Notes for FROM ETERNITY TO HERE (2010), by Sean Carroll

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From Eternity to Here, by Sean M Carroll, is a book about the role of time and entropy in the evolution of the universe. Time has an obvious direction. Whether or not that needs explanation in itself, there is a conspicuous correlate, which is that the entropy of the universe as a whole is steadily increasing, and has been for as far in space and as far back in time as we can see. This must be the result of a time in the past when the entropy was lower everywhere. The big bang is the presumed cause. Carroll explores the possibilities, and offers another one, that the time of the big bang was not the beginning of the universe, or of time, but was some other kind of event resulting in a widespread low entropy state.

There are a lot of speculative ideas in the book, since the subject is not fully understood, as Carroll points out many times in the book. I am not a physicist, but a retired engineer leading a discussion group (at the Boulder Public Library, see http://www.sackett.net/cosmology.htm). I cannot evaluate everything in the book, and have omitted some minor lines of reasoning, either for being speculative, or because they seem not to affect the conclusion. I have used color where I am unsure in one way or another. All errors are mine, and I welcome corrections and clarifications.

Prologue

P. 2-3. Time has a preferred direction, the arrow of time, while the spatial dimensions do not. A major theme of the book is that this is *because* time moves in the direction of increasing entropy. While it is easily seen that many macroscopic processes are irreversible, it seems a stretch to say that *determines* the direction of time. In any event, in what we can observe (so far) time does move in the direction of increasing entropy. This requires that the early universe was in a state of very low entropy, for which the leading explanation is the big bang.

P. 3-4. Much of the book tries to explain this low entropy initial situation in different ways. Carroll offers an explanation that the big bang is not the beginning of the universe, but only the beginning of the part that we can see. The larger context is a multiverse which is continually spawning "baby universes" with very low entropy. This has the advantage that each local universe can evolve as ours does, without requiring special circumstances in the beginning. (One of his major concerns is to avoid postulating an extremely unlikely initial condition in order to reach the present state. However, at some point (multiverses?), the complexity of the theory may become a bigger issue than the improbability of the situation it avoids. But Carroll presents this as an example of how to explore possibilities of a larger theory, not as a final theory.)

Chapter 1

This chapter describes time in three different ways, all of which are relevant in physics.

P. 10-14. Time as a coordinate. Just as with space, time gives a location of an event in time. It establishes an order of events on a macroscopic continuum. The three spatial coordinates, together with one time coordinate, define a specific event. The set of all such events (*not including* whatever might have occurred there) make a four dimensional entity called spacetime. A particular object in spacetime traces a world line in this space, connecting all of the points (events) it passed through.

P. 14-21. Time measures duration. Different events occur at different times, and the difference can be measured. A clock is just a generator of brief intervals of the same length, so time measurement is reduced to counting these intervals, just as space is measured by counting small spatial intervals on a measuring stick. With the advent of special relativity, it was found that the time between different events depends on the path followed between them, so it is impossible to establish a uniform time coordinate for all observers.

P. 21-25. Time as a medium through which we move. We perceive time as flowing around us, but a more consistent view is that we are moving through time at a fixed rate of one second per second (ignoring relativity). This allows spacetime to be viewed as a complete entity through which we move. Special relativity prohibits the definition of a "present" which is the same for all observers, forcing the view that all of spacetime exists simultaneously. ("Block time", "block universe", or "eternalism", as opposed to "presentism", where only the present exists.)

Chapter 2

Chapter 2 introduces the concepts of entropy and the arrow of time. Entropy is a slippery concept, with various definitions, not all in agreement. We will mainly deal with thermodynamic entropy, and mostly within its description in terms of micro- and macrostates. There is another way of introducing entropy, which is to emphasize the concentration or dispersal of energy, which relates to its usability. (See http://en.wikipedia.org/wiki/Entropy_%28energy_dispersal%29.

Most physical laws and microscopic physical processes are reversible in time. Many macroscopic processes are irreversible, e.g. you can't unburn a piece of paper, returning it to its original form. The reason for this is that entropy always tends (statistically, but to an overwhelming degree) to increase. The disorder of the system increases (it's no longer a regular shape), the number of available states of the system increases (the individual molecules are no longer confined), and the energy is less concentrated (localized chemical energy is converted to heat, which spreads out freely). Much of the book deals with how entropy explains various phenomena, and the cosmological question of how the universe came to be in a state that allows nearly unlimited increases in entropy.

Carroll tends to view the arrow of time as being *defined* by the increase in entropy. To me, this may be too strong. If one adopts the eternalist view of the universe, where all time exists at once, and one observes it from "outside", the direction of increasing overall entropy surely *indicates* the forward direction of time. Nevertheless, entropy throughout the universe is increasing in spite of the reversible laws governing detailed processes. For this to happen for a long period of time, there must have been a point in the past with very low entropy, i.e. the big bang or something like it.

Heat is a form of kinetic energy, and temperature is proportional to the average kinetic energy per particle. Thermodynamic equilibrium is the condition where the energy has spread out as far as possible, and everything is at the same temperature. Open and closed systems are distinguished by whether significant influences from the outside may occur. In open systems, entropy can decrease, because an external influence is causing it to do so, although that influence is causing an entropy increase elsewhere.

> Entropy change δS can be measured as heat transferred δQ divided by the temperature of the medium it moves from or to (i.e. for small transfers and negligible temperature change, $\delta S = \delta Q/T$). Using the dispersal of energy view of entropy, flow of heat from a hot body to a cold one disperses the energy. Since the source body is hot and the destination body is cool, the transfer of energy from the hot body to the cold one decreases the entropy of the source less than it increases the entropy of the destination, and net entropy increases.

The state space view of entropy considers the number of ways the system can be arranged. There may be confusion between thermodynamic and information states. The thermodynamic view defines entropy as the logarithm of the number of microstates that make up the current macrostate. The microstates are the detailed arrangements of the elements of the system, and the macrostates are the aggregated sets of microstates that "look the same" for the current purpose, such as ice cube melted or not. Entropy increase is described as occurring because disturbing a system generally changes it from a macrostate with fewer microstates to one with more (frozen to melted). This tends to happen because random disturbances do not generally respect the special circumstances (order or structure of a defined macrostate) they occur in, and there are more ways to be disordered (different) than ordered (similar).

Earth is an open system. We have a source of low entropy, concentrated photons coming from the hot sun, and a cold place to dump the high entropy diluted photons that result from warming by the sun. Each photon arriving from the sun is balanced by the energy radiated into space by about 20 lower energy photons. On Mars, that's about all that happens; the sun warms it, and it radiates an equal amount of thermal energy. But here, the potential utility of the high energy photons has resulted in the evolution of chlorophyll, which traps them and retains some of the concentratedness (low entropy) to use for other things. The energy so trapped is stored in photosynthesized sugar, which is less concentrated than the sun's photons, but more so than the thermal photons we ultimately get rid of. Animals consume this sugar as food and metabolize it, releasing part of the energy as heat (dilute) energy, and retaining part of it in lower entropy forms such as the structure of our bodies. After a while, the machinery wears out, and it rapidly degenerates into more dilute and less ordered forms, such as carbon dioxide and water and thermal photons to be radiated into space. By capturing the incoming low entropy, we get to use it for a while for our own purposes, while continually degrading it to maintain our capacity to continue using it. Without the external source, nothing would happen, and without a place to get rid of the degraded energy, heat would build up until chemistry would work just as well backwards, and nothing would happen.

