

Poor Man's Guides to an Accelerating Universe: Shadow Puppets, Holograms, Black Holes, and Horizons

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Some of my classmates will remember the torture called undergraduate laboratory courses, which was to be endured for four long semesters if you did not want to tell the parent that you are cut from the University. Of course you cannot do that since they think you are the hope of not only the immediate family but the entire web of relatives.

Actually I am exaggerating: Not about the “parent” part but about the “torture” part. Only those few guys whose motor skill resembles that of a bull dozer would concur. I knew early on, even when I was very little, it was no use trying to draw pictures or play soccer. Those skills solely belonged to my brother who used to carve nice daggers and stuff for me.

Anyway, the savior for me turned out to be no farther than the next chair, where the trusted, frustrated, and unfortunate partner (forced to team up with me by an administrative machine)

would sit patiently and manage to produce expected data.

One of those partners was an air force officer who enrolled in the physics department as a part of national defense program; he was no less than a real pilot who flied jet fighters on a regular basis. By the time we graduated together he was wearing a pair of glasses, which, it turned out, automatically disqualified him from active duty of sitting in a jet fighter cockpit. Can you guess who he blames for this disaster? His bumbling partner who was no good at sticking an eye into an interferometer and counting rings of lights.

Despite such heroic effort by my colleagues, things were still screwed up, given an opportunity. A case in point happened during my junior year, when we were supposed to produce a hologram. A dark room or more precisely a dark tent is put in one corner in the lab, with a laser mounted inside. We were supposed to illuminate a small

object with the laser light and make a hologram imprinted on the glass plate.

Well, what happened? After countless and futile attempts, only thing we ever got was a completely clean and transparent piece of glass. Not only did we fail to reproduce a three dimensional image encoded on the plate, but we never got any evidence that we actually performed the experiment. We blamed the “stupid” laser and that was the end of it.

I have wisely chosen to become a theorist, and in fact still try to stay away from a real laboratory, lest I should destroy a neighbor’s experiment. Yet, after all these years, it seems that I finally have to confront and “manipulate holograms”, albeit theoretical ones.

When Lenny Susskind was here last October, he was preaching doom for the 20th century physics of fundamental interactions. His concern stems from his long-held belief that the world itself should be thought of a giant hologram. This idea, although it sounds very much ludicrous, has been already well tested in some idealized setting. One of many concerns of string theorists now is to understand how this idea is realized in real world.

The idea itself, when accepted as a fact, has a far reaching implication for the way we understand the universe, especially if the latter is really accelerating as indicated by recent supernovae survey. But before getting there, it probably makes sense to explain the idea itself.

As an illustration, let us imagine a hollow ball full of some elementary particles, say electrons. If I want to describe a microscopic state of electrons at any given time, I would start by

saying where those electrons are located at any given time. Since an electron could be anywhere inside that ball, the amount of information I need to specify increases or decreases as the size of the ball increases or decreases.

In particular, total data necessary for describing a state grow exponentially with the volume of the ball:

$$\begin{aligned} \text{Amount of Necessary Data} \\ = \exp(c \times \epsilon \times \text{Volume}) \end{aligned}$$

Here $1/c$ would represent the volume of a unit cell which we want to use as the smallest possible volume to which a particle can be localized. The number ϵ depends on what fraction of these cells is occupied by electrons. Obviously it would be a very small number if the actual number of electrons is very small. We will call the above the bulk information.

Further, suppose that the surface of ball is translucent but not transparent. A professor of physics comes along and puts a single source of light at the center of the ball, and shadows of individual electrons are projected onto the surface of the ball. The professor then tells me to stay outside the ball and yet figure out motion of individual electrons inside just by watching this shadow image projected on the spherical shell.

I would protest vehemently that there cannot be enough information on the shadow image. For instance, can we ever tell how deep inside an electron is by looking at its projected shadow image only?

Those who lived in the days when electricity outage was a fact of life may remember playing “Shadow Puppets” with candle lights. Stick your

hands between a lit candle and the wall and you can make rabbits and whatever image out of the shadow. But you also know there is more to the shadow than its shape and position: you can pretty much tell where the hand is just by looking at the size as well as the position of the shadow. So my sister would say to me, "What's the big deal? You are just being lazy."



Besides, did I already forget that there is such a thing as hologram? Doesn't a hologram have a 3-dimensional image encoded on a surface? Perhaps all I need to do is to demand a better light source, capable of keeping quantum coherence to improve my chance.

"Not quite!" I should say to my sister: "Imagine shadow images of two hands overlap completely. Can you tell the two hands apart? If one hand is nearer to the wall, its shadow will be completely engulfed by the others. There should be always some loss of data when projecting to a surface."

"The same is true of hologram. The latter essentially captures three dimensional positions of the curved surfaces of objects in terms of patterns on a flat glass surface. It cannot possibly tell you anything about inside of that object. You are bound to lose some information when projecting onto a surface."

Indeed, the maximum amount of information that can be encoded on any surface would scale with

the area of the surface,

$$\text{Amount of Information Storable on the Surface} \leq \exp(c' \times \text{SurfaceArea}),$$

which looks much smaller than the bulk information if the size of the ball is large enough: The volume increases much faster than the surface area with increasing size of the ball. Here, $1/c'$ would be the size of a unit pixel on the surface, which we use to record where the spot is dark or light. Let us call the above the surface information.

A "hologram" in our theoretical context means precisely that the bulk information is actually all encoded on its surface. In ordinary circumstances, thus, such an idea seems so very much absurd and would be laughed at.

In the middle of 1970's, a crisis emerged. What about Black Holes? They cried. "Can we ever look inside a black hole? If not, can we know anything about inside of a black hole?"

A black hole is a sort of ball with such a large mass that gravitational interaction is extremely strong within itself. It is an unavoidable feature of modern theory of gravity in that any object with sufficiently high mass will always turn into one. The name derives from the fact that it traps everything, even lights, and the surface of a black hole is called "Horizon" meaning that those outside can never see what's inside, "beyond horizon."

Existence of black holes is by now almost an observationally confirmed fact, and seems unavoidable theoretically. And this gives us a dilemma. Either be content with absence of information about inside of black holes, or somehow find a way to "see" inside. Black holes

presented for the first time a real possibility that there is a fundamental and unavoidable mechanism for information loss.

Things look especially bad since black holes are famous for eating things up, and along the way could garble up whatever information on them. Blindfold your self, throw a television into a black hole, and long after try to tell what brand it was by looking at the black hole surface. There is seemingly no possible way: the TV is already garbled up by the black hole, and we have no way to look inside its stomach.

You might say that the same is true if you threw that TV to the Sun instead. Sure, but the difference is that the latter difficulty is a matter of impracticality while the former is that of a fundamental obstruction.

For decades, some of finest minds around the world debated this quandary. S. Hawking insisted that information loss is inevitable in gravity, and the ultimate theory of everything, whatever it might turn out to be, must have this possibility built-in. One of more vocal opponent to this idea was G. 't Hooft who imagined that somehow everything is stored safely on the horizon of a black hole. The debate went on for a decade and half.

Educated readers may wonder why this issue is such a big deal to begin with. "Have not physicists already abandoned 'determinism,' and thus given up keeping track of information, when they accepted Heisenberg's uncertainty principle?" a philosopher will ask. But, this is nothing but a very widely held misconception. Quantum mechanics never did that. Rather it simply said that amount of simultaneously maintainable information is a bit smaller than thought previously.

On the verge of a new century, what do we

think about information book-keeping and black holes? A new insight to the problem came about recently from taking advantage of new idea called string theory. The latter idea is the only practical implementation of quantum gravity