Does the second law of thermodynamics rule out theories such as inflation, in which the initial conditions of the universe are supposed to be “generic”?

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In this essay it is argued that the theory of inflation is compatible with the second law of thermodynamics, despite dictating that the initial conditions of the universe are ‘generic’. Here, generic initial conditions for the universe are interpreted to be highly chaotic and close to thermal equilibrium. This follows definitions of ‘primeval’ or ‘primordial’ chaos previously used[1][2][3][4]. In particular, an argument is made for a chaotic model of inflation similar to that proposed by Linde[5] and Albrecht[6].

The structure of the essay is as follows: Firstly, the second law of thermodynamics and the theory of inflation are briefly introduced. Subsequent discussion attempts to explain why the two are compatible, despite inflation implying generic initial conditions, putting it in apparent contrast with the existence of an arrow of time as a result of the second law of thermodynamics (which depends on special initial conditions[4]). In light of this development, common arguments against the inflationary picture are addressed. Specifically, the possibility of a universe arising through a non-inflationary Big Bang and the Boltzmann Brain argument against Big Bang cosmology are investigated. Finally the key points of the essay are summarised.

The second law of thermodynamics is an axiom of thermodynamic theory which dictates how systems evolve in time through their phase space (the space consisting of all possible configurations of the system). There have been several different statements attributed to this law although all are generally considered to state as a corollary that physics in our observable universe exhibits time asymmetry[7][8]. Specifically, this time asymmetry is expressed by the phenomena that isolated systems beginning from a specialised low-probability (as defined by the number of corresponding microstates) initial macrostate will always evolve dynamically towards higher probability equilibrium macrostates. This is often expressed quantitatively by defining a state variable, entropy, which will always increase with the passage of time in an isolated system.

Despite being empirically derived, the consistent increase in entropy in isolated systems is supported by a large amount of experimental data and is observable in day-to-day life. For example, a glass which falls off a table will never jump back on it and reassemble itself, nor will all the gas molecules in a box suddenly collect in one corner. Such occurrences would look incredibly strange to the casual observer. However, if a film of these events were viewed in reverse they would look standard. Realisations such as these lead to the definition of a thermodynamic arrow of time [4][9][10][11] in which special configurations of a system (such as the atoms in the glass existing in a regular crystalline structure on the table or the gas molecules being in the corner of the box) dynamically evolve into generic configurations (the glass being shattered across the floor or the gas molecules being spread across the box evenly).

Inflation was first proposed in 1980 by Alan Guth [12] as a potential solution to several cosmological puzzles concerning why the observable universe appears so flat and homogeneous. It was later shown to predict the cosmic microwave background highly accurately, as well as the formation of galaxies due to quantum fluctuations during the inflationary stage [13][14]. The theory proposes a scalar field known as the *inflaton* which, under certain conditions, can mimic the cosmological constant term initially proposed and later retracted by Einstein in his formulation of general relativity to allow for a static universe[15]. When the inflaton in a region reaches this special *potential-dominated* state [4] the region expands to many times its initial size in a process known as *inflation*. It has been shown that this results in a very flat universe where variations in homogeneity are suppressed[12].

The question is then, how does inflation support generic initial conditions despite requiring this special initial condition of the inflaton? The second law of thermodynamics defines an arrow of time which suggests we came from a seemingly unlikely low-entropy state. This idea is known as the *past hypothesis*[16]. How does this arise from the high entropy initial conditions of the universe? In chaotic inflation theory this question is answered as follows: At the Planck epoch, the universe is in highly chaotic 'generic' conditions. A small patch of this undergoes a thermal fluctuation such that its inflaton field enters a potential-dominated state, providing the necessary conditions for inflation [5][17]. This patch then inflates into our observable universe. The fluctuation that occurs is highly unlikely for any given patch although arises as part of a much larger background and in this sense inflation is likely to start somewhere. In this framework, the special initial conditions of the universe necessary for a thermodynamic arrow of time are passed from the universe as we observe it onto the inflaton field[4]. The arrow of time then arises as a symptom of the universe tending back toward generic conditions probabilistically.

One criticism levelled against chaotic inflation theory concerns the idea that the inflaton state arises as a thermal fluctuation. If this large background in which thermal fluctuations occur exists at the Planck epoch, then surely it is possible that the observable universe could arise in its improbable state as a random fluctuation without the need for inflation? This viewpoint can be argued in conjunction with the anthropic proposition that the observers may only be able to exist in a universe as flat and homogeneous as our own. Since we have no grasp on the probabilities of observers existing in universes with differing conditions to our own[18], nor on how large the chaotic background of the universe at the Planck epoch is, it is an assumption to say our universe arising from fluctuations without inflation is unlikely. Yet it is on this assumption that the need for a theory to explain the apparent unlikely conditions of the observable universe is founded!

However there are two flaws with the above argument. The first is that if we develop a theory which uses one new parameter (the inflaton) to predict the values of several other observables previously considered as 'inputs' to the old theory (flatness, homogeneity and the inexistence of magnetic monopoles) then the new theory is better than the old [4]. The other argument against this idea derives from the fact that we find ourselves in a universe on a Hubble scale. If the universe could arise from fluctuations without inflation and it is accepted that small fluctuations are more probable than large fluctuations, it would be far more probable for the observable universe to be much smaller, perhaps only a few galaxies across

[3][19]. Inflation solves this problem due to the dynamic of e-folding, where the universe grows to many times its initial size in a very short period [12].

Another common argument used against inflation is the Boltzmann Brain (BB) argument. This is the idea that universe we observe does not come from a big bang scenario at all, inflationary or otherwise, but rather from fluctuations in a thermal bath. A proponent may argue that such a universe is significantly more likely than the classic thermodynamic picture; a fluctuation to a universe in its current state via Poincare recurrence is more likely than to earlier lower-entropy states Thus the most probable situation is that the universe has just 'popped' into existence in its current state and that the past is an illusion. Whilst these theories are very difficult dismiss outright it can be argued that this is very unlikely. The standard argument is that the most probable BB universe to exist would consist of a single observer in a thermal bath [20][21] and thus for one or more observers to exist on a universe of our scale would be very improbable. Another flaw in the BB hypothesis is its cognitive instability[22]; if we accept it we have no justification to accept the reasoning that lead to our conclusion. This is because, as we have seen, a Boltzmann brain is most probable to have just sprung into existence in which case any of its memories are an illusion. Hence a Boltzmann brain could not trust its own previously made deductions and could not construct a logically consistent argument for being a Boltzmann brain. Furthermore, the same argument would apply to all derivations and thus logical thought would be rendered impossible.

To summarize, it has been shown that the theory of inflation is compatible with the second law of thermodynamics. In this inflationary picture the existence of a thermodynamic arrow of time is predicted as opposed to being an obstacle. This is because the universe we inhabit is recovering to its initial conditions from a fluctuation which, although unlikely, is probable when considered as part of a larger chaotic background. Whilst events which contradict the second law of thermodynamics are possible they remain highly unlikely and thus are not observed. It has also been argued that whilst a universe as homogeneous and flat as ours could arise by a fluctuation in a chaotic background without the need for inflation, this is likely than the inflationary scenario and does not explain why the universe is of the proportions we observe. Finally the possibility of the observable universe arising by a Boltzmann Brain scenario was discussed however this was deemed

ultimately unlikely and furthermore cognitively unstable. Therefore it can be concluded that after considering the second law of thermodynamics and the resulting arrow of time we observe, the theory of inflation remains possible and furthermore the most likely explanation of how our universe came into being.
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