On p. 40-41, Carroll introduces an idea that he uses various times in the book. The idea is that memories or any other record of the past depend on the existence of a lower entropy condition in the past. The gist seems to be a statistical argument that without knowing that the entropy was lower in the past, any memory or record is more likely a random fluctuation from a higher entropy state than a real record. This is explained in more detail later, and used to argue that the whole visible universe was indeed in a lower entropy state in the past.

Chapter 3

Chapter 3 presents an overview of the standard model of cosmology, with a bit of extra attention to various points of interest for this book. Foremost among these is the question of why the universe had a time in the past with very low entropy, or concentrated energy, which allows interesting things to happen as it dilutes.

Expansion of the universe was accompanied by local clumping of matter into galaxies and clusters. On scales larger than galaxy clusters, it remains statistically smooth. The expansion was expected to be slowing due to gravity, but was found to be accelerating in 1998. The simplest explanation for this is that empty space itself contains dark energy, which does not dilute as space expands, but maintains constant density.

On p. 63-4, Carroll lays out the main issue of the book. If the microscopic laws of physics are really reversible, then there must have been a prior time when the entropy of the universe was much lower. Since we can see a very long distance in space and into the past, and it all looks similar, this early state must have been very long ago and must encompass the entire currently visible universe. The big bang or something very like it must have happened 13.7 billion years ago. Carroll sees two possibilities: The low entropy condition came from the big bang, which established a boundary condition at the beginning of time; or it might have come from a phase change or similar event in a pre-existing universe. Carroll argues for the second possibility on the grounds that it is simpler by not requiring the addition of a special boundary condition. As a lead-in for Part Two, he points out that dark energy may be needed for this hypothesis.

Part Two: Chapters 4-6

Part Two introduces relativity, especially as it applies to time. This is mostly background material for the discussion of time and entropy in the context of the entire universe.

Chapter 4 describes the Special Theory of Relativity, including the symmetry of space under translation and uniform velocity, the constancy of the speed of light, its role as a limit of relative velocity, and the dependence of elapsed time on the specific path through spacetime taken between two events. An event is the combination of a place and a time. The elapsed time between two events (measured on a clock carried along on the path between them) is *longest* if the spatial velocity is constant between them. If the travel is at the speed of light, the elapsed time is zero for that portion of the path. Light cones are introduced in p. 77-80, along with spacetime diagrams and world lines, to describe and codify allowable motion in spacetime and relations between events. These ideas preclude any definition of simultaneity that applies at all points in space, which in turn strongly encourages the block time view that all of spacetime exists simultaneously and forever. The ideas in this section are worth understanding for later use in the book, and because they are frequently used in other discussions involving relativity. In passing, Carroll mentions that the particular spacetime we live in seems to have exactly three dimensions of space and one of time. There is no reason known for this (except the anthropic reason that it seems to be necessary for our existence). Additional space dimensions are considered in string theory. Additional time dimensions are interesting but problematic.

Chapter 5 gives a very brief introduction to the General Theory of Relativity, which brings in the equivalence between gravity and acceleration and the curvature of space. Carroll mentions that energy conservation may not apply to the entire universe when General Relativity is considered, especially with the inclusion of dark energy, even if gravitational energy is included. In some models, the total energy of the universe is zero. Black holes and white holes are introduced.

Chapter 6 discusses time travel and closed time-like curves, which may be possible under General Relativity, but which introduce a variety of paradoxical consequences. Time travel into the future is obviously possible, just by waiting. To travel faster, it is necessary to move through space at a very high speed, which really just slows down your perception of time relative to the rest of the universe. But it *seems like* you got ahead of time that way. Travel into the past is more problematic, and introduces paradoxical possibilities. Possible methods are traveling faster than light, finding or making a wormhole, a region of space that is curved enough to allow past and future light cones to overlap on some paths. All have some theoretical justification, at least at the level of the fundamental effect that would be needed to achieve that result. Tachyons are theoretical particles that only travel faster than light. They are not known to exist, and even if they do, they are unable to cross the v=c boundary, which requires infinite energy. Wormholes may exist, but only briefly, and seem to require negative energy to persist. Curving space enough to make a closed curve may require more energy than the universe contains. Carroll briefly considers disallowing these by a principle that nature will not permit inconsistent situations to arise. This requires that nature somehow is able to detect inconsistencies and prevent them, even though they do not violate any laws locally. He quickly decides that the more likely case is that the mechanisms are just impossible on a macroscopic scale.

Chapter 7

Chapter 7 is about the reversibility in time of the laws of physics. Importantly, this must be defined as preservation of the laws under some set of state transformations that *include* reversal of time. Reversibility depends on the evident time-reversal symmetry of the underlying microscopic laws. It also depends on the conservation of information in physical interactions. Together, these make physical interactions deterministic, both toward the future and the past. I'm not clear on the connection, but this backwards determinism, uniqueness of the past situation that leads to the present, seems to be necessary to Carroll's argument about how time-symmetrical laws and a gross asymmetry between past and present can coexist.

On p.122, Carroll introduces a checkerboard analogy for evolution of the states of a physical system, where each row's black/white makeup is a successor state of the one below it. This is a useful illustration of the state space view of physical law (see below). It also makes a neat analogy for science itself, as the process of deducing the pattern on the visible part of the checkerboard, and checking the guess by uncovering more of it. The checkerboard is used to illustrate symmetries of various kinds of laws for the evolution of states. Each row is the state of a system at a moment of time, and the laws governing the system determine how each row determines the next. We will be interested in how the laws are affected by flipping the board top to bottom, i.e. reversing time. In some cases (p. 127-8) it will be necessary to make some other transformation to keep the form of the laws the same.

On p. 128-32, we have a more detailed description of the state space idea. Carroll describes a template for a physical theory as 1) a set of objects, 2) a set of conditions the objects can be in (the "state space"; e.g. position and momentum of each particle in the case of classical dynamics), and 3) a set of rules describing how any state evolves with time. The state space includes every possible condition the system can be in, and the rules of evolution describe the laws of physics that govern the system's state changes. The number of dimensions in the state space is very large (six times the number of particles). This state evolution model of physical theories is widely used.

P. 132-4 apply the state space model to Newtonian mechanics and show how time-reversal symmetry requires not only reversing the time ordering of the states, but also transforming each state by reversing the direction of its momentum. Although this is intuitively obvious, the state space representation makes it explicit.

