The Second Law and Cosmology

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Abstract. I use cosmology examples to illustrate that the second law of thermodynamics is not old and tired, but alive and kicking, continuing to stimulate interesting research on really big puzzles. The question “Why is the entropy so low?” (despite the second law) suggests that our observable universe is merely a small and rather uniform patch in a vastly larger space stretched out by cosmological inflation. The question “Why is the entropy so high” (compared to the complexity required to describe many candidate "theories of everything") independently suggests that physical reality is much larger than the part we can observe.

[APPLAUSE] Thank you very much. It’s a pleasure to be here. I was asked by the organizers to speak of the second law and cosmology, and one’s gut reaction to such a title is: “Wait a minute – the second law of thermodynamics has nothing to do with cosmology!” When I first heard about the second law, I thought it had more to do with Murphy’s Law and the kind of physics that takes place in my kitchen, especially now with two young boys in the mornings. You know, eggs break and they don’t unbreak. And this local arrow of time that we perceive, what could that possibly have to do with the universe? Yet, as we’re going to see, it has everything to do with the universe. Indeed both Dick Bedeaux and Charles Bennett mentioned that a key to understanding our local arrow of time here is to understand why we started out in such an unusual low-entropy state. And understanding how we started out is of course the business of cosmology.

So a little bit more quantitatively, with one way of counting, what’s the entropy of our observable universe, this sphere in space from which light has had time to get here so far during the 13.7 billion years since the big bang? This entropy is in the ballpark of $10^{89}$ bits. So crudely speaking, a googol bits. My talk will have two parts. I’m going to talk about two questions:

1. Why is our entropy so low?
2. Why is our entropy so high?

By the first question, I will mean why is it that the $10^{89}$ bits is still much lower than thermal equilibrium or whatever that means? Much lower than the $10^{122}$ bits which is the Hawking and Bekenstein bound on how much entropy a volume of this size can have. The second question is why on Earth is this number still so much bigger than something like zero? Where did all this complexity come from?

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1 This is a verbatim transcript of a 10/4-2007 talk at the MIT Keenan Symposium, published in “Meeting the Entropy Challenge”, eds. G P Beretta, Ajmed F Ghoneim & G N Hatsopoulos, AIP, New York, 2008. A video of the talk, including slides and animations, is available at http://mitworld.mit.edu/video/513.
Let us begin with the first question, “why is our entropy so low?”, which is of course crucial to understanding our arrow of time. I first have to tell you what I mean by entropy. I’m going to stick with the microscopic definition. I will keep measuring it in bits, just like Charles Bennett did, which you can think of as using units where Boltzmann’s constant is equal to one. Towards the end I’m also going to take some liberties and use entropy rather loosely to refer to algorithmic information or algorithmic complexity. I’m going to take these liberties because, frankly, we have severe problems to even define entropy in cosmology, which you’re welcome to ask me about afterwards. And as John von Neumann once said, nobody knows what entropy really is, so in a debate, you’ll always have the advantage.

So with those caveats, why is the entropy so low in our solar system? And how did our solar system end up so far from thermal equilibrium? The whole reason we have life here on this planet, the driving force of thermodynamics behind the arrow of time here, is that we have this 6,000 Kelvin sunlight radiating onto our 300 Kelvin planet, which is in turn radiating back out into a 3 Kelvin universe. This is the number one driver of thermodynamic processes that are happening here. How could it end up this way? If you think about it, it’s really shocking. We’ve all learned that when the universe was much younger, the temperature was almost exactly the same everywhere. We started out 400,000 years after our big bang in a situation where the density was almost perfectly uniform throughout our observable universe, and the temperature was almost exactly the same everywhere to within a part in $10^5$. This was the subject of last year’s Nobel Prize in physics to Mather and Smoot. So how could you take something with almost the same temperature everywhere and then make something really hot here and something else really cold? How did that happen?

Well, take a look at this animation. We have classical physics a la Boltzmann where you have a bunch of atoms, which are starting out clumpy and end up in a more uniform situation. This is the usual way in which we think of the second law of thermodynamics, taking something clumpy and making it more uniform. Well, in cosmology, it tends to be almost exactly the opposite. And the reason is gravity. This happens when there is no gravity, whereas when we have gravity, if we just remind ourselves of what Dick Bedeaux told us, when we look at this usual Boltzmann factor $e^{-H/kT}$, the Hamiltonian here will contain a potential energy term from gravity here in the exponent, which can go negative. And it can go arbitrarily negative in classical gravity: if I take two particles and put them arbitrarily close to each other, I can get an almost infinite negative energy. And what that does is it gives you an intrinsic instability, a thermodynamic instability. And as a result, as I’m going to show you now, what actually has happened in our universe is that it’s gone from being almost uniform to being very, very clumpy. Let me make this a little bit more visual by showing you a supercomputer simulation from Ben Moore and his group in Zurich.

