which an observer in one vacuum injects energy and creates a large, long-lived bubble of another, asymptote, as the energy goes to infinity, to static, stable domain wall solutions. Fortunately, in a beautiful series of papers some years ago [4], Cvetic and collaborators made a comprehensive study of domain walls in supergravity, in a variety of situations. Here I will only give a partial summary of their work, and I urge the reader to consult the original papers for more detail and for the description of situations with dilaton fields and/or AdS vacua, which are not relevant to the present paper.

It is well known that SUGRA can have supersymmetric vacuum states with non-positive values of the cosmological constant. The value of the cosmological constant is determined by the value of the superpotential at the supersymmetric points. There are static, stable BPS domain walls between two such vacua with different values of the cosmological constant. The tension of the BPS walls is proportional to the difference of superpotentials in the two vacua.

By examining solutions with the symmetries of domain wall spacetimes in the thin wall approximation, Cvetic and collaborators established a number of remarkable results. Perhaps most strikingly, the BPS tension is the crossover point between two radically different kinds of behavior of domain wall spacetimes, and coincides with the Coleman-DeLuccia [5] bound on the tension of bubbles created by vacuum tunneling. Coleman and DeLuccia showed that, as a consequence of gravitational effects, tunneling into a lower energy vacuum did not always occur. In AdS space, volume scales like area and so the flat space argument that sufficiently large bubbles of lower energy vacuum always grow, fails. Bubbles will only grow if the tension in their walls is below a certain value, which Cvetic et. al. show coincides with the BPS tension. This is a terribly interesting result, whose significance has probably not yet been fully understood.

For tension below the BPS bound, domain walls are not static, but instead correspond to the infinite radius limit of expanding bubbles of false vacuum. Similarly, for tensions greater than the BPS bound, there are no static solutions. Rather, if we imagine one of the vacua to be asymptotically flat, then the solution looks like a
domain wall with constant acceleration, which comes in from infinity and then accelerates away. It spends most of its history moving with respect to the observer in the asymptotically flat region with speed almost equal to the speed of light. Cvetic et. al. describe this situation by saying that both sides of the wall seem to be living on the inside of an expanding bubble of false vacuum. I think instead that these solutions are simply providing evidence that an asymptotically flat observer cannot prepare states that correspond to arbitrarily large bubbles of the other vacuum. The would be infinite radius limits of such bubbles do not admit deformations that would allow us to embed them in asymptotically flat space.

For the purposes of the present paper, we are interested in pairs of vacua which both have vanishing cosmological constant. In this case the BPS tension goes to zero and the domain walls behave as described above. We do not expect large bubbles in this case either.

Before leaving this section I should note that Cvetic et. al. also investigated models with a dilaton field with a potential which had no minimum for asymptotic values of the field. They generically find naked singularities on the side of the domain wall where the dilaton can run. This investigation was not carried out for the most general form of dilaton potential one could imagine in the asymptotic region. It bears on the question of whether isolated vacua are in the same theory as weakly coupled string regions (so that one could hope to gain information about them by resumming string perturbation theory), and deserves further investigation.

3. The trouble with bubbles

After these preliminary considerations, it is time to set up the main problem to be solved to resolve the question under study. We will consider a Lagrangian with only a single scalar field coupled to gravity. Multiple field Lagrangians, with generic metric on field space, and the same scaling properties as the Lagrangian below, will behave in exactly the same way. The Lagrangian is

\[ \mathcal{L} = -\sqrt{-g}[M_P^2 R + (\nabla \phi)^2 + M^4 V(\phi/m)]. \]  

We will assume \( M \ll M_P \) to assure the validity of effective field theory. Lagrangians of this type can be derived for moduli in various regions of M-theory moduli space. For example, in Horava-Witten like compactifications [11] we can take \( M \) to be related to the eleven dimensional Planck scale by \( M^4 = \frac{(M_{11}^P)^6}{M_P^2} \). \( m \) would then be \( M_P \) or
depending on whether $\phi$ was a bulk or boundary modulus. In weakly coupled heterotic string theory with Kahler or racetrack stabilization, we might imagine $M$ to be calculated in terms of the string scale and coupling as some nonperturbative effect, $M \sim m_s e^{-c/g^2}$ while $m$ was of order the string scale. Note that in this case one would, for phenomenological reasons, want the string and Planck scales to be very close to each other. A variety of other possible choices for scales could be achieved in brane world scenarios with low fundamental scale.