> Jumping ahead to p. 137, there are three reversal operations in physics that initially appear to be independently valid symmetries. They are time reversal, parity inversion or mirror reflection, and charge conjugation or particle/antiparticle substitution. Consecutive repetition of any of these restores the original state. They are collectively called the CPT symmetries.
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> > Overall, the symmetry of a quantum mechanical system can be restored if another symmetry *S* can be found such that the combined symmetry *PS* remains unbroken. This rather subtle point about the structure of Hilbert space was realized shortly after the discovery of *P* violation, and it was proposed that charge conjugation was the desired symmetry to restore order. (http://en.wikipedia.org/wiki/CP_violation)
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> Back on p. 135, we have the first example of these ideas applied to subatomic particles. Kaon oscillation is the process in which the neutral kaon and its different but also neutral antiparticle "decay" into each other. Both also decay into other sets of particles, which are distinguishable. Since a batch of these produces slightly more of one final output product than the other, the transition has a different half life in opposite directions. Thus an energetically neutral process occurs at a different rate in opposite directions.
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> In 1956 (p. 138), Lee and Yang found that there was no existing evidence that required the weak interaction to obey P symmetry, and Wu and Ambler and another group quickly performed experiments showing that it did not (http://ccreweb.org/documents/parity/parity.html). In fact, the simplest case indicates that the preference of the weak interaction for left-handedness is 100%, i.e. complete parity violation. It was suspected that combining charge conjugation with parity inversion would yield a universally conserved CP symmetry, or symmetry under combined

C and P inversion. However, in 1964, Cronin and Fitch measured the asymmetry of kaon oscillation described above. The observed T symmetry violation implies a corresponding CP violation.

There is a theorem, called the CPT Theorem, which proves that the combined CPT symmetry is valid, under a reasonable set of assumptions. In fact, all of the C,P,T symmetries are violated individually, as well as all pairs, leaving only the combined CPT symmetry universally intact. Since T symmetry is only valid if C and P transformations are included with it, time reversal symmetry requires C and P "adjustments" to be considered valid.

> It can be shown that any violation of a single or paired symmetry must be accompanied by a corresponding violation of another symmetry to preserve CPT symmetry (http://en.wikipedia.org/wiki/CPT_symmetry).
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> The CPT Theorem predicts equal amounts of matter and antimatter, ultimately leading to an empty universe. The presently observed substantial excess of matter must have been either arbitrarily created in the big bang, or the result of other conditions (http://en.wikipedia.org/wiki/Baryogenesis).

An important condition for time reversibility is conservation of information across state changes, i.e. any state must not only lead to a unique successor state, it must result only from a unique predecessor. With reversible microscopic laws and conservation of information, the behavior of a system is completely determined, both in the future and the past, by a single state. In the last section of the chapter, Carroll uses his checkerboard analogy to illustrate how time-reversal symmetry fails in a process if information is not conserved.

Chapter 8

Chapter 8 goes into more detail about entropy, beginning with the initial concept of disorder. To me, this isn't a very satisfactory definition, because order is not a precise concept. For example, coffee with cream well stirred should be very orderly, since it has no features to be disarranged. It only looks disorderly if you look at the molecules, yet physicists call it disorderly. Two refinements are needed to tighten this up. One is to introduce the idea of molecules and their arrangements, and the other is to declare somewhat arbitrarily that some arrangements of molecules are treated differently from others.

Using ordinary observable criteria, we select some arrangements as having special interest, while others do not. Consider two kinds of systems; gas in a container, and a block of wood in air. The interesting states might be: All gas molecules residing in half of the container, or most energy in a system confined in the block of wood. The corresponding uninteresting states would be all gas molecules distributed evenly, or the energy of the wood spread out in a cloud of smoke and heated air. These four arbitrarily defined, overtly distinguishable arrangements are called macrostates of their respective systems. Any of these can of course be composed of any of a very large number of arrangements of individual molecules (microstates), that we consider to be the same macrostate. This leads to the helpful fact that there are relatively few ways to build the macrostates of interest, and many more ways to build the uninteresting ones from the same molecules. However, like "orderly", "interesting" is subjective and sometimes misleading. Entropy is based on probability, the number of ways a particular macroscopically defined arrangement can be created, not on what we think of it.

This forms the basis of the Boltzmann view of entropy as distribution of microstates among macrostates. Macrostates are defined as being low entropy states if there are relatively few ways to arrange the molecules to form them, and high entropy if there are many ways to form them. Then, when molecules are getting jostled around, it is natural to expect that low entropy macrostates will become less like their specific macrostate definition and more like a macrostate of higher entropy. This is strictly because there are many more ways to be in the high entropy macrostates, and all the microstates are presumed to be more or less equally likely to occur. Carroll likes to use this evolution to indicate the direction of "the arrow of time". It surely *indicates* which way time is moving. Sometimes he seems to say that the direction of entropy increase actually *causes* time to flow in that direction, although I'm not sure if he really believes it.

On p. 153-7, Carroll discusses the view of entropy as the utility of forms of energy. This is essentially the same as degree of concentration, since energy in a concentrated form (region of high heat, fuel, or some other localized source, i.e. low entropy) will tend to spread out uniformly to reach equilibrium (high entropy). Utility is a meaningful characterization of concentration, because clever devices (such as steam engines) can extract useful work from concentrated energy as it spreads out.

Then, on p. 157, we have a discussion of microstates, macrostates, and <u>coarse-graining</u>, which is the defining of the macrostates of interest in the situation. Again, microstates are the completely detailed descriptions of everything about the system, including exactly which atom is where in a given microstate. Macrostates are large scale descriptions of the system state, identified because all of the microstates in them "look the same", or have the same property that we are interested in. Coarse-graining means grouping the individual microstates into the chosen set of macrostates. There is a large degree of choice in this, depending on what you can observe, what you are studying, and what features of the system state matter. Frequently, macrostates will be defined by bulk properties such as temperature or pressure, while microstates are always completely specific with regard to each molecule. Even the most constrained macrostate will have a huge number of microstates in it, because at the very least, all molecules can have a range of positions and momenta without changing the behavior of the whole. But this constrained macrostate still has vastly fewer microstates than the high entropy equilibrium state, where anything can be anywhere and it doesn't matter. Boltzmann's definition of entropy refers to the entropy of any specific macrostate, and is a measure (proportional to logarithm) of the number of microstates that it contains. Carroll does not always emphasize it, but this always refers to the entropy of a specific macrostate.

> The act of defining a macrostate as some set of similar microstates is a form of forgetting or ignoring some of the available information. It involves a choice of which information to discard, i.e. what differences do or don't matter for the problem at hand, and how precisely we wish to define them. This arbitrariness contributes to some of the slipperiness of the subject.

> The arbitrariness of macrostates is quite flexible. For example, the entropy of a whole system could be defined by considering the single macrostate of the system's existence. Then, you just count all the ways to arrange the system while preserving its existence, regardless of other characteristics. At the other extreme, cryptographers might only care about three macrostates of a message: Correctly received, correctly received and decoded (each containing only one microstate of character arrangement), and an error condition (containing all other possible character arrangements).

> In most situations, we identify a few macrostates that have useful and identifiable properties, and all other microstates fall into the single "useless" macrostate. Usually, the "useful" macrostates have things arranged in a small subset of the possible ways, and are thus lower entropy than the "useless" ones. As nature takes its course of jostling things around, special arrangements degrade randomly into un-special ones, just because there are more of them, i.e. entropy increases. This applies however you define "special" arrangements.