What we have here is an enormously large cube, many hundreds of millions of light years on the side, filled with almost uniform matter, and all they put into this supercomputer is the laws of gravity. We run this forward and you see a nearly uniform distribution gets more and more clumpy. An intuitive physical way of thinking about why this is happening is that if you started with something perfectly symmetric and uniform, of course by symmetry it would have to stay that way. But if you have a clump
Here with a little more stuff than in its surroundings, then that clump will gravitationally attract more stuff from its environment and become a bigger clump, which in turn gets still better at stealing stuff from its environment. The clump gets bigger and bigger and before you know it, these tiny over-densities at the level of $10^{-5}$ have grown into galaxies, stars, planets, etc. Basically the rich get richer. That’s what gravity is doing here.

So let us zoom in on one of these clumps, which is about the size of the dark matter halo that our Milky Way galaxy lives in, and see more examples of the second law in action in cosmology. This is a supercomputer simulation now by Mattias Steinmetz and his group in Potsdam, Germany, where they have also put in besides gravity, basic gas physics. What you see on the left is a top view of this same thing that you see from the right, from the side view here, which is gas gradually getting denser and denser and forming stars, and things are getting messier and messier. Except, again, compared to the way we usually think of entropy increasing in a gas, getting more uniform, this is not getting more uniform. It’s getting more and more clumpy and complicated. And if you let this go for a billion years or so, you end up with something which looks quite a lot like the Milky Way galaxy that’s our home.

If we zoom still closer to home now into the environment of just one of these little specs of light here, just one star, we can see again the second law. We have a gas cloud. It contracts because of gravity. It dissipates and radiates away much of its energy and settles into a disk, and the contraction and clumping continues in the center of this until the gas gets so dense that nuclear fusion ignites in the core of this clump and a star is born. And all the while, further clumping has been taking place in the outer parts of this disk, and once the nascent star blows away the the residual gas, you see these clumps that are formed here: planets.

We started out wondering why the entropy is so low here in our solar system: why we have very different temperatures of different celestial bodies that let us have life here, and so on. The good news is that astrophysicists have made a lot of progress on that, as these computer simulations illustrate, because there’s no magic that’s been put in here — we just put in Einstein’s theory of gravity and basic gas physics, and end up with what looks like the universe we observe.

However, deep questions remain. Why then was it that things were so uniform in the beginning? Because as I just told you, that in fact corresponds to very low entropy in cosmology. Why was it that the gas that filled our observable universe was about as uniform as the gas in this room? The air has fluctuations at the $10^{-5}$ level because of the sound waves caused by my speaking about this loud. Why was it so uniform back then? And besides, why is it all so big? Why is space expanding? There’s a host of questions which have really haunted us for a long time. And then our colleague Alan Guth here at MIT came up with a completely crazy sounding answer for this called inflation, which has caught on like wildfire and is now strongly supported by observation. His answer to why the universe started out so uniform is that it didn’t. Instead he said that if you just have one tiny region of space, much, much smaller than an atom, which for whatever reason is very, very uniform and also very, very dense, then this process of inflation can take hold and expand space, as Einstein and Friedman long ago showed us that space is allowed to do, and expand space exponentially, so it keeps doubling its size over and over and over again, perhaps every $10^{-32}$ seconds or so, until this subatomic region of
space has become so huge that you’ve made all the space in the part of the universe that we can see and more. And it makes it all uniform. So in this picture, you could start out with something which is a total mess, maybe close to some sort of thermodynamic equilibrium in some vague sense, but a little piece of it could stretch out and become so uniform. And since it fills everything we can see, we get fooled into thinking that everything was uniform just because we hubristically like to think that everything we can see is all there is.

