Sundry Topics in Inflationary Cosmology

— Alan Guth —

New Horizons in Inflationary Cosmology
Stanford University
Stanford, CA
March 3, 2017
A TALK OF THREE TOPICS

1. Inflation and the Arrow of Time
2. Modeling the Landscape
3. Celebration of Inflation
TOPIC 1: ARROW OF TIME

What is it that distinguishes the future from the past?
(Work with Sean Carroll and Chien-Yao Tseng.)
Mystery of the Arrow of Time

Real Events:
Mystery of the Arrow of Time

Real Events:

Arrow of time
Mystery of the Arrow of Time

Real Events:

Laws of Physics:
Mystery of the Arrow of Time

Real Events:

![Sequence of images of an egg cracking and breaking]

Arrow of time

Laws of Physics:

Time symmetric
But What About CP Violation?

Since 1964 and the famous work of Fitch and Cronin, we have known that $CP$ symmetry is violated. Since $CPT$ is a valid symmetry in any Lorentz-invariant local quantum field theory, we assume that $T$ must also be violated.
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Our point is that CPT, which is exact, is a time-reversal operator.
Cosmological “Solution”

For lack of any other explanation, it is usually assumed that the low entropy initial state was fixed by whatever unknown physics determined the initial conditions for the universe.
Does Inflation Explain the Arrow of Time?
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Does Inflation Explain the Arrow of Time?

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PAUL DAVIES

LETTERS TO NATURE

Inflation and time asymmetry in the Universe

P. C. W. Davies

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NATURE VOL. 301 3 FEBRUARY 1983
“The recently proposed inflationary Universe scenario explains several of the mysteries of modern cosmology. I argue here that it also provides a natural explanation for the origin of time asymmetry (‘time’s arrow’) in the Universe.”
Don Page:
Inflation does not explain time asymmetry

Don N. Page

Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA, and Center for Theoretical Physics, University of Texas, Austin, Texas 78712, USA
“Davies has argued that the inflationary cosmological scenario provides a natural explanation for the time asymmetry of the Universe. Here I dispute this argument by noting that the inflationary scenario implicitly invokes time asymmetry with the assumption of the absence of initial spatial correlations. No scenario based on CPT-invariant dynamical laws can explain the time asymmetry apart from postulating or explaining these special initial conditions, as Penrose has emphasized.”
“Davies has argued that the inflationary cosmological scenario provides a natural explanation for the time asymmetry of the Universe. Here I dispute this argument by noting that the inflationary scenario implicitly invokes time asymmetry with the assumption of the absence of initial spatial correlations. No scenario based on CPT-invariant dynamical laws can explain the time asymmetry apart from postulating or explaining these special initial conditions, as Penrose has emphasized.”
I will argue that this sentence is false:

No scenario based on CPT-invariant dynamical laws can explain the time asymmetry apart from postulating or explaining these special initial conditions.
Proposal: Spontaneous Two-Headed Arrow of Time


Upcoming paper: Carroll, Chien-Yao Tseng, and me.

⭐ **KEY IDEA:** If the maximum possible entropy is INFINITE, then the entropy can increase from any given starting point! The metaphor of a gas in a box becomes a gas without a box.
Toy Model: A Gas Without a Box

Purpose of this toy model: to show that it is possible to create an arrow of time from time-symmetric laws of physics AND time-symmetric initial conditions.
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★ Purpose of this toy model: to show that it is possible to create an arrow of time from time-symmetric laws of physics AND time-symmetric initial conditions.

★ The gas without a box is a metaphor for eternal inflation.
If we evolve the system forward in time, entropy will start to grow, approaching its maximum value of infinity, and an arrow of time will develop.
If we evolved the system backwards in time, it would behave the same way, but at large negative times the arrow of time would point the other way!