Entropy tends to increase because there are more ways to increase than decrease, as the microstate keeps changing (fig. 45). Therefore, the increase is a statistical phenomenon, not an inviolable law. But even this very robust observation is affected by macrostate definitions. In the extreme, consider that each microstate is its own macrostate, i.e. every state has unique significance, like a roulette wheel. Then, every state is low entropy, and the entropy doesn't change.

Since the other laws of physics are reversible in operation, nothing prevents a system from running backwards. ("Running backwards" in dynamics really means that a state could be constructed with everything the same, except with all motion reversed. It would satisfy the same microscopic laws, and the same states would occur in reverse order.) In that case, it would evolve from a high entropy state into a lower entropy one. This is never observed, because there are very few microstates in the high entropy macrostate that would actually lead to the earlier, lower entropy state if reversed. You'd never be able to create one, except by magically reversing the direction of all molecules in a system. Other very similar ones would look the same at the start, but would continue to evolve toward higher entropy. He refers to this idea repeatedly. I'm not sure why.

I think Carroll went off the deep end a bit at the bottom of p. 162, with the people in his time-reversed world only remembering what we see as their future. He says the arrow of time is a *consequence* of the direction of entropy increase, and "The direction of the time coordinate on the universe is completely arbitrary, set by convention; it has no external meaning." I think he's made too much of it, although if you accept the block time version of the universe, maybe you need something like this. Besides, even if you lived in a part of the universe that had its entropy spontaneously decreasing, your personal physiology would probably still depend on consuming low entropy food and releasing higher entropy heat. So you might see strange behavior around you, but your memory would remember events in the same order as elsewhere in the universe.

Much of the rest of the chapter is a skip through the minefield of interpretations of entropy. To me, the idea of disorder isn't helpful, because it is subjective, sometimes focuses on the wrong things, and in the case of gravity, can be quite misleading. The Principle of Indifference, the idea that large classes of microstates are equally likely, is useful, particularly for its consequence that that microstates in small subsets (low entropy macrostates) usually evolve into larger subsets (higher entropy macrostates). This evolution is quite reliable, whether the macrostates have any meaning or not. However, the principle fails when considering reversing time to reach a prior state. Most of the microstates in the current macrostate could *not* have evolved from the actual history. A few can, but the other ones could only be reached by way of some prior state that did not in fact occur. Thus the probabilities of microstates in the two subsets are not equal. I think that part of the problem is that there is an inclination to get too specific when the macrostates are too vague. Another part is that the concept of entropy applies to many different kinds of situations, and various explanations and analogies apply to some and not others.

The section beginning on p. 169 mentions other definitions of entropy and the arrow of time. There are still more at http://en.wikipedia.org/wiki/Arrow_of_time#The_thermodynamic_arrow_of_time. The definitions are many, not always related, and perhaps not always consistent.

Pages 174-8 introduce the idea that we need a low entropy boundary condition somewhere in the past to explain the evolution that we see. This is called The Past Hypothesis. This arises from considering how a medium-entropy state in the recent past could have arisen. Suppose all microstates are equally likely, the laws of physics are reversible, and the universe is near thermal equilibrium. Then a recent low entropy period probably arose spontaneously from the much more numerous high entropy states available that preceded it, for the same reasons that it will probably evolve into a higher entropy state. On any large scale, that's too unlikely to spend much time thinking about. To save ourselves from that, The Past Hypothesis allows us to assume that entropy has increased (nearly) uniformly during the past from a low entropy starting point. We trade the question of how did entropy spontaneously decrease to a minimum before increasing again, for the question of how did the universe have a low entropy beginning. The big bang can help with this, but there are other possibilities. Carroll will eventually dismiss the whole "entropy fluctuation" idea as too unlikely when you consider the scale required (the whole observable universe) to match observations. Another source about specific issues of entropy and time, particularly the Past Hypothesis, is http://plato.stanford.edu/entries/time-thermo/. This is from the Stanford Encyclopedia of Philosophy, which has many scientific entries. (Section 2.5 of this link discusses the idea that time may have an inherent directedness, which would save us a lot of trouble.)

Chapter 9

Chapter 9 contains an assortment of topics about life, information, and entropy. Carroll begins by asserting that the important differences between past and future arise from the Second Law, the increase of entropy. (No implication of causation in this particular phrasing.) Without the Past Hypothesis, records of the past (loosely, "memories") might most likely be explained as meaningless fluctuations in the arrangement of matter to a lower entropy state from a higher entropy one. With it, they are more likely to mean what they appear to mean.

Leaving human memory out by using cosmic microwave background photons as an example of a record sharpens the argument. One possibility is that the CMB photons could be the result of a fluctuation from some higher entropy state. However, if we consider a low entropy past, it is much more likely that the present state came directly from that (and what they appear to mean is true), rather than by way of some still earlier high entropy state. He is really making a very broad argument here, that any record of the past is unreliable unless we accept the Past Hypothesis to constrain the ways the record could have been created.

> The logic seems to be as follows: Since there are many more high entropy states than low entropy ones, *without the Past Hypothesis*, the most likely explanation for the present state is that it is a random fluctuation from a higher entropy prior state. This is unlikely but not impossible. In this case, the memory or record is false, a product of the fluctuation. If we consider a larger portion of the universe, such as two people having a similar memory, this is even less likely as a fluctuation from higher entropy. As we consider ever larger present conditions that may reflect possible past conditions, the probability of all of them being false records by fluctuation rapidly gets smaller. The weight of progressively more contrivances to explain the present eventually makes the fluctuation probability less likely than the probability of a universe-wide low entropy prior condition (despite its own low probability). Given that everywhere we see in the observable universe has entropy similar to this region, the probability that *all of it* is a false record becomes less than the probability that the low entropy prior condition really existed, and that the records of it are correct. That is the Past Hypothesis.

On p. 186, a discussion of Maxwell's Demon begins, with emphasis on entropy. By sorting slow and fast molecules, the Demon reduces the entropy of the gas in his domain. Carroll argues that this entropy has to go into the Demon or his record keeping. Somehow, either recording or erasing information moves entropy around. I'm not sure how well worked-out this idea is. For example, on the bottom of p. 188, Carroll states that a blank record sheet is low entropy, while on the top of p. 191 he compares an unlikely (high information) message to low entropy. This depends on some sort of quantitative measure of entropy, precise enough to track as it moves from place to place. More complete explanations of this are even harder to understand. I don't know if the information theoretic and statistical mechanical concepts of entropy can be made compatible.

> On p. 190, we get a glimpse of Claude Shannon's information theoretic view of entropy. It seems somewhat similar to Boltzmann's view, except that the concept of macrostates may not be important, and specific microstates are quite important and not at all equal in probability.