Before beginning our general analysis, let me note that if $m \sim M_P$, as seems plausible in a variety of contexts, then one can rescale the variables in the Lagrangian in such a way that the equations become independent of all parameters. In such systems there is really only a single scale, $M^2/M_P$. Thus, if our contention that “otherworldly” bubbles have a maximum size and lifetime is valid, it implies that the order of magnitude of the maximum size is this universal scale. Thus for bulk moduli in Horava-Witten compactifications, the maximal size of bubbles is of order $M^2_P/(M_P^{11})^3$ or about $10^9$ times the Planck scale. This is also the order of magnitude of their lifetime, and it is hard to imagine ever distinguishing them from all of the other highly unstable states in such a theory.

It is worth inserting a short comment on energy scales in string theory at this point. Indeed, the argument above appears to be much stronger for cases where the barriers between vacua are of order the Planck scale. In the Horava-Witten case one is faced with the question of what the qualitative difference is between bubbles which are $10^9$ times the Planck scale and those which are $10^{10}$ kilometers in size. I think the correct answer to this is that we really have no understanding of why any scale in string theory should be much smaller than the Planck scale. Our penchant for thinking otherwise is based on experiment. In cases with a moduli space, one can always get low energy scales by going to boundaries of moduli space. But it is very difficult and may be impossible to find an isolated vacuum in such a regime.

The other generic idea for producing low energy scales involves marginally relevant operators in effective field theory. A modestly small deviation from a fixed point along a marginally relevant direction can generate exponentially small energy scales. The two classes of extant examples in M-theory involve four dimensional models with either eight or four supercharges. In the former case there seems to be no reason for the gauge theory energy scale to have anything to do with the size of the barrier between M-theory vacua. The gauge theory does not produce a potential on the moduli space. When there are only four supercharges we often generate a small potential on the moduli space.

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4This parametrization may be misleading, in that it holds only in the region of moduli space where the internal volume is large. At the end of this section we will argue that the barrier between a realistic Horava-Witten vacuum and other isolated vacua is of order the Planck scale.
but the cosmological constant is generically nonvanishing and we are not in the class of asymptotically flat vacua we have been investigating in this paper. While there are supersymmetric gauge theories which generate a small superpotential and have isolated vacua with R-symmetry at the minimum\(^5\), it is not clear that any of them are realized in string theory.

The question of scales takes on a new light in view of the conjectures presented in [1]. There are two classes of low energy scales that are indicated by experiment. The first is the collection of scales associated with standard model physics. It is plausible that all of these are related to the SUSY breaking scale, and if the conjecture of [1] is correct, they would not be present in a limiting, asymptotically flat supersymmetric theory of the type we are studying here. The other class are the three pieces of evidence (coupling unification, neutrino mass, and amplitude of the cosmic microwave background fluctuations) for a scale a few orders of magnitude below the Planck scale, which is unrelated to SUSY breaking. In Horava-Witten compactifications, this scale is related to a small potential on moduli space generated by branes in a bulk with eight supercharges. However, the small value of the potential is itself attributed to the fact that the minimum is in an extreme region of moduli space where the volume of the internal space is large in Planck units. It is not easy to understand (particularly in the Horava-Witten context where the codimension of the standard model brane is 1) how the system could have a minimum in this regime. Thus, it is not implausible that other isolated minima are in fact separated from the one describing the real world by barriers of order the (relevant) Planck scale.

