Les Houches Lectures on Cosmic Inflation

Four Parts

1) Introductory material

2) Entropy, Tuning and Equilibrium in Cosmology

3) Classical and quantum probabilities in the multiverse

4) de Sitter equilibrium cosmology

Andreas Albrecht; UC Davis
Les Houches Lectures; July-Aug 2013
Les Houches Lectures Part 2

Entropy, Tuning and Equilibrium in Cosmology

Andreas Albrecht
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Les Houches Lectures
July 2013
Part 2 outline

1. Entropy and tuning
2. Equilibrium (& toy models)
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1. Entropy and tuning

2. Equilibrium (& toy models)
Intro

- $2^{\text{nd}}$ law tells us that the early universe was dynamically “unusual” (low entropy, past hypothesis)
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- 2nd law tells us that the early universe was dynamically “unusual” (low entropy, past hypothesis)
- Inflation is supposed to teach us that the early universe was dynamically “typical”
Today
Today

Statistical arguments
Statistical arguments
What we actually believe

Today

Statistical arguments
Statistical arguments

Today

What we actually believe

• The thermodynamic arrow of time

• The “past hypothesis”

= “Fine tuning”
Today

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What we actually believe

Adding reheating and inflation seems to make all this worse
Statistical arguments

What we actually believe

Today

- The thermodynamic arrow of time
- The “past hypothesis” = “Fine tuning”

Adding reheating and inflation seems to make all this “worse”
The thermodynamic arrow of time originates with the very special initial conditions of the cosmos: the early universe is very homogeneous on scales \( l > l_{\text{Jeans}} \) very far from Eqm. (= black hole)

\[
S_{\text{Univ}} \approx 10^{-35} S_{\text{bh-Max}} = 10^{-35} 4\pi M^2_{\text{Univ}}
\]

Cosmic Microwave Background uniform to one part in \( 10^5 \)

Entropy increase is realized mainly through gravitational collapse (destruction of homogeneity)
The everyday link to gravitational collapse
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Beware “temporal provincialism*”:

The tendency to slip in assumptions about (and thus tunings of initial conditions) without even realizing it

Related issues:
• Arrival Terminals

* L. Susskind
Beware “temporal provincialism”:
Beware “temporal provincialism”: Neglecting “arrival terminals” ➞ extreme fine tuning of initial conditions (AA & Stoltenberg in prep)

Landscape Model

“Departure Terminals”

Harlow et al 2012
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\[ \dot{S} > 0 \]

Gibbons & Turok
Dyson et al.
Carroll & Tam
Shiffren & Wald
Penrose
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NB Same issues with cyclic models:
\[ \dot{S} > 0 \]
“but it’s infinite” (!)
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• Belief in “naturalness” of high energy density starts

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Equipartition argument (equally likely anywhere on potential)
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Equipartition argument (equally likely anywhere on potential)

Entropy arguments give exponential suppression of higher $V$ values

$$\text{Compare with}$$

$$P_{12} = \frac{\exp(S_1)}{\exp(S_1)} = \exp(S_1 - S_2)$$

$$= \exp\left(\frac{M_P^4}{V_1} - \frac{M_P^4}{V_2}\right)$$

$$\approx \exp\left(-\frac{M_P^4}{V_2}\right)$$
Beware “temporal provincialism”: Equipartition argument (equally likely anywhere on potential)

“Why would you want to start with high entropy? You should end with that”

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\[ = \exp \left( \frac{M_P^4}{V_1} - \frac{M_P^4}{V_2} \right) \]
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Entropy arguments give exponential suppression of higher \( V \) values
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• And what about those short wavelength modes in their ground states?
Cosmic structure

Here

Cosmic structure originates in quantum ground state in inflationary cosmology

Scale factor (measures expansion, time)
Cosmic structure originates in quantum ground state in inflationary cosmology.

- A very special choice.
- Is it a finely tuned initial condition? I think so.
- Critical for current understanding of eternal inflation.
- Also another area where it is a challenge to adapt normal physics to cosmology.

Cosmic length scale (measures expansion, time)
At end of self-reproduction our observable length scales were exponentially “below the Plank length” (and much smaller than that *during* self-reproduction)!

\[ \frac{\delta \rho}{\rho} \approx \frac{\dot{\phi}}{\dot{\phi}} = 1 \]

Black Holes/Strings

Perhaps this domain has important things to teach us about initial conditions in cosmology.
Start of day 2
Comment on Linde comment on anthropic selection of physical laws.