Life is complicated and hard to define, and tracking the progress of (low) entropy through biological processes is difficult. However, a much simpler analogy can be made with the energy and entropy of the earth as a whole (p. 192). Using the energy concentration view of entropy, it is easy to see that the earth receives a lot of low entropy energy (visible photons from the sun), and releases *all* of it at higher entropy (infrared photons radiated from our own lower temperature). If (low) entropy is a conserved and transferrable medium, some of this low entropy can be used to reduce the entropy of the biomass on earth from arbitrarily high (mostly CO_2 and water, in the extreme case) to any desired specific configuration (lions, tigers, bears, physicists, etc.). From that perspective, life needs only to be able to capture low entropy energy (sunlight, food), use some of the energy to do work or keep itself warm, and transfer some of the (low) entropy into its internal structure to build, repair, or reproduce itself. The available (deficit of) entropy is more than ample in the low entropy solar photons.

A similar explanation makes use of the concept of free energy. This name may be on the way out, since it may suggest energy that has already been liberated from a confined form into heat at equilibrium. In fact, free energy means the portion of total energy in a system that is available to do something useful, i.e. the part that is *not* at equilibrium. From that perspective, food contains free energy (as well as low entropy) which can be used to drive the effort to seek more food, and to repair biochemical and physical damage in order to maintain the organism's preferred configuration of low entropy and free energy against the inevitable forces of degradation.

The chapter closes with a bit about Kolmogorov or algorithmic complexity. This is an interesting aside about measuring the complexity of something by the length of the minimum description of it. By that measure, pi or sqrt(2) are simple, since they can be simply described by geometric construction or other simple algorithms, while most real numbers cannot. Alas, we still do not have much about the unification of energy, information, and entropy.

Chapter 10

Chapter 10 is about the possibility that the Past Hypothesis may not be needed, because the universe could have fluctuated into a low entropy state by itself, without having started out that way. Boltzmann accepted the idea that the Second Law is statistical, not absolute. Therefore, it is possible that in enough time, an equilibrium universe could randomly evolve into a lower entropy state. If the universe truly had no beginning, as was believed at that time, a great variety of states of the universe will eventually appear spontaneously. No *a priori* low entropy state is needed.

However, if states are continually changing randomly, unusually low entropy states will eventually occur. If we wait long enough, a state unusual enough to produce the observed universe will occur. Figure 54 shows a possible plot of total (normalized) entropy of the universe. Several pages of discussion of this (p. 212-21), with much flirtation with the idea that the direction of entropy change *defines* the direction of time, leads to a refutation based on the absence of Boltzmann brains in the observable universe. This seems unduly convoluted to me.

> The gist of the argument is this: The universe is in a state that allows us to exist. If it got there by statistical fluctuation from a universe mostly near equilibrium, the most likely case is that the entire visible universe didn't go low entropy at once, but only enough was affected to produce what we need to exist. That might be one "Boltzmann brain" isolated observer or one planet, with nearly everything else still in a high entropy state. Or it might be one galaxy or galaxy cluster like ours, with nearly everything else high entropy. But with modern astronomy, it is easy to see that *everything* seems to be in a relatively low entropy state similar to ours. That everything went low entropy at once is far less likely than just a minimum volume doing it, so we're probably better off to assume that it all got that way by some other path (p. 222). A quote from Feynman sums it up nicely on p. 224. Again, the point is that as we observe ever larger volumes of spacetime, it *all* has entropy similar to our local patch. The probability of ever

larger fluctuations into a low entropy state goes from extremely low to extremely low to an extremely high power. But the probability of a universe-wide low entropy past/initial condition remains only extremely low (absent some explanation), so it is more likely to be the case. Since Boltzmann's time, the big bang has emerged as a much more likely alternative. Carroll will propose another. Note that there is a typo, acknowledged by Carroll in his blog, on p. 226. Seven lines above the section break, "… it's still much more unlikely than…" should read "less unlikely". For completeness, the next paragraph seems to need to state that even the whole-universe fluctuation is much more unlikely than the Past Hypothesis.

Somewhere around here, I think I realized what bothers me about the idea that the direction of entropy increase *defines* the forward direction of time. The concept of block time, all of spacetime existing at once, does not seem to preclude the possibility of time having an inherent direction. Causality seems to work just fine in that view, so why can't there be something inherent about time, not subject to reversal with transient conditions of entropy reversal? Did I miss something?

Chapter 11

I have been wondering how Carroll will deal with the apparent lack of reversibility of quantum wave function collapse. Most of the chapter is a summary of various basic points of quantum mechanics: Wave functions, interference, irreversibility, collapse, etc. On the bottom half of p. 241, there is brief consideration of wave function collapse. Carroll says it introduces or defines an intrinsic arrow of time. In any event it doesn't help with the low entropy initial condition problem. In the last section, he seems to use the quantum multiverse idea and decoherence to make an analogy between the loss of information in collapse/decoherence and in coarse-graining. This, he suggests, allows quantum behavior to be regarded as reversible, and therefore all prior arguments about entropy and the laws of physics still apply (p. 255-6). At the end, he decides to ignore it all and go back to the assumption of reversibility. (Back on p. 230, Carroll states, "Most modern physicists deal with the problems of interpreting quantum mechanics through the age-old strategy of 'denial.'" I don't follow those discussions well, but perhaps this is an example.) The short version is on p. 231.

On p. 230, there is a brief paragraph which, along with note 195, explains why not to mix scientific and nonscientific reasoning "in an attempt to create tangible connections out of superficial resemblances."

Chapter 12

From here on, the book is more speculative. If entropy itself isn't confusing enough, we now get to apply it to black holes and the entire universe. Black holes are important to the study of both general relativity and quantum thermodynamics because they are the most accessible (known?) example where both gravity and quantum mechanics are deeply involved.

P. 262 outlines three frameworks for considering quantum gravity. For the sake of generality and broader context, you might add item 1.9 for quantum field theory: Quantized particles in the flat spacetime of special relativity. This is where QED and gravitons are introduced, but it doesn't count as quantum gravity since the curvature of spacetime is not considered, even statically.

The bottom of p. 262 to p. 264 introduces an entropic view of black holes. Much of the rest of the chapter considers this further.

P. 269-70 have a very concise summary of quantum field theory: Fields are everywhere, but when we look at them, we find particles. The more variable the field is, the greater the particle density that creates it. Theoretical work by Bekenstein and Hawking shows that the entropy of a black hole is proportional to its surface area, or the square of its mass. In fact, this is the maximum amount of entropy that can be placed in a region of that size. The fact that maximum entropy increases more slowly than volume suggests that something strange is happening with the entropy, such as compression of information.

Quantum field theory implies that the sea of transient virtual particles everywhere in space will allow black holes to gradually evaporate. A pair of virtual particles of undefined energy appears near the event horizon; one of the pair falls in, causing the other one to become real, with positive energy – Hawking radiation; the one that fell in must therefore have negative energy; therefore the BH is smaller (p. 272). If a BH can evaporate away, where did the information about its contents go? Is the process reversible? Is the information carried away by the Hawking radiation the same as went in, or is it new, arising from the virtual particles? P. 276 describes a famous bet on this, still not fully resolved. More at http://en.wikipedia.org/wiki/Thorne%E2%80%93Hawking%E2%80%93Preskill_bet.

