# Appendix: the anthropic principle

*Notes from Prof. Susskind video lectures publicly available on YouTube*

In view of the wide interest for it, I would like to say a few words about the anthropic principle. To make sure that I answer your specific questions, let's treat it as a questions / answers session.

Q.: What is exactly the anthropic principle?

A.: Can I give a crisp answer to that question? No, because the anthropic principle means many things to many people. But I can explain what is, in my view, a rational use of it.

I won't claim that my explanation is right, but I'll say that in some circumstances it can give a rational explanation of some of the puzzling things we observe in the universe.

First we have to understand what *fine-tuning* means. There is a small number of instances in physics. The classic case of an extreme fine-tuning is of course the *cosmological constant*[1]. The cosmological constant is very small. In natural units, that is in Planck's units, it is 123 decimal places small.

What is the difference between being small and being fine-tuned? They sound like the same thing but they are not the same thing.

I'll give you an example that I cooked up to explain this once to a bunch of condensed matter physicists who didn't know what fine-tuning was. As soon as I talked about it, they said: "oh we know that." But in truth they didn't

[1]The cosmological constant is extensively described, explained and used in volume 5 of the collection *The Theoretical Minimum* on cosmology.

make the difference with just being small.

It is a silly example. And it is the only example I ever made up like this. It doesn't have fish in it, but it does have submarines and also balloons.

Let's suppose that you are a certain kind of creature that can only exist at a certain altitude where the air was just at the right temperature – well, not only the right temperature, but the right temperature, the right density and so forth.

So you find yourself at that temperature and density and so forth. You are in a blimp floating in the atmosphere, figure 19.

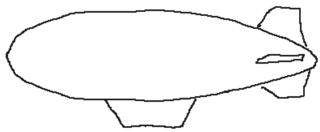

Figure 19: Blimp floating in the atmosphere, with creatures in the nacelle.

And you notice that you are neither rising nor falling. Isn't that lucky?

You are at some stationary height. And at that stationary height you have been there for several billion years, long enough to have evolved and evolved in just the right way to live at that temperature and that density.

Isn't it very lucky that this blimp happens to be exceptionally light so that it floats? Yes, you may say, you are lucky. The blimp happens to be light enough that it floats with you in it.

And *there is a small number involved.* It is the density of the material inside the blimp. In this case it is not horrendously small, but it is small. It might be the density of hydrogen. Or it might be the density of helium.

Notice, though, that the mass of helium and the mass of hydrogen differ by a factor of 4. So the density can vary over a wide range. Still, you float somewhere. Your helium will support you. Or your hydrogen will support you. So you are ok.

Indeed, since the density of the air varies, you will find an equilibrium at some altitude. And you will just hover at that altitude of equilibrium forever. That is, you will stay there long enough to evolve your species and adapt it to the conditions.

That is an example of a small number. The small number in this case being that by luck your system happens to have a *low density* – just low enough that you float in your blimp.

*There is a small number, but there is no fine-tuning.*

It didn't matter if it was helium or hydrogen. And it would not matter if it was a mixture of helium and hydrogen. You could change the parameters of the gas quite a lot, by several hundred percent, as long as it stays lighter than air.

So, if there is luck, it is that the density of the blimp is a small number. But there was no exceptional fine-tuning of anything. You didn't have to fine-tune in any detail the percentage of hydrogen and helium.

So that is the case when there is a small number.

Now let's talk about another situation. The object in fig. 20 is not a blimp, it is a submarine, a yellow submarine.

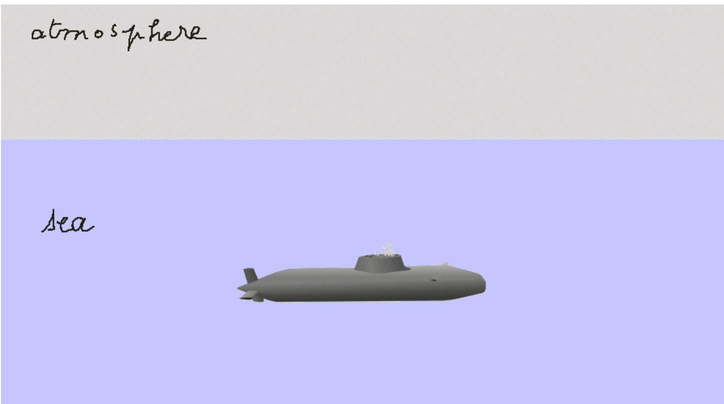


Figure 20: Submarine floating in the sea, with creatures inside.