This is a very, very crazy sounding idea, so why should you believe a word of it? I want to remind you that all of cosmology was viewed with extreme suspicion throughout the sixties and seventies. It was considered a very flaky subject, somewhere on the borderline between metaphysics and philosophy. And yet Science Magazine wrote this article in 2003, saying that the number one breakthrough of the year is that we can now actually start to believe what these cosmologists are saying. And why did they write that? They wrote that because there’s data. Like Bob Silbey mentioned, we’ve enjoyed a revolution in measurement, in our ability to quantify things out there in space. And just to give you one example of this, I’ve already spoken a bit about three-dimensional galaxy maps. Another one is these baby pictures of the universe that George Smoot and John Mather got the Nobel Prize for last year. Don’t worry about what these axes mean. What’s important is that the black crosses here are measurements with one sigma error bars and that the red curve is a theoretical prediction from inflation. This is very, very far from back in the sixties when you could speculate about anything because there was no data to prove you wrong. This is a really impressive quantitative fit. And it’s because of this kind of measurement that more and more people are beginning to think that Alan Guth also is going to get a free trip to Stockholm at some point. Because this theory is looking very believable.

So we’ve spoken at some length now about why our entropy is so low. In other words, why at least the part of space that we are in is so far from thermal equilibrium. And let me spend my remaining five minutes just very, very briefly saying a few words about why the entropy is so high. It is a huge number, $10^{89}$ bits. Now who ordered that? Here at MIT a lot of people like to walk around with T-shirts with fundamental equations on them. And my colleagues in theoretical physics have their Holy Grail hope that one day they will discover not just some equations, but the equations, for the theory of everything. They are going to give a complete description of our universe. And what they’re particularly hoping is that they’re going to be elegant enough that they’ll even fit on a T-shirt, right? This may be a vain hope. But suppose it’s true for a moment. Let’s just entertain that thought and see where it leads us. Then how much of this information really needs to go on a T-shirt? Does a T-shirt have to have an equation which has the number eight in it that says that we have eight planets? No way. Because we know that there are many other solar systems with three planets, two planets, zero planets and so on, so the number eight is just telling us something about where we happen to live, right?

Would that T-shirt have to specify all the initial conditions for our observable universe? No. It wouldn’t, because inflation predicts that space is not only big, but actually infinite. So if you go sufficiently far away, by the kind of ergodicity arguments that we heard about earlier this morning, all kinds of initial conditions will be realized somewhere else. So those initial conditions, which made up the bulk of those $10^{89}$ bits, are just telling us where in space we live. Those $10^{89}$ bits are just telling us our address.
in space. So they should not go on a T-shirt, because the T-shirt describes the whole space, the whole theory, right? And in the previous beautiful talk by Charles Bennett on quantum physics, suppose you take a quantum random number generator like your Stern-Gerlach apparatus and you start to produce a whole bunch of quantum-generated random numbers, should these numbers go on a T-shirt as something fundamental about the universe? Well, if you give Charles Bennett a sufficient amount of beer, he will confess to you that he believes that quantum physics is unitary and that likewise, all this, all these bits are also just telling us where we are in this big quantum Hilbert space where all of these different outcomes happen.

What should go on the T-shirt then? This is from a recent paper I wrote with my colleague Frank Wilczek here and Martin Rees and Anthony Aguirre: you might want to put the 32-dimensionless constants of nature, which we need to calculate everything from the masses of the elementary particles to the strengths of the interactions and so on. That might seem like a good thing to put there. We don’t know yet where these come from. They really tell us something about our universe. Or maybe we put some equations, including the standard model Lagrangian. I have a feeling this T-shirt wouldn’t be very viable financially. But maybe one of you will come up with some more elegant equations of string theory or whatnot, of which this is just a special case. But even here there is a bit of a surprise that’s come out of string theory recently, which is that it may well be that in this infinite space even the values of these constants may not be completely constant throughout all of space. They may just be constant in a big patch that inflation has made. And they may have other values somewhere else, in which case even some of this information is also just telling us where we live. The key point I’m making is that most of the information that we thought described something fundamental about the universe may turn out to be merely our address, akin to our cosmic phone number.

So if you ask yourself the question “is all we observe really all there is”, I would argue that our high entropy, the fact that $10^{89}$ its is such a big number suggests “no, there’s probably more than we can see”. Or putting if differently, if what we can observe here requires much more bits to describe than a complete mathematical description of the world to put on a T-shirt, then we’re in some kind of multiverse or basically some much larger reality than what we can observe.