The idea that black holes have very large entropy in spite of our recognition of only three very simple properties suggests that they must have a very large number of internal states. These states are apparently made invisible by the enforced coarse-graining that limits our observations. What the internal components are that have these internal states is presently unknown. The apparent fact that the entropy is proportional to surface area, not mass or volume, is taken as a powerful clue about quantum gravity, but it is not yet understood.

I have given this chapter very superficial treatment. In spite of some good general information in the middle part of the chapter, I didn't find much directly related to the overall theme of the book.

Chapter 13

This chapter deals with the entropy of the entire universe over its lifetime, including gravitational and relativistic effects. Here we get into much less settled territory. After describing the big bang as low entropy for most of the book, Carroll now says that the early state of the universe is very high entropy, nearly in equilibrium (p. 289-90). Resolving this is problematic, and I'm afraid I haven't grasped it all very well. (It seems that the conventional definitions of "high" or "low" are relative to the maximum entropy possible for some set of fixed parameters, like the number of particles and the volume they occupy. More on p. 294.)

Carroll clarifies his definition of the "observable universe" as essentially anything this side of the cosmic microwave background as seen from here, as that sphere expands from zero size. Since there is apparently no boundary within that volume, it is provisionally justified to call this an approximately closed system. This comes from the assumption that there is no boundary nearby in any direction, so particles crossing the visibility boundary are equal in number and properties going out and coming in (p. 291).

Pages 292-4 are about conservation of information, which I don't understand very well. In mechanics, that seems to mean that the laws are reversible, and that any state could have come from only one prior state. This makes sense when the total number of states is fixed. However, if space is expanding, the intuitive view would be that the number of states is increasing, because there are more locations available. That would mean that some of the new states are unreachable by forward progression, and hence need not be traceable to prior states. (Those that favor reversibility seem to dislike this idea, I suppose because there shouldn't be anything special about the unreachable states.) Alternatively (Carroll's view), there may have been an equal number of early states, but most of them "have an irreducibly quantum-gravitational character" (mid p. 294). The last paragraph on p. 294 gives another view, that it doesn't matter, as long as our working assumption is that the number of states of actual interest was much smaller in the past.

In ordinary situations, structure is low entropy while uniformity (degraded structure) is high entropy. The section beginning of p. 295 argues that when gravity is important, clumping of matter into structures is an increase in entropy. I'm not sure if this is universally accepted or not, although Carroll does say it is not well explained theoretically. This is one example where the concept of "orderliness" is misleading.

From p. 299 on, Carroll describes the evolution of the universe to infinity in general terms. The entropy of a tiny big bang would be about 10^88, considering only enough of it to expand into the present observable universe. Eventually, it all collapses into a single black hole with entropy of 10^120. As this black hole evaporates away into Hawking radiation, total entropy increases a bit more. Any matter that manages to escape eventually tunnels into its own black hole which also evaporates. The universe becomes a very dilute gas of Hawking radiation, which would be the highest possible entropy (p. 302-8, note 246). That, Carroll claims is the most likely state for the universe to be in.

If there is a positive vacuum energy (dark energy) causing the presently observed acceleration of expansion, the radiation gets more dilute forever. But since the vacuum energy has a temperature of 10^-29 K, fluctuations are still possible, including into something that looks like the entire visible universe. But as before, that isn't nearly as likely as a local fluctuation just barely capable of supporting life, so it probably didn't happen. But we can't be sure, unless the vacuum energy decays to zero over time, which doesn't fit existing models well. The upshot of all of this is that we still need the big bang or something like it, to explain the improbability of finding the entire universe in the state it is now.

Chapter 14

Inflation is the hypothesized hyper-acceleration of expansion in the very early universe, from about 10^-35 to 10^-32 seconds after what we think of as the big bang. We could even think of inflation itself as the big bang, since it was probably a lot louder than anything that happened shortly before. This expansion is similar to the very slow acceleration of expansion that began several billion years ago, but it is much faster. The simplest model for both of them is the cosmological constant, aka dark energy, vacuum energy, etc., although the difference in rates between the two cases is unexplainably huge. If the entire universe underwent inflation all at once, starting from a very small point, and expanded by a factor of at least 10^27 in 10^-32 seconds, that would solve a lot of problems. The flatness, monopole, and horizon problems are neatly solved by inflation, and almost all cosmologists accept it in some form. As Carroll points out several times in this chapter, it gets progressively more speculative from here.

For lack of any actual evidence, a common approach to inflation is to postulate an inflaton field with a non-zero vacuum value as the source of the vacuum energy that drives inflation (p. 325). A suitable energy density can produce any desired inflation rate. That takes care of the running of inflation, but something is needed to make it start and end.

Some sort of a phase change is needed to make inflation stop and convert its vacuum energy into all of the matter and energy in the universe (p. 327). When it does, the quantum fluctuations in vacuum energy can be the source of the very small fluctuations in the cosmic microwave background, which will later grow into the large structures of the universe (p. 328). There are various models. Guth's original version, "old inflation", postulates initial inflation with bubbles of non-inflating space appearing, growing, and uniting to fill the universe. This doesn't work, because the bubbles cannot appear densely enough or grow quickly enough to combine and fill space, or else can't last long enough to produce the expected results (p. 327). "New inflation" allows the bubbles to last longer, but they never combine. Our entire observable universe had to originate in a single bubble of non-inflation, and the rest of space continued inflating and spawning more bubbles (p. 329) (or whatever else it might have been doing). This implies that even during inflation, space was infinite, and that it always had been, i.e. there was no beginning. Carroll does not emphasize this in the book, but does seem to believe it (http://en.wikipedia.org/wiki/Inflation_%28cosmology%29#Initial_conditions). This just pushes the "Why was it that way?" problem and the special initial conditions back to the beginning of inflation.

Since new inflation keeps spawning new non-inflating bubbles forever, it is a multiverse theory. Note that it did *not* arise because something we know happened was so unlikely that we need a lot of tries to get it. It arose because something that seems very useful as an explanation is naturally inclined to occur repeatedly. This also means that the cosmological principle is not as valid as we hoped, because somewhere outside our horizon, there is a boundary between our non-inflating bubble and the larger universe (which is still inflating, or hasn't started yet, or whatever). We might not be at the center of our bubble, and might not be able to see its edge, but it's out there somewhere, and things are very different outside, in this view (p. 330-1).

In the inset paragraph on p. 333, Carroll gives a capsule view of part of his model. In the first line, I think "the extremely early universe" probably means any place that hasn't gone through the inflation cycle yet. Since it is probably very hot and dense and has been so forever (he never says this), its entropy has increased by gravitation, and it is now far from smooth (if it ever was). Yet somehow, a small region dominated by the inflaton field starts to inflate. That stretches it flat and almost completely smooth. Then, somehow, after inflating by a factor of 10^27 or so, it stops inflating, turns the inflaton field energy into matter and energy particles, and begins the usual post-inflation evolution.