We all live in a yellow submarine. The submarine has no motor, it just floats somewhere at an intermediate depth.

If the submarine approached the sea bottom or the sea level, we would die. Down at the bottom the submarine would be crushed by the pressure. And near the sea level, we could not survive either, for the water is too acid there or there are harmful radiations or whatever. For us to live, the submarine has to float in between. Maybe it doesn't matter exactly how high we are. But we have got to be neither near the top nor the bottom.

Our submarine has existed in that configuration long enough for us to evolve. In other words, for billions of years it has been hovering in the water without falling nor rising.

We know that because we are here. Or these people who live in the submarine are here. And they know that, if there was any significant tendency to fall, they would be dead. If there was any tendency to rise, they would be dead.

Let's also assume for simplicity that the water has the same density from the bottom of the sea to the top of the sea, which is approximately true in reality.

What do these people in the yellow submarine conclude?

They conclude that whatever the submarine is made out of, the density of that submarine is *finely tuned.* It is made out of some iron, together with some brass, maybe a little bit of concrete and a few other things. Plus it is hollow in the interior. And all that – with us inside – is such that its average density is very very close to that of water.

If it was any denser than water it would sink. If it was any lighter than water it would rise. And, what is more, it has been sitting there at that compromise position for billions of years.

From that you can conclude that, whatever the chemical composition is, it is very finely tuned. If you were to change the ratio of iron to concrete by one part in a thousand or even one part in a million, you would be dead.

Remember this submarine has been sitting there for a long time. Let's say 4 billion years, or 13 billion years. For 13 billion years, it has been right somewhere in the middle of the vertical zone.

That is extraordinary! It is extraordinary because, unlike in the case of the blimp in the atmosphere, there is *no feedback mechanism* whereby if it started to sink something would tend to make it rise, and conversely.

If it was just a little bit too heavy it would slowly sink to the bottom. If it was a little too light it would slowly rise.

And so somebody very fortunately has tuned the chemical composition, and the amount of hollowing out, and the weight of everything inside it, to one part in a fairly large number, to make sure that the submarine hovers.

Now the submariners are curious about it. They want to know why is this true. They have no explanation for it at all. Their first reaction is: this must be something like the whatchamacallit, the dirigeable, the Zeppelin, the blimp. It the blimp goes too high, the air density goes down and the blimp sinks back. When it goes too low, the air density increases and the blimp rises up again.

But the mariners do a few calculations, and there is no question of feed-back mechanism. The density of water is too constant over the range from the bottom to the top. There is no possibility to use that to explain the stability of the depth of the submarine. They try all kinds of mathematical tricks, symmetry principle, whatever they have, to explain their still being here alive.

Nothing works. And the reason nothing works is because this is one of these very fine-tuned things. If you change the chemical composition a tiny bit this way or a tiny bit that way, the whole thing breaks down.

What kind of conclusion could they come to?

They do a little more calculations using whatever laws they know. And they discover something very interesting about the nature of the fluid that they are in. It has instability: it makes bubbles. And the form of these bubbles is submarines.

At various places and times in the fluid, "pop", bubbles "nucleate", i.e. appear. And when they appear, they morph into submarines.

But the trouble is the submarines which they can nucleate into are generally not of the right kind. In fact, as it turns out, the submarines can nucleate with different chemical compositions. Some of them have a little more brass. Some have a little more iron. They can be more or less hollowed out. And so there is just a whole huge variety of different species of submarines which nucleate.

The mariners figure that out. They make these calculations. And they discover that it is a property of the fluid they live in.