### 3.1 Properties of bubble solutions

The investigation of spherically symmetric bubble solutions proceeds by introducing an ansatz for the metric and scalar field in terms of angular coordinates \(\Omega\) and a two dimensional, radius/time space \(z^a = (t, r)\). The metric is

\[
ds^2 = g_{ab}(z)dz^a dz^b + \rho^2(z)d\Omega^2. \tag{3.2}
\]

and \(\phi\) is taken to be a function only of \(z\). The equations of motion may be derived from the two dimensional Lagrangian

\[
-\sqrt{-g}[M_P^2 \rho^2 R + M_P^2 (\nabla \rho)^2 + \rho^2 (\nabla \phi)^2 + M^4 \rho^2 V(\phi/m)]. \tag{3.3}
\]

The stress tensor of the matter field is

\[
T_{ab} = \partial_a \phi \partial_b \phi - g_{ab}(-\frac{1}{2} (\nabla \phi)^2 - M^4 V(\phi/m)). \tag{3.4}
\]

We are looking for solutions that have the following properties at late times:

\[^{5}\text{I thank A. Nelson for pointing out a large class of examples.}\]
• There is an inner region where $\phi$ is approximately constant and equal to one of the isolated minima of $V$.

• The metric is asymptotically flat and $\phi$ asymptotes to some other minimum of $V$.

• The variation of $\phi$ between the two minima takes place principally in a region of geodesic size $l$. We will call this the bubble wall.

• There is a moment of maximal expansion of the bubble wall, when all fields are instantaneously static.

The motivation for the third property, as well as determination of the length $l$ comes from the standard energetics of domain walls. The distance between the two minima in field space is of order $m$. Thus, the energy of the wall at radius $R$ is approximately

$$ E \sim 4\pi R^2 [(m^2/l) + lM^4]. \quad (3.5) $$

This is minimized at $l \sim \frac{m}{M^2}$, giving a tension $T \sim mM^2$.

Reserving a detailed investigation of these equations of motion for future work, we borrow an old result of W. Israel [12]. Israel studied bubbles whose walls were made of dust $i.e.$ matter with vanishing pressure. Though this is not necessarily a good approximation to a scalar field stress tensor in the present circumstances, I believe it captures the essential physics. Israel worked in a coordinate system whose radial coordinate is just the field $\rho$. He took the bubble to be infinitely thin and parametrized its position by a function $R(t)$ where $t$ is proper time in the comoving frame of the bubble wall. The metric outside the wall is, by Birkhoff’s theorem, the Schwarzschild metric with mass $M$. In our system $M = 4\pi R_{\text{max}}^2 T$, where $R_{\text{max}}$ is the maximal value of the radius and $T$ is the tension estimated above.

The equation of motion of the bubble wall is

$$ \mathcal{M} = \mu(\sqrt{1 + \dot{R}^2} - 1/M_P R). \quad (3.6) $$

where $\mu$ is an integration constant. This determines $\mu = \mathcal{M}/(1 - 1/R_{\text{max}})$.

The problem comes in the consistency condition that $R$ remain outside the Schwarzschild radius of the external metric. This reads

$$ R > 2\mathcal{M}/M_P^2 = 8\pi T R_{\text{max}}^2 / M_P^2. \quad (3.7) $$

A fortiori this must be satisfied at $R_{\text{max}}$ so we obtain an order of magnitude bound

$$ R_{\text{max}} < \frac{M_P^2}{M^2 m}, \quad (3.8) $$
which is the result announced in the introduction. The introduction of a more realistic model of the scalar stress tensor should not change this result dramatically.

We conclude then that an asymptotic observer who tries to create too large a bubble of otherworldly vacuum will instead create a black hole. Note that for domain wall tensions of order 1 TeV the maximum size bubble is of order $10^{10}$ km, so discussions of multiple vacua in low energy quantum field theory are not substantially effected by our bound. However, the size shrinks rapidly with rising energy scale for the domain wall tension, and once we are in the range of unification scales the gravitational corrections are significant.