That summary seems pretty crude, but Carroll isn't saying it's finished yet. In fact, although inflation solves the problems it was invented for, the special low entropy conditions that allow inflation to start are still unexplained. We're still left wondering if the universe started out poised for inflation to start, or if it fluctuated randomly into a suitable state (p. 334-5).

The last two sections of the chapter review the corner we're painted into. Carroll considers that his dilemma depends on two major assumptions. The first is that our comoving patch of the universe is approximately a closed system, not affected by the rest of the universe because what's outside is very similar to what's inside and all influences are balanced.

The second assumption is that the laws of physics are reversible and information conserving in spite of the apparent vast increase in the number of states as the universe expands. He seems quite wedded to this, and I'm not sure why. To me, small size is a good enough reason to assume that entropy is lower than when the system has expanded. He really wants to keep the total number of states the same over time. That means that the tiny universe could easily have been big, so it's very unlikely that it isn't (or maybe all of those extra states are hidden somewhere in the small size). That means it is in an unnaturally low entropy state, which needs explanation. I haven't been able to follow all the threads to this point, but p. 336 seems to be pretty explicit about this. He does say that this problem is not specific to inflation, but applies to any low entropy initial condition. He seems to be explicitly rule out (while acknowledging that not everyone agrees) the possibility that a high entropy member of a very limited subset of states (i.e. due to small size) could also be a low entropy member of a much larger set.

Rather than give up the fixed state space model, Carroll prefers to consider that our part of the universe is not a closed system, but is affected by adjoining regions of the multiverse in some way. As he says, this is getting very speculative.

Chapter 15

In Chapter 15, we get an overview of all of the different models of the universe the book considers. Carroll agrees that we need the Past Hypothesis, that the entropy of our visible universe was much lower in the past. His main concern seems to be to find a way that a low entropy initial condition could have arisen naturally, rather than having to specify it arbitrarily. He prefers to disregard anthropically plausible low entropy origins that start with random fluctuation of a region of space into a low entropy condition on the grounds that they are overwhelmingly likely to lead to minimal universes only big enough to support observers ("Boltzmann brains", http://en.wikipedia.org/wiki/Boltzmann_brain) that see a small habitable region surrounded by high-entropy chaos.

Carroll asserts that the overt manifestations of the directionality or "arrow" of time (other than wave function collapse, which he never really addresses) come from the increase of entropy. In addition, he repeatedly suggests that the direction of time (subjective or otherwise) may be *determined* by the direction of entropy increase, possibly even if that somehow changes. This may come out of the block time view of the universe, and seems to be related to the desire to maintain a fixed size of state space, reversibility of all possible states, non-existence of unreachable states, and conservation of information. In that context, he also repeatedly mentions the idea of medium-entropy states that naturally evolve into low-entropy states. I have not been able to understand this group of ideas, and I'm not sure how generally accepted they are, or how necessary to his argument.

In order to keep each model's description separate, I will summarize each section separately.

Evolving the Space of States

The simplest way to get a low entropy initial condition is if that were the only possibility. The small size of the early universe offers an easy route: Small size means small state space, which means low entropy compared to the larger state space of the later universe. However, Carroll considers that allowing the size of the state space to increase as the universe expands requires a major revision of the laws of physics.

If the same number of states exists in the early and late universe, then most of the early ones are hidden ("have an irreducibly quantum-gravitational character", p. 294), *not* "states that look like gentle vibrations of quantum fields around a smooth background" which we know how to describe. This seems to be acceptable to him.

If there are more states late than early (i.e. entropy really was necessarily lower early on due to smaller state space), most of the later ones are not reachable by forward evolution in time (p. 341 figure 8 center). On the top of p. 341, Carroll says this is the way many cosmologists implicitly speak about this issue. Later in the same paragraph, he says, "Almost nobody would claim to support such a position, if they sat down and thought through what it really meant." Then he goes on to say he rejected this possibility when he argued that the universe was finely tuned.

> Did he mean "*not* finely tuned"? It seems to me that high entropy relative to a small state space is not fine tuning, so arguing against fine tuning does not necessarily preclude small. But if he is arguing the universe *is* finely tuned, then he means small is finely tuned but excluded for some other (unmentioned) reason, and he must want another fine tuning scheme. *I thought he was arguing that the universe was not finely tuned*. Very confusing.

If the number of states changes with time, that contradicts the usual way the state space model is used, in part by requiring a time parameter that has effects beyond those normally postulated (i.e. "outside the universe"). While clocks may be part of the universe, Carroll seems unwilling to allow their predictably repetitive ticking to reflect anything other than the internal state of the universe. Would clocks run at a different speed, or even backwards, in a universe that was evolving differently? (Speed? Maybe with general relativity, but only if you compare different locations or world lines. And that has nothing to do with entropy.) Why can't time at least have an inherent direction? Maybe this is an example of what he means by "temporal chauvinism". And why can't a fundamental change in a system, such as the size of the universe, cause its state space to change size? It is not clear to me why that is a revision of the laws of physics, and not just a revision of the state space model.

Irreversible Motions

If the number of states is fixed, then laws that do not conserve information could allow processes that cause entropy to decrease. He does not give a well-defined example of this. Fortunately, he doesn't find it likely. I have never understood this argument, although he has used something like it several times.

A Special Beginning

Now Carroll abandons the irreversible possibilities and assumes that the laws are reversible, the number of states is fixed, and information is conserved. Since we need to get a low entropy state somehow, the simplest possibility is that the universe started out that way. This works fine, but without a reason, it seems arbitrary. He admits that this could be the whole story, and no explanation may be found, even to indicate if it was a lucky fluke, one successful try among many failures, or a necessary result of unknowable reasons.

Throughout the book, Carroll is bothered by the improbability of randomly landing in a special (low entropy) state when a much greater number of (high entropy) states should all be equally likely. An anthropic argument is frequently used in physics to avoid unlikely things that might have "just happened", such as our universe. In that case, various multiverse schemes are proposed to avoid the improbability of our universe being like it is on the first try. By allowing lots of tries, of which only one need succeed, our chances to exist are much better. But he argues that the desire to avoid the anthropic argument can be a spur to seek a deeper explanation. In the case of inflation, the improbable flatness, uniformity, and absence of monopoles could have just happened, or happened once out of many tries, but worrying about it led to a single hypothesis that explains all three at once, and more besides. A natural and high probability explanation is preferable, so he keeps looking.

A Symmetric Universe

The universe could have started in a low entropy state, expanded, and might contract into another low entropy state. This would eliminate the temporal chauvinism of differences between the past and future. However, with the discovery of the acceleration of expansion of the universe, a collapse seems ruled out. There is no evidence for this model, and there are too many other problems to list.

Note 279 is interesting in comparing the reversal of time and the branching of the wave function. I've never understood the former, and the latter seems to violate the normal use of state space ideas (at least). I probably won't have time or expertise to check the references on this.

Before the Big Bang

Maybe the big bang was genuinely low entropy, but wasn't the beginning of time or the universe. This is plausible. Since our present theories predict a singularity at the big bang, we have no way of predicting anything before that. We still need a low entropy state to explain our observed early universe, so some specific possibilities follow.