So they find this answer: there must be zillions of different kinds of submarines, a huge number of them. And, moreover, they keep nucleating and nucleating and nucleating in this fluid. So the fluid just keeps producing more and more and more of them, of every conceivable type, 10% iron and 90% brass, 20% iron and 80% brass, and all other possible compositions.

Most of them either sink to the bottom and lie crushed on the sea floor, or they rise to the top and rot at the surface. You may even add, if you like, the feature that the creatures inside, despite their remarkable adaptive capabilities, don't have time to adapt to the extreme environments of the bottom or the top.

But a tiny fraction of the bubbles will nucleate with the right properties, just because everything that could happen will happen.

And so they are not particularly lucky[2]. They just are in a submarine which nucleated with exactly the right density to hover.

[2]To talk about luck or not luck in this setting is a matter of point of view. If we ask a zillion people to flip a coin a thousand times, most of them will produce approximately half heads and half tails, but some will turn 1000 heads. We won't be particularly lucky to witness that. But the ones who produced such a series by definition will.

If all of that really happens, and these mariners really have a genuine scientific reason to believe in submarine nucleation in their sea, and they could see that the bubbles could nucleate in a vast variety of different types of submarines, they would have what – I would say – is a reasonable explanation of what is going on: there is a lot of stuff; the sea is very big; a long time has passed; every conceivable kind of things have nucleated many many times; they are just in a kind where survival is possible.

That is the logic that, I think, the anthropic principle, when it is rational, is making use of. That fine-tuning is a consequence of many many possibilities and many actual events taking place creating the submarine that we live in. Some fraction of them will be liveable. And we happen to be in one of them.

Then it becomes a non-mystery why we live in a fine-tuned universe. That is a logic that I find personally acceptable.

There are alternative possible answers. Another answer is that some intelligence designed the submarine with exactly the right properties. There are some people who like to believe that. Most of my scientific friends don't take that as an acceptable solution.

Are there other explanations? At this time[3], within our current framework of thinking, there aren't any other possible answers to why certain things are fine-tuned.

[3] Course taught in 2013.

What is it in our universe that is playing the role of the density of the submarine in the funny little illustration? It is the cosmological constant.

If the cosmological constant is slightly negative, the universe will recollapse, see volume 5 in the collection *The Theoretical Minimum* on cosmology. However, if the negative cosmological constant is really very small, that is like the density of the submarine being only a tiny bit higher than that of the water. Then the universe will take a long time to recollapse in a very similar way that it would take a long time for the submarine to fall to the bottom of the sea if the difference between water density and submarine density was very small.

So if the cosmological constant, assuming it is negative, is small enough, the universe will last long enough without recollapsing for us to be here and survive and so forth.

Then we have the case that the cosmological constant could be positive. In that case the universe doesn't crunch, but expands. And it expands in an exponential way.

But if it expands too fast, then it prevents structures from forming. If the universe was accelerating very rapidly, then the material in it would be carried along with the acceleration and would simply be incapable of contracting to galaxies and stars and so forth.

So there is some window analogous to the window of submarine density inside which the submarine could last for billions of years.

The cosmological constant is like the parameter density of the water minus density of the submarine. And if it is small enough in absolute value, the universe can recollapse, or expand, sufficiently slowly that in either case we can be here.

The window of possible values of the cosmological constant allowing us to exist is extremely small. It is extremely small because the time scale is so long. It is the same reason the window is very small for the submarine. To become what we are, we have to be able to survive for eons. That implies that the possible imbalance in the cosmological constant, i.e. its difference from zero measured in natural units, has to be unbelievably tiny.

Now there is another sense in which the cosmological constant is like the density of the submarine. The density of the submarine is made up out of a composite of densities of several materials in various proportions. It is not just that some odd number happens to be small. It is a compound of numbers that are very finely adjusted.

The same is true of the cosmological constant in quantum field theory. It gets contributions from many many different sources. Basically it gets a contribution from every quantum field that exists. Bosons give positive. Fermions give negative. Shift a little bit the mass of the particles that are associated with these quantum fields, and the cosmological constant that results from them shifts a little bit.