Bottom line: for a finite amount of time near the starting point, there is no arrow of time. But for infinite periods of time in the future and in the past, the arrow of time is well-defined.
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Important question: for the case of an eternally inflating universe, how should we describe the time-symmetric state indicated by the question mark.
TOPIC 2: MODELING THE LANDSCAPE

Aazami & Easther (2005): Considered a model landscape with a random potential for many scalar fields. Assumed that the matrix elements of the Hessian (2nd derivative matrix) were random, independent variables. “If the ... off-diagonal terms are of the same order as the ... diagonal terms we show that essentially all extrema are saddles, and the number of minima is effectively zero.” Issue: eigenvalue repulsion makes it very unlikely for all eigenvalues to be positive.

Marsh, McAllister, & Wrase (2011): Built an $\mathcal{N} = 1$ supergravity model with $N \gg 1$ scalar fields. Found that the probability that all eigenvalues of the Hessian are positive at a stationary point is very small, $\propto e^{-cN^p}$, with $p \approx 1.2$ to 1.5. But “the number of vacua remains vast.”
Newer Approaches

Instead of considering a Gaussian orthogonal Hessian, consider the potential function to be a Gaussian random function.

References:

2) Bray & Dean (2007): $N \to \infty$ limit of Gaussian random functions.
3) Bachlechner (2014): considered supergravity models with Gaussian random potential functions. Found probability that a stationary point is a minimum $\propto e^{-cN}$. 
Mathematical Issue: Correlations

Gaussian Orthogonal Ensemble:

\[ \langle H_{ij} H_{k\ell} \rangle = B \left[ \delta_{ik} \delta_{j\ell} + \delta_{i\ell} \delta_{jk} \right] \]

This means that each element is correlated only with itself. Leads to strong eigenvalue repulsion.

For ANY random function that is statistically spherically symmetric and rotationally invariant,

\[ \langle V(\vec{\phi}_1)V(\vec{\phi}_2) \rangle = C \left( (\vec{\phi}_1 - \vec{\phi}_2)^2 \right). \]

But then

\[ \langle H_{ij} H_{k\ell} \rangle = \lim_{\vec{\phi}_2 \to \vec{\phi}_1} \frac{\partial^4 C}{\partial \phi_1^i \partial \phi_1^i \partial \phi_2^j \partial \phi_2^\ell} \]

\[ = 4C''(0) \left[ \delta_{ik} \delta_{j\ell} + \delta_{i\ell} \delta_{jk} + \delta_{ij} \delta_{k\ell} \right]. \]
Suppose we want to consider random potentials which are not statistically invariant under translations or rotations. Is the Gaussian Orthogonal Ensemble a possibility?

NO!

Topology from Morse theory: If $N_i$ is the number of stationary points with $i$ negative eigenvalues in the Hessian,

$$\sum_{i=1}^{N} (-1)^i N_i = \text{Euler characteristic.}$$

For $N = 2$ with $V \rightarrow -V$ symmetry, Morse implies $N_{\text{saddle}}/N_{\text{min}} = 2$, while GOE predicts ratio is 4.82.
Minima Are Not Rare

Assuming a Gaussian random function for $V(\vec{\phi})$, we find that minima are NOT RARE. We found numerically, by calculating up to 100 fields, that the probability that a stationary point is a minimum is well fit by the formula

$$P \propto 2.39^{-N}.$$
TOPIC 3: CELEBRATION OF INFLATION
Planck 2015 TT Power Spectrum
Planck 2015 TE Power Spectrum

$DTE_\ell [\mu K^2]$ versus Multipole moment $\ell$
Planck 2015 EE Power Spectrum
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I find it completely mind-boggling that it has been possible to put together ideas that have been developed by perhaps a century of research in general relativity, cosmology, quantum theory, and particle physics, and to use those ideas to try to describe the behavior of the universe at times as early as $10^{-37}$ second. And then it is absolutely astounding that our experimental colleagues have been able to design and actually carry out measurements, like the ones I just showed you, that allow us to test the predictions of these theories with spectacular precision. The era of precision cosmology has truly arrived, and I believe that it has been a spectacular testament to the power of the scientific enterprise.