To summarize, I think that not only does the second law of thermodynamics have a lot to do with cosmology, but it gives some really intriguing hints about future research to pursue. Why is entropy so low? Probably because inflation happened. Why is it so high? I’m guessing it’s because we’re in some sort of multiverse. Do we know this? Absolutely not. But my key point is these are very active research questions. And if you feel it sounds too crazy, I think especially for the biologists in the room, we have to give credit to Charles Darwin here. He told us that we evolved intuition as humans for things which had survival value to our ancestors, like classical physics, the parabolic orbits of a flying rock being hurled at you. That’s the kind of stuff we’d expect to have intuition for, nothing else. So it’s no surprise then that when we looked at very small things in the quantum world, it seemed counterintuitive, when we looked at very big things, very fast things, black holes, time-dilation, it seemed counterintuitive. And I think if we categorically reject ideas and science just because it feels crazy, we’ll probably reject whatever the correct theory is too.

Finally, I would like to come back to the anthropic principle which was mentioned by
Charles Bennett here. Now the ultimate form of this, the most extreme culinary form of it, would be that, you know, the universe has to be such that we like it. And the great physicist Richard Feynman had something very interesting to say about this, which I would like to end by showing you in this video clip.

Feynman: Then there’s the kind of saying that you don’t understand meaning “I don’t believe it”. It’s too crazy. It’s the kind of thing I’m just, I’m not going to accept. [...] If you want to know the way nature works, we looked at it carefully, looked at it — see, that’s the way it looks. If you don’t like it, go somewhere else! To another universe where the rules are simpler, philosophically more pleasing, more psychologically easy

So let’s conclude with something which I’m sure we all agree on. I think we all agree that despite its old age, the second law is not old and tired. Rather, it’s alive and kicking. And I hope these cosmology examples have helped illustrate that the second law of thermodynamics is continuing to stimulate really interesting research on really, really big puzzles. Thank you!

DISCUSSION

GIAN PAOLO BERETTA (1): OK, well, I was trying to make sense of the connection between the previous talk and your talk and I have a question for you. Because in the previous talk I was told that the prevailing view is that since the entropy, overall entropy of the universe, if we include everything, should be zero. It should be in a pure state. And yet here you say that it’s 10 to the 89. I don’t know how you measure it, but I believe you. So my question is, does it mean, you seem to suggest that the resolution is that you’re not counting, you’re missing something in your accounting which would be correlated with what appears to be the universe so that the overall entropy is zero. So there is something else, some other place to go. But suppose there wasn’t another place to go. And suppose that your single bits, each one of them had a little entropy in itself. Would that be compatible with your theories?

TEGMARK (1): That’s a very good question. Let me make a couple of remarks on it. First of all, is the entropy of the universe zero? If you think of the universe as a classical quantum system in a pure state, you might say by definition it’s zero. But we must remember that we don’t have that theory of quantum gravity right now, which is what we would obviously need to describe general relativity in a quantum way. And it’s even more embarrassing because as I’ve alluded to, there are two different instabilities in the theory of gravity, which make it really hard to define entropy. One is this thermodynamic instability that makes things cluster and creates black holes. And the other one, which is even more severe, is the one which underlies inflation. But you can take a finite amount of space and make just much space ad infinitum. And what happens when you try to define in a rigorous way then the entropy of this system it gets infinitely many degrees of freedom and it just keeps making more degrees of freedom and more space. And I think it’s fair to say that this is an example of how the second law of thermodynamics is leading to questions which the leading experts of the world still argue viciously about. How do you even define something like the entropy of the universe? And I think we
really haven’t heard the last word on this. There are business issues like the holographic bound in relation to the Hawking Bekenstein bound, for instance, where we really need to understand what it even means.

JIM KECK (6): Sorry to monopolize the microphone, but I have to ask, what formula or what body of data was used to compute the numbers you put on the screen? You’ve talked about the entropy. But you did not give us a definition.

TEGMARK (2): So the top number here, the $10^{122}$, the Hawking-Bekenstein bound, is simply the area of this sphere measured in Planck units. And this is what it comes out to be when you plug in the actual radius of this volume that we can observe. And that should, of course that just [UNINTELLIGIBLE] to this volume. If by universe you mean the entire infinite space you would then get an infinite number here.

KECK (7): Well, one thing that bothers me is you’ve only shown us half the problem. You’ve shown us what happens in configuration space and not what happens in momentum space. And the entropy depends on both. And I’m a little concerned. I don’t see where $r_0 \log r_0$ has gotten into the picture.