So the whole thing, all of the constants, all of the particles, all of the contributions, making up the cosmological constant have to balance very finely, exactly the same way the densities making up the submarine have to balance. If there is a little too much iron, we sink and are crushed. If there is a little too much brass, we go belly up. Same thing with the cosmological constant: put in a extra fermion species in the theory and the cosmological constant gets too negative and the universe implodes; put an extra boson, the cosmological constant gets too big and we are out of luck in a tiny fraction of a second.

Q.: What is the meaning of "making a change that compensates"? Is it just a different submarine, but still floating?

A.: Yes, you could change some of your parameters in physics, such as various masses, coupling constants, and so forth; you could change one thing one way a little bit, which might increase the cosmological constant, and change something else another way a little bit, which might decrease the cosmological constant. And you might be able to keep its value the same.

It is not that there is just only one chemical composition of the submarine that can survive. There is a thin surface[4] in some space of different configurations.

It is the same thing in our universe. You can change things. But you have to change them in a very very fine-tuned way. You change one thing by this amount, you ought to change

[4] In a space with $n$ variables $x_1,\ x_2,\ \ldots\ \ x_n$, the constraint $f(x_1,\ x_2, \ldots, x_n) = 0$ defines a surface. And if we relax the condition into $|f| < \epsilon$, that is like the constraint on the submarine density for it to float in mid-depth, or on the cosmological constant for our universe to be habitable.

this other thing by that amount. And it has to be adjusted to 123 decimal places!

Q.: So will this sea water, that produces every kind of submarine, make various submarines that have the same suitable density, but look different than the one represented in figure 20? So these correspond to alternate universes?

A.: Well, they are *all* alternate universes. But some of them are capable of sustaining themselves for long enough time, and have people. Others are not.

The fact is, we know very little about this. Our knowledge of the space of possibilites is extremely limited.

String theory seems to say that there are endless huge numbers of possibilities, analogous to every possible chemical compositions. So that is a plus.

I don't know whether you regard that as a plus for string theory, or a plus for the anthropic principle, or a plus for cosmology. But string theory does seem to fit together with the idea of the anthropic principle.

And the fact is that there is no other known explanation. For many years now people have been looking for explanations, without turning up anything convincing.

There is one more thing to stress about the submarine. The submariners, as I said, might look for a mathematical explanation, some symmetry in the equations which would make the submarine density exactly equal to the surrounding water's.

They have this theory called "rope theory" or something. They can't quite prove it, but they sense, if they only had the right idea, that rope theory would say that the submarines always come out with exactly the right density. Some symmetry keeps water and submarine at the same density.

We feel that it is within reach. We don't quite understand it. But we know that if we understood that theory better, it would tell us why the cosmological constant, or the density of submarines, has exactly the right value.

But then, to their horror and dismay, the submariners discover that their own submarine density doesn't exactly have the right value. In fact their submarine is slowly sinking. It really is slowly sinking. How long does it take for it to sink? More than 10 billion years.

Their finest measurements tell them: nope, it is not that things are perfectly adjusted. So we don't have to explain why they are perfectly adjusted, because they are not.

They are only adjusted to 123 decimal places. And at the 124-th decimal place, they are sinking.

Q.: Isn't this precision violating the uncertainty principle?

A.: No. Any measurement taken alone can be as precise as we want.

Q.: You say this is a use of the anthropic principle, to explain our universe, which you are comfortable with. What are other uses that you are not comfortable with?

A.: I have no idea whether there is an intelligence who created the universe. I do not know, and I don't pretend to know.

Q.: So you say that some people give that idea spin?

A.: I suppose. Not many scientists do.

There are other uses of it which I find much less compelling. There are all sorts of modest coincidences. If any of them were not satisfied, they might be enough to make our universe inhabitable.

If we were to make a list of the elementary particles, we would find that almost all of the known ones are necessary for our own existence.

On the other hand, our understanding of particle physics would allow just about anyone of them to not be there, or other ones to be there.

For example, let's start thinking about the particles we are familiar with. Photons are light. Where would we be without photons? There would be no light, no heat, no Sun. Worse than that, there would be no photons jumping back and forth between the atomic nucleus and the electrons to hold them together. No chemistry. We would not be here.