I have work that takes such an approach, and which actually makes some interesting predictions, such as Lorentz symmetry

For recap/clarification at start of 2\textsuperscript{nd} day: This discussion is just to point out that believing in the 2\textsuperscript{nd} law involves believing that the universe is in a special state today (vs all possible microstates consistent with what we see).

- The thermodynamic arrow of time
- The “past hypothesis” = “Fine tuning”
What we actually believe: Statistical arguments

The specialness of this state is directly equivalent to the homogeneity of the universe that Guth sought to explain (which is the origin of the thermodynamic arrow of time).

The thermodynamic arrow of time = “Fine tuning”

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This discussion is just to point out that believing in the 2nd law involves believing that universe is in a special state today (vs all possible microstates consistent with what we see).
The specialness of this state is directly equivalent to the homogeneity of the universe that Guth sought to explain (which is the origin of the thermodynamic arrow of time).

The thermodynamic arrow of time

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- And what about those short wavelength modes in their ground states?

- For this discussion “Entropy” has just helped us assess tuning in phase space
- Could always embrace tuning (e.g. “wavefunction of the universe” or whatever just gives the initial state)
- These issues get much more serious if your model actually is in equilibrium. Then Entropy concrete physical facts about the universe
Beware “temporal provincialism”:

“Entropy” has less tuning in phase space tuning (e.g. the universe” or the initial state) much more serious physically is in

Entropy concrete physical facts about the universe

• And

ground
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Why consider an eqm system?

• I like finite: Better shot at controlling measures, more physical (we will never measure infinity).
• Finite systems are at risk of being eqm systems long-term.
• I *like* eqm because of its independence of initial conditions

But: Issues related to Boltzmann Brains seem problematic
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Essentially all the zillions of inflation models out there have unresolved measure problems.
Eqm system with fluctuating entropy
Very rare fluctuation
$S - S_{\text{max}}$ in the Universe
Us in the Universe
$S - S_{\text{max}}$

Competing fluctuations

Us in the Universe
Competing fluctuations

Past hypothesis, 2nd law, OK here, not here

Us in the Universe
"Boltzmann Brains"

Competing fluctuations

Us in the Universe
“REAL Boltzmann Brains”

and why are we not up here, anyway?
and why are we not up here, anyway?

"REAL Boltzmann Brains"

NB: Need not have eqm. To have Boltzmann Brain issues
Where I stand:

- Still inspired by Guth idea of dynamics creating non-tuned picture
- Despite going up against the 2\textsuperscript{nd} law
- Most arguments made so far for non-tuned scenarios are suspect in my view (seem to depend too much on assumptions to do with arrow of time, wave function of the universe vs inflation dynamics)
- Suspicious of infinite systems (hidden tunings)
- I like the way eqm. liberates you from issues with initial conditions
- Need to face BB problem etc. of finite eqm. systems
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Next: Address these issues in a toy model
Toy model A:

- Eqm state machine with “normal” behavior
- Small fluctuations more likely than large ones
- As a cosmological model, would have Boltzmann Brains, no 2nd law.
Toy model B:

• **Eqm** state machine with proper *cosmological* behavior

• Small fluctuations *less* likely than large ones

• As a cosmological model, would have suppressed Boltzmann Brains,

• 2\textsuperscript{nd} law, past hypothesis *OK*

• Achieved by introducing additional “trans-micro” degrees of freedom, which are the ones in eqm, and which course grain up to cosmologically correct behavior. (“familiar” Micro states are *not* in eqm.)
1. Temporal provincialism is everywhere!
2. Rule of thumb: Find tuning by asking “why is the time reverse of this process not present?” (ie arrival terminals)
3. Should we accept tuning?
4. Eqm. cosmology possible in principle (can avoid Boltzmann Brains, have 2nd law). But in practice?
Part 2 Conclusions

1. Temporal provincialism is everywhere!

2. Rule of thumb: Find tuning by asking “why is the time reverse of this process not present?” (ie arrival terminals)

3. Should we accept tuning? (Creationist?)

4. Eqm. cosmology possible in principle (can avoid Boltzmann Brains, have 2nd law). But in practice?
Part 2 Conclusions

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