4. Discussion

There are, I believe, two possible interpretations of the results of this paper. The most straightforward is the one advertised in the introduction. Isolated asymptotically flat M-theory vacua, and more generally, disconnected components of the moduli space of vacua with four dimensional $N = 1$ SUSY are truly in different theories. One cannot access one from the other.

One might, as in field theory, hope to evade this conclusion by examining the high energy behavior of the theory, but here again black holes and the UV/IR connection get in the way. High energy scattering in M-theory is almost certainly dominated by black hole production and decay [8]. Black holes decay by Hawking radiation and the Hawking temperature goes to zero with the mass. Thus, by examining the final states in high energy scattering processes, one probes the low energy spectrum of the theory. It is simply not true that high energy physics becomes independent of the choice of isolated vacuum state.

Note by the way that the same conclusion can not be drawn for the case of two different points on a continuous moduli space. The low energy excitations are the same in this case: massless moduli and gravitons and gauge fields. Thus, the asymptotics of high energy black hole production will be the same at the two points.

Another, more bizarre, interpretation of our results is motivated by the idea of black hole complementarity [13]. We have seen that otherworldly bubbles of too large a size end up inside a black hole. As part of the explanation of the black hole information paradox, Susskind and collaborators proposed that the Hilbert space describing physics as seen by observers falling into a black hole is actually a part (a tensor factor) of the Hilbert space of external observers. The great disparity between the description of physics by these two classes of observers is ascribed to noncommutativity between their preferred classes of observables.
Could it be that a similar statement applies to the Hilbert spaces of two isolated vacua: that superpositions of the states of “our” world (if it were asymptotically flat) correspond to states in a completely different vacuum? It is not clear what mathematical content such a statement could have. Any two infinite dimensional separable Hilbert spaces are unitarily isomorphic to each other. So the Hilbert space of asymptotically flat M theory is the same as that of any quantum mechanics problem, even one with a single bosonic degree of freedom. Quantum theories are distinguished by the differences between their Hamiltonian operators and other preferred observables. Once we have fixed those they are surely unitarily inequivalent for different vacua.

Although I cannot at the moment see a way in which such a complementarity between different isolated vacua could make sense, I can also remember the time when black hole complementarity made no sense to me. So perhaps it is worthwhile to keep this crazy idea in the back of our minds.

The most likely conclusion then is that the quantum moduli space of AFM-theory vacua has disconnected components. Different components cannot be viewed as a part of the same theory, at least not in any of the ways familiar to us from classical or quantum field theory. The components are partially classified by the number of asymptotically flat dimensions and the number of supercharges. For eight or more supercharges, it is plausible (but not proven) that the moduli spaces have only a few connected components, and that we can even pass from lower dimensional compactifications to higher dimensional ones by going to the boundaries of moduli space. For four supercharges it is likely that there are a large number of different theories, one for each connected component of the moduli space. We may view these as being labelled by expectation values of scalar fields, but this description has only a limited, low energy, utility. We cannot explore regimes of the scalar field potential near the Planck energy since any attempt to do so leads to the creation of black holes.

There are two questions closely related to the issues explored in this paper, which deserve further study. The first is the relation between isolated supersymmetric vacua and extreme regions of moduli space. Much of our information about M-theory is gleaned from an examination of weak coupling string theory or low energy SUGRA, and certain approximate vacuum states in this regime look tantalizingly similar to the universe we inhabit. On the other hand, it is very likely that the real world does not inhabit such a regime, even in the limit in which the cosmological constant vanishes and SUSY is restored. What then is the relation between perturbative string or SUGRA vacua, and isolated SUSY minima? The results of [4] suggest that domain walls between an isolated minimum and a weak coupling regime have problematic naked singularities. It is of great interest to understand the implications of this result for processes within a given asymptotically flat theory.
Finally, we come to the question of whether or not there is a component of the moduli space of AFM-theory with no SUSY whatsoever. In [1] I suggested that there was not, and a primary motivation for the present paper was the thought that these considerations might provide a proof of my conjecture. So far this has not occurred, but the issue is far from settled.

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