What about no neutrinos? If there were no neutrinos, there would be no nuclear reactions of the kind which created the elements out of the Big Bang. So the existence of carbon and all these other elements that make ourselves would not be here without neutrinos.

What if there were no electrons? With no electrons, it would be a clear disaster. There is no question of that.

What about no quarks? No quarks, then no protons or neutrons.

What if you changed the parameters a little bit? For example it was a puzzle for many years, and it still is a puzzle: why is the proton lighter than the neutron? In the early days of nuclear physics this was a great puzzle because the proton is charged. We would have thought its electrostatic energy would have made it a little bit heavier than the neutron.

Neutrons and protons are twins. They are almost exactly the same, except that the proton has a little bit of positive electric charge. Ordinarily we would say that this increases its energy. It takes energy to pull together a charge.

So the protons should have been a little bit heavier than the neutrons. Yet, if we take the mass of the neutron as the unit, the respective masses are

$$\begin{aligned} \text{neutron} &= 1 \\ \text{proton} &= 0.99862349... \\ \text{electron} &= 0.00054386734... \end{aligned} \tag{21}$$

In fact it would have been a disaster if the proton had been heavier than the neutron, because proton would decay to neutron, instead of neutron decaying to proton. If the proton decayed into neutron, there would be no hydrogen. There would be nothing. We would not be here.

So the little tiny difference between proton and neutron – which is indeed very small, and which happens to go in the wrong way to expectation –, is absolutely essential to our own existence.

All sorts of other things appear to be lucky[5]. What would happen if the electromagnetic coupling constant, the fine-structure constant which is 1/137.035999139..., what would happen if it was 1/10 instead? Then the atom would be very very tightly bound and ordinary chemistry would go awry.

And what would happen if the electron were heavier than the proton? They would be very deep inside the center of

[5]Notice that this meditation about the luck we have to be in a habitable universe, can also be taken up by any individual – you or me for instance – wondering that he is lucky to be alive considering all the chances he had not to, for instance if the spermatozoid that lead to his birth didn't hit the ovule.

the atom instead of having their present cloud structure.

So you can look at physics as we know it, which means largely particle physics, and say: there is so many different things which could have changed by 10 or 20% or even 1% here and there, and any one of them would have destroyed our existence.

I can easily imagine 1% accidents. I can even imagine ten 1% accidents, so it gets a little harder. Are those accidents sufficient to really push us in the anthropic direction? I am not going to answer that; I don't have an answer to that. It is largely a matter of taste.

But the accidents of 1 part to $10^{123}$ or one part to $10^{30}$, in another case having to do with the Higgs boson, those are not the kind of accidents that you can imagine are accidental.

So I think, if it wasn't for the cosmological constant and the other comparable fine-tunings, we would not be considering the anthropic explanation. Most serious physicists would be rejecting the anthropic explanation, maybe not completely but with less hesitation.

For the time being, it is a working explanation for want of better one. That doesn't mean every physicist approves of it. There is just no other around.

Q.: Isn't this like the inflationary paradigm? It is the best explanation available, although many people say basically most inflationary models don't work?

A.: Who says that?

– Paul J. Steinhardt, Abraham Loeb, and Anna Ijjas[6] .

– Ok. These are contrarians. The vast vast vast overwhelming majority of cosmologists and physicists agree with the cosmic inflation theory.

– They say that the data from Planck satellite, that were presented in 2013, seem to support better another model.

– Sure, people make up a lot of wild models. Then we sift through them and keep only the sensible ones[7], provided they are not in contradiction with observations of course. Plank satellite data don't knock out the inflation theory.

There are people with axes to grind. Physics is not devoid of politics. Even in our community, there are people who get very highly politicized about their own ideas.

Going around saying things like Planck data infirm the inflation theory, I think, is irresponsible.

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[6]See for instance: `https://www.scientificamerican.com/article/cosmic-inflation-theory-faces-challenges/`

[7]As early as the XIV$^{\text{th}}$ century, when modern scientific thinking, resting on experimental observation, had finally taken off, William of Ockham (c. 1287 - 1347) recommended, among the various consistent explanations of a phenomenon, to retain the simplest. This principle is called "Ockham's razor".

