ANTHROPIC SELECTION

EWAN D. STEWART
Department of Physics, KAIST, Taejon 305-701, South Korea
E-mail: ewan@kaist.ac.kr

I discuss anthropic selection and related topics.

1 What is the Anthropic Principle?

There are two versions:

1.1 The Strong Anthropic Principle

The Fundamental Theory should be such that it gives rise to life. This is more religion than science.

1.2 The Weak Anthropic Principle

This is just a selection effect. What we observe is biased by the fact that we are not external observers but are part of the universe and live in particular places. For example, we see an oxygen atmosphere, liquid water, etc. although these are known to be rare in the universe as a whole.

$$\begin{pmatrix}\text{Probability of}\\ \text{observable}\\ \text{being observed}\end{pmatrix} = \begin{pmatrix}\text{Probability of}\\ \text{observable}\\ \text{in the}\\ \text{Fundamental}\\ \text{Theory}\end{pmatrix} \times \begin{pmatrix}\text{Probability of}\\ \text{observer}\\ \text{being there}\\ \text{to observe it}\end{pmatrix} \tag{1}$$

One cannot deny the Weak Anthropic Principle. The real question is for which observables is it an important selection effect.

2 The Structure of the Fundamental Theory

Again, there are two versions:

2.1 Unique vacuum

The Fundamental Theory uniquely predicts the observed low energy physics. This would seem to require the Strong Anthropic Principle, though most physicists who favor a unique vacuum vehemently oppose the Strong Anthropic Principle!

2.2 Many vacua

The Fundamental Theory has many vacua and associated low energy laws of physics. The observed low energy physics is selected by a combination of anthropic selection, random chance, and possibly other factors. This is the weak anthropic approach.

3 Conjectured Structure of String Theory

Many ($10^{10^?}$, ∞?) discrete non-supersymmetric vacua (this includes vacua with low energy supersymmetry breaking) and many continuous families of supersymmetric vacua.

This fits well with the Weak Anthropic Principle.

4 Structure of the Eternally Inflating Universe

There are many types of inflation that are natural from the particle physics point of view:

1. False vacuum inflation

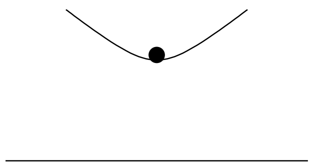

Figure 1. False vacuum inflation

This inflates eternally.

2. Rolling scalar field inflation

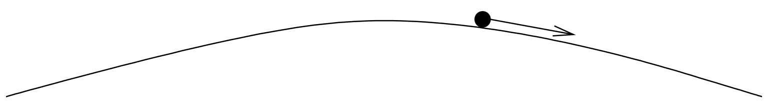

Figure 2. Rolling scalar field inflation

Inflates eternally at the maximum if $m^2 \leq 6V_0$, in units where $8\pi G = 1$.

3. Thermal inflation

Even this inflates eternally if $T_{\rm Hawking} \gtrsim T_{\rm critical}$.

4.1 Discrete Eternal Inflation

Slow-roll inflation is motivated by observations requiring the spectral index of the density perturbations to be $n \simeq 1$ and is not necessary for, and is probably not relevant for, eternal inflation.

Instead, one expects eternal inflation to be dominated by the more generic types of inflation listed above, and so to occur at the discrete points in field space corresponding to false vacua and maxima, with quantum tunneling between these

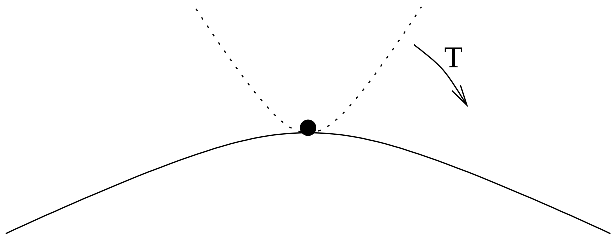

Figure 3. Thermal inflation

points. This will populate all the eternally inflating points in field space, somewhere in the eternally inflating multiverse, allowing all the (connected) vacua and their associated low energy laws of physics to be realized.

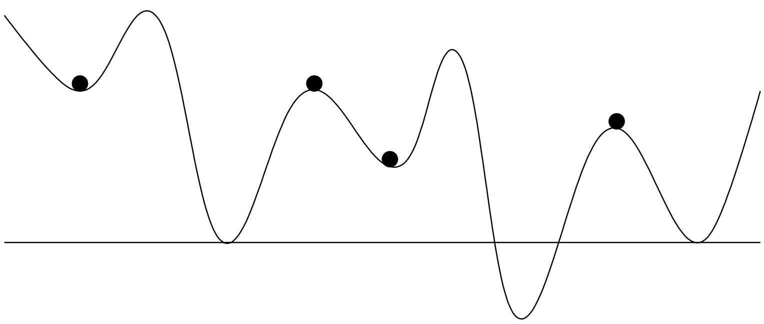

Figure 4. Discrete eternal inflation

However, the infinite expansion factors of eternal inflation make it impossible to give a probability to any given final state vacuum. Cosmology doesn't seem to help much with vacuum selection.