TEGMARK (3): OK. Well, the main thing I wanted you to really take away from everything I’ve said is, I have not tried to give you, to tell you here is the answer to all the questions. I’ve rather tried to emphasize that the second law is posing new and interesting problems. Effectively what I think we’ve succeeded in doing in cosmology is we’ve taken the frontier of our ignorance and we’ve pushed it backwards in time. Because a hundred years ago, we had no clue what it was that was even causing the sun to shine. We hadn’t discovered nuclear reactions. Right? We had no clue how the solar system got here. And it was taken just as some kind of magic initial conditions, right? Now I’ve showed you some really realistic computers simulations of how you can make a solar system and a star and all of that, which to Boltzmann was initial conditions from some other initial conditions you have to put in earlier. But I did not tell you why we started out with this uniform expanding stuff, because we still don’t know.

THEO NIEUWENHUIZEN (4): I would also like to come up to this point of extend to the 122 bits. There was some recent idea put forward by people called [Motola and Mazur?], who see a big black hole as some quantum thing, whatever that may mean. But in any case, it would not have this entropy, so in short let me formulate the question as follows. Let us suppose that Mr. Bekenstein and Hawking, that their prediction has nothing to do with nature, then how would this change the talk that you have given now?

TEGMARK (4): Not much. The key point about inflation is, you know, we have a theory which, you don’t need to, let me take a step back. What is it that we have assumed to get these predictions which Science magazine felt meant we should start taking the field seriously as a quantitative physics field rather than just some flaky speculation. OK. What was it that was assumed in this kind of calculations? Only two things, general relativity. And you don’t even have to assume that you know how it works with strong gravity like black holes. You only have to assume general relativity and limit the weak gravitational fields. That’s the first assumption. And the second assumption you have to make is that you know how to do basic thermodynamics with gases. So you have to understand how hydrogen works at 3,000 Kelvin and so on. So you just put in those two
assumptions. Then if you start out with a hot expanding bunch of gas you will make all these things that we can measure in great detail. So that I think is a striking empirical success, regardless of what it all means. But I do not want in any way downplay the theme you’re mentioning here, which is that there are big mysteries remaining.

And I said inflation, for example, is a very popular theory for explaining what put the bang into the big bang and what made things expand, but you’ll be amused to know that there’s still absolutely no agreement on how inflation started. There’s an annoying theorem says that inflation must have started. It couldn’t have gone forever to the past. And that’s just another example then of how we can push [UNINTELLIGIBLE] back in time, but we’re still stuck.

And it reminds me also of the first talk when we heard about many efforts to prove the second law, right, and we kept saying OK, we can prove it from something else, but then how do you prove that?

GEORGE HATSOPOULOS (4): Well, first of all, let me thank you for that beautiful presentation, because at the beginning when we conceived the idea of having this symposium on thermodynamics, our whole purpose was to stimulate people to, especially young people that come to MIT that thermodynamics is not an old topic. It’s not closed. There’s a lot to be done and I think that you have managed to indicate whoever is here or whoever reads the record of this symposium that there’s a lot more work to be done. That was our purpose. So I’d like to thank you for that.

TEGMARK (5): Thank you.

HATSOPOULOS (5): Second, I want to point out something pertaining to the previous lecture, Mr. Bennett. I think I fully understood what he was talking about, but namely that if it is possible that if the universe started at zero entropy and split up in various parts that were correlated with each other and we lived in one part, we could observe really entropy in that part or the effects of entropy even though the whole got started at zero entropy and continued as a whole to [being?] zero entropy. OK. I understand his point.

Nevertheless, what I don’t understand is do we have any evidence that, any evidence at all why do we have any evidence that the universe started at zero entropy or was in a pure state?

TEGMARK (6): To me, the most hopeful route to addressing that very important question is look for a theory of quantum gravity. And I think it’s very important that we’re modest here today. Because yes, we humans have managed to figure a lot of stuff out. Yes, we have a very successful theory of general relativity that can deal with all the big stuff and quantum theory that can deal with all the small stuff. But we don’t have a single self-consistent mathematical theory that unifies them, right? And until we have that, I really don’t think we with any confidence can claim to know the answer to this sort of question. We’d like to know what kind of mathematical object is it that’s evolving and I would like to encourage anyone in this room who is interested in those questions to not just shy away from that as being some kind of boring old hat question, but as being something which we really have a pressing need for.

BJARNE ANDRESEN (1): I have two questions for you. One was the one that he asked
a little while ago. And if you had extended that time evolution picture or film that you
have of the universe, how many lumps would the second law permit you to end up with?