An Arrow for All Time

If the universe existed before the big bang, it might have been essentially similar to ours, but contracting. At some minimum size, it might bounce and become the universe we now see. If entropy increased continuously, the problem of the original low entropy state is merely pushed farther into the past, with still lower entropy.

A Middle Hypothesis

If entropy decreased in the contraction phase, we need a reason why. To successfully reach a low entropy contracted state at the bounce, we either need irreversible laws before and reversible laws after the bounce, or a carefully chosen state (low entropy, even though it might *look* high entropy) when the contraction starts. Since we've discarded irreversibility, we still have to find a reason for some very improbable state at some time.

Baby Universes

If we are to avoid the need for some low entropy state in the whole universe, maybe we can find a way that total entropy can increase forever, while allowing new low entropy regions to develop. This is Carroll's preferred scenario (p. 368.). On p. 356, he introduces the distinction between <u>pocket universes</u> (previously discussed fluctuations of the *contents* of spacetime to lower entropy within a high entropy background), and <u>baby universes</u> (where a piece of *spacetime itself* somehow actually separates from the parent spacetime and undergoes inflation into a separate universe). Although it might not be immediately apparent, this is a radical difference.

The highest entropy, most probable state of a universe like ours seems to be a nearly empty, low vacuum energy de Sitter universe, containing only a dilute gas of Hawking radiation. On p. 356, Carroll states that de Sitter spaces (empty except for vacuum energy, VE) are low entropy if the vacuum energy is high (during inflation) and high entropy if the vacuum energy is low (a dying universe). But if the energy is non-zero, the temperature is also non-zero, and fluctuations can occur, both in the contents and possibly in space itself. If such a fluctuation in a low VE space becomes a separated high VE inflating bubble, we have a new low entropy region to grow into a new universe, with total entropy increasing in the process. The new universe starts as a low entropy, high VE, rapidly inflating de Sitter space (in addition to the original, but separate). It doesn't even have to be specially selected for low entropy if the possible mechanism to create the baby universes only creates rapidly inflating, high vacuum energy, low entropy bubbles. (The laws need to enforce this.) It inflates until the transition of inflation's VE into matter and energy, then becomes a normal expanding universe, and finally reaches "heat sleep" as a high entropy, low VE de Sitter space, which can eventually produce another baby universe to start it all again.

> I'm not sure how this keeps the number of states from increasing, if or why additional energy is not needed (p. 358), or even if we need to worry about those things. I'm not sure why the

newly inflating region needs to detach from the parent universe either (p. 356-7). However, it is its own separate mechanism, so if that's what it does, then it does.

This is similar to the previously rejected fluctuation of part of the universe into something that looks like us. That was rejected by the argument that it is most likely that the fluctuation would only include a small part of the observable universe, with the rest (potentially visible to us) looking very high entropy. The same argument about "why is the fluctuation big enough to include everything we see?" might apply here, but is countered if a baby universe is detached from the parent so that everything visible in it is all the same age and entropy.

We have provided a way for our low entropy condition to occur naturally, but we still need special laws to allow it to happen. The special laws needed here are that 1) fluctuation-creation of an inflaton field in a near-empty space with small positive vacuum energy is possible, 2) that it can create a detached low entropy inflating space that leads to a new full-sized new universe, and 3) (if needed for perpetual recurrence) that some of these universes keep their non-zero vacuum energy long enough to produce offspring. If there was a beginning to this series, the first universe might not need any matter at all, but only vacuum energy to get things started. At least these are laws that could always apply, rather than initial conditions only invoked for one purpose.

A Restless Multiverse

This section is mostly a continuation of the previous section's ideas, with some loose ends tied up. On p. 359-60, Carroll distinguishes between the behavior of entropy fluctuations previously considered and the new fluctuations leading to baby universes. The former can be arbitrarily small and lead to many more minimal universes that could be recognized by inconsistent entropy levels. The latter lead to separate universes that are entirely in the new low entropy state. This uniformity is presumably a result of the separation, but no explanation is given. Thus, even if the new universe is very small, it would not be possible to see outside it to the conditions of the parent universe. He assumes these universes must have positive vacuum energy. This is necessary to allow the process to continue forever as the parent universes continue to expand and reproduce. If the vacuum energy reaches zero, that particular universe can no longer reproduce.

The overall universe never reaches equilibrium, because it can always spawn baby universes and entropy can continue to increase forever (p. 359-60). But unbounded entropy means unbounded size of state space. Was it always unbounded, or is it now allowed to increase? He refers in various places to the need for a fixed state space, but does not explain this in the book.

On p. 362 (and earlier on p. 354 and elsewhere) Carroll more explicitly states the idea that the "arrow of time" depends specifically on the direction of entropy increase, that it could be a local condition, and could even point in opposite directions in different regions of the same spacetime. This seems only to serve to avoid having to distinguish the past and future directions of time flow.

He also seems to imply (or state somewhere that I couldn't find later?) that in empty space with exactly zero vacuum energy (Minkowski space, where entropy never changes?), there is no arrow of time at all. I'm not sure what that might mean, except possibly that time is a completely passive dimension with no inherent directedness at any point. Maybe the block time view allows this, but so far I'm still inclined to stick with my temporal chauvinism. He also states that low vacuum energy means high entropy. But if empty Minkowski space has zero vacuum energy and only one state, it should have zero entropy (log 1 = 0), giving a discontinuity. Maybe this is pushing entropy definitions too far.

On p. 363-4, Carroll points out that this model includes both pocket universes with Boltzmann brains and baby universes that are internally complete. We still have to worry why we see a complete separate universe instead of a partial embedded fragment, but he says that the relative likelihood of these cases may eventually be calculable. (Note that these are two different mechanisms. The pocket universes discussed in most of the book are localized regions of space where the matter fluctuated into a lower entropy configuration. The baby universes of this chapter are the result of quantum fluctuations which produce an inflaton field which causes a region of space to actually detach from the original space and start to inflate.)

Bringing it Home

He warned us that it would be speculative. We're not done yet. We don't know nearly enough about quantum gravity to evaluate these ideas, and we have not really tried to include relativistic quantum theory and wave function collapse in models of state space. The perpetual spawning of baby universes depends on vacuum energy never vanishing, which is not certain. In fact, the ability of spacetime to fluctuate structurally at all is hypothetical. I still don't understand why the number of states isn't allowed to increase as the size of the universe increases, and why baby universes don't do that in his preferred model.

Epilogue

The Epilogue begins with a still briefer summary of the main ideas of the book. Then, in **The Empirical Circle**, Carroll turns briefly to more philosophical matters: The empirical nature of science, fitting data versus explaining observations, the importance of the possibility for observation to falsify, or contradict a theory. He goes on to say that the multiverse concept is not a theory. It is a set of predictions or hypotheses that cannot presently be tested. Its value is as a framework in which to attempt to organize other facts and ideas in order to seek more unified understanding that may eventually consolidate into a testable theory. By being openly provisional, it is partly freed of some of the constraints that apply to more complete theories. Intuition, preferences, wild guesses are all allowed within limits until the framework is complete enough to test empirically.