Q.: Couldn't the cosmological constant change over time?

A.: There is no good theory in which it varies gradually.

It can vary in a jump, if one of these submarines nucleates with a different value of its density.

But there is no good theory in which it varies smoothly over such a long time scale, slow enough to be consistent with what we observe. There is a theory with a very slowly varying cosmological constant, but it doesn't seem to fit with anything we know.

In any case, if we had a slowly varying version of it, it would require fine-tuning of several parameters. Not only the vacuum potential energy but several of its derivatives would have to be fine-tuned. So it is not a very satisfactory explanation.

The truth is that nobody at present knows where the theory of the birth of the universe is going to go.

There are contrarians. There are people who have a political agenda. I don't. I'm not the inventor of the cosmic inflation theory. I don't have a big stake in it. I'm not going to earn the Nobel prize if it is confirmed.

The cosmic inflation theory is highly confirmed. Somebody will earn the Nobel prize for it.

The logic of the cosmic inflation theory, for me, is extremely compelling. And I honestly cannot understand these people who say that Planck satellite's data is ruling it out.

Q.: Does inflation theory imply nucleation of universes?

A.: It doesn't fit with it very well.

Go back to the submarines. All the anthropic principle itself says is that we live in a submarine which is of the right type for us to live in.

Which is cause, and which is effect? Do we explain the fact that we live in the right kind of submarine by the fact that we are here?

*We are here.* $\Rightarrow$ *We live in the right kind of submarine.*

Or do we explain the fact that we are here by the fact that we live in the right kind of submarine?

*We live in the right kind of submarine.* $\Rightarrow$ *We are here.*

I prefer the latter. That is I prefer to explain why we are here as a consequence of there being enough right kind of submarines.

The former seems scientifically backward. It would put us again at the center of Nature to some extent.

In other words, we misuse the anthropic principle, in my view, when we start to try explaining why the laws of Nature have to be the way they are because we are here.

It seems to me much less egregious to say that the laws of Nature and the possible environments are highly variable – which theories tend to suggest anyway –, and that we live in a temperate zone. We don't live in a inhospitable universe for the same reason we don't live in Antartica. It is just too damn cold there.

The real question is: how are we going to find out?

The agenda of those who hate the idea and those who love the idea should be identical. Take it seriously enough to either kill it or make it into science. And the fact is that it looks very very hard to do either. It looks extremely hard to find signature of these kinds of things in data, that will either kill or confirm the hypothesis of many universes. That is the real problem.

The problem is not that it is bad philosophy, or that it is religious, or that it corrupts the youth. One of my friends thinks that the anthropic principle is a terrible thing to propose because young people will have their minds deformed by it and they will stop thinking about other explanations. Other people think it is bad because it enables the religious right to say: ha, you see, the world was created with just the right properties[8]. They are political reasons. But none of this is science.

The scientific question is: is it true, or is it not true? And

[8]See for instance: Susan George, *Hijacking America: How the Secular and Religious Right Changed What Americans Think*, Polity, 2008.

how are we going to find confirming or infirming evidence?

Q.: We want to observe other submarines nucleating?

A.: Right. So, if you are very lucky – or unlucky, as the case may be – you might bump into another submarine. You would be lucky if it doesn't kill you and you thus find out there are other submarines out there, confirming that you win the Nobel prize. Or it could be bad, the other submarine could make a hole in your submarine and then you would sink to the bottom.

In principle there could be collisions between regions of space with different properties. Computation seems to say that it is extremely rare. Basically computation seems to say that the ocean is exceedingly big. But the nucleation of submarine is very rare. It doesn't happen very often in time or space. So most submarines will last a long time without banging into another.

We find no evidence in the cosmic microwave background for collisions of this kind.

The only question is then: what other possible kind of signatures could there be for the physics that goes into this kind of theory? And it is hard. Nobody has a really good idea. That is the worst aspect of the anthropic principle: it looks overwhelmingly hard to find convincing data for it or against it.