TEGMARK (7): So if we keep going forward in time I can actually show you what
happens.

ANDRESEN (2): Oh, great. So you’re a sorcerer. You can predict the future.

TEGMARK (8): And I hope I won’t make you too depressed by showing you this.
Because. Here we are, our solar system in red orbiting around the center of our Milky
Way galaxy every few hundred million years. This is now how far we are in the future,
about a billion years. And we’re not alone of course. Here’s another clump, our nearest
neighbor, a big clump, the Andromeda galaxy. You can see it’s not falling straight
towards us because there’s a lot of other matter here in the vicinity pulling on it.
However, now something rather bad is going to happen and you will soon get one
clump less, smack. About 3.5 billion years from now our solar system is in a much more
precarious orbit around this monster black hole in our galactic center, and out comes the
big whammo here, about 5 billion years from now. And soon we’re going to get a giant
corporate merger here and even the two black holes are likely to merge with each other.
And we are in a very funky orbit around now [Milcomada?] or whatever they decide to
name this. We will keep merging all these things nearby into one giant galaxy, whereas
all the other more distant galaxies will keep flying away if our current understanding
of dark energy is correct, until all we can see in the sky is just empty space, no other
galaxies within our [ent?] horizon, except this one big merged blob. But I suggest you
not get too worried about this because I still think that the main challenges we have to
meet in the short term are caused by humans.

ANDRESEN (3): OK, so just one lump got left. Yeah, the other question is how much
entropy is stored in that overwhelming part of the universe that got squeezed away in
this rabid inflation? There was one point, tiny point that expanded and almost filled the
entire thing, but before that there must have been a lot of entropy stored in what got
pushed aside. How much?

TEGMARK (9): Yeah, so this is actually an interesting, one argument that you might
heuristically for why the total entropy should be near zero, because if everything we see
once came from a region which was a little bigger than a Planck region, you might say
there’s no way there could be more than a few bits of information there by the Hawking-
Bekenstein bound. And then insofar as it’s isolated, just like causality, it should stay
being basically zero.

ANDRESEN (4): But what about the [rest?] outside part that did not come from that
tiny spot?

TEGMARK (10): Well, it’s still out there, doing its own thing. And if you take inflation
seriously what it predicts is that this inflation process just goes on forever and then in
some places in space it stops and you get a more leisurely expansion and you make
galaxies and stars like us. So if that’s true, we should first of all be a little more careful
and not hubristically say our, say the universe when we talk about this sphere. But that
should be called just our local observable universe. And second, we shouldn’t say that
the big bang is the beginning, because we should rather call it the end of inflation in this
part of space. That’s what we’ve traditionally called the big bang, the time when all of
the stuff we see here was very hot and dense. And it ended here, but it keeps going in
other places. So if we could zoom out, in other words on our universe, and look at the
bigger picture, you should expect to see much more stuff there and much more entropy.

ANDREW FOLEY (1): I have a quick question. Isn’t the problem with the second
law that we’re discussing today really just how you define it? One man defines the gas
expanding as an increase in entropy, because he sees the energy lost from the expansion.
In the next breath you say oh, it collapses with gravity. Well, another person would see
that as potential energy being recouped and hence entropy is this reversal process, and
it’s all in the definition. The other problem I would argue is where we’re very loose
with the definition. We’re confusing our data transfer as entropy, and that’s not the same
thing. And we’re kind of, we’re making problems where none exist really. And as for
the level of entropy at the beginning of the universe, really that depends again on a
personal definition. How much of that expansion could we actually capitalize as work?
And again, that’s depending on how you could extract the energy.

TEGMARK (11): I agree with those points. If you take in classical physics the proba-
bility distribution phase space and you look at it coarse-grained, and to proved that it’s
entropy will increase, you have to make these assumptions that we heard about earlier
this morning about some uncorrelated phases or some such. And like wise if you take
the density matrix of the whole universe and then partial trace out all the degrees of
[freedom?] except the [single?] subsystem, you’ll typically see entropy increased where
we are if again you make some assumptions about the initial conditions, maybe lack of
entanglement, low initial entropy. Right? But it still leaves that question dangling. Why
those initial conditions and not some other initial conditions. And if we think that the
most generic initial conditions are thermo equilibrium, then we’re stuck again. So I still
think no matter how hard we work on these kind of beautiful mathematical theorems,
we still have to answer this question of why we started out with so low entropy in this
part of space.