5 The Accelerating Universe

Observations of distant supernovae have shown that the expansion of the universe is accelerating. The simplest explanation of this is that the energy density of the universe is dominated by (positive) vacuum energy. Such vacuum energy would have magnitude

$$\rho_\Lambda = \left(2.2 \times 10^{-3}\,\mathrm{eV}\right)^4 = 2 \times 10^{-59}\,\mathrm{TeV}^4 \tag{2}$$

This is about 10^{60} times smaller than particle physicists can understand. Furthermore, to understand the coincidence that it is just *beginning* to dominate *now* seems to require anthropic arguments.

Table 1. Current composition of the universe

Vacuum energy	65% $\pm$ 10%
Cold dark matter	30% $\pm$ 10%
Ordinary matter (baryons)	5%
Stars	0.5%
Neutrinos	0.3% $\times (m_\nu / 0.1\,\mathrm{eV})$
Cosmic microwave background radiation	0.006%
Spatial curvature	0% $\pm$ 10%

6 Anthropic Selection Rules

For anthropically selected fine-tuning to be a consistent explanation we require:

1. Enough freedom in the Fundamental Theory.

   For anthropic selection to select a vacuum, the vacuum must exist in the first place. For example, $\gtrsim 10^{10^2}$ vacua are needed for accidental cancellations to produce a vacuum with a sufficiently small cosmological constant.

2. There should be no better solution.

   For example, before the discovery of inflation it was legitimate to use anthropically selected fine-tuning to explain the small value of the spatial curvature. However, it is no longer legitimate. Any anthropic selection mechanism would simply choose inflation rather than fine-tuning.

   In this respect, supersymmetric vacua are a challenge to the anthropically selected fine-tuning explanation of the value of the cosmological constant. Either supersymmetric vacua must be extraordinarily rare, at least 10^{10^2} times rarer than non-supersymmetric vacua, or supersymmetric vacua must somehow be incompatible with life. My guess is the latter, perhaps because matter would be unstable to bosonization and subsequent collapse because of the loss of Fermi exclusion.

3. Small changes in the observed value should have a significant effect.

   For example, current bounds on the spatial curvature disfavor an anthropic explanation for its small value.

   Small changes in the observed value of the cosmological constant have a significant effect on galaxy formation making an anthropic explanation plausible.

7 Anthropically Selected Fine-Tuned Cosmological Constant versus a Solution to the Cosmological Constant Problem

There are two classes of theories for why the cosmological constant is so small:

1. There is some symmetry or other mechanism which can set the cosmological constant to zero.

2. There is no mechanism (compatible with life - see comments above on supersymmetric vacua) which can set the cosmological constant to zero and anthropic selection selects a vacuum, which has a cosmological constant sufficiently small for life due to accidental cancellations, from a large number of vacua.

The first predicts the cosmological constant should be zero. If the symmetry is broken (this includes quintessence scenarios) it predicts an a priori roughly speaking logarithmic type probability distribution which, when combined with the anthropic bound, would predict a value essentially no different from zero.

Detailed calculations of the second predict a probability distribution for the cosmological constant with expected values of order or a small factor larger than the current matter energy density.

Observations have confirmed the latter prediction which is highly unlikely in the former scenario. Note that this observational evidence strongly suggests that it is a waste of time looking for a 'solution' to the cosmological constant problem.

It is also important to note that the case of the cosmological constant is different from that of many other parameters that appear to have an anthropically fine-tuned value. Firstly, it is cleaner, but more importantly the observed value is on the extreme edge of the anthropically allowed region (on a roughly speaking logarithmic type scale). This would be extremely unlikely if a symmetry were at work. However, for most other apparently anthropically fine-tuned parameters the observed value seems to take a typical value within the anthropically allowed region (again on a roughly speaking logarithmic type scale). In these cases it would be quite consistent and even likely for anthropic selection to select a symmetry or other mechanism to obtain an anthropically allowed value rather than merely using brute-force fine-tuning. Thus in these cases it *is* important to look for (broken) symmetries or other mechanisms to explain the observed value even if the value seems to be anthropically fine-tuned.

8 Outlook

$$\text{String Theory} \longrightarrow \text{Map of the world} \tag{3}$$

The field space of String Theory is a map of the local laws of physics, in particular of vacua and the associated low energy laws of physics. It is string theorists' job to draw this map.

$$\text{Cosmology} + \text{Particle Phenomenology} \longrightarrow \text{You are here} \tag{4}$$

Cosmological and particle physics observations will determine where we are in the field space of String Theory.

$$\text{Cosmology} + \text{Anthropic Principle} \longrightarrow \text{Why we are here} \tag{5}$$

We will need to use cosmology and the Weak Anthropic Principle to understand why we are here and how we got here.

Acknowledgments

This work was supported by the Brain Korea 21 Project and Korea Research Foundation Grant (2000-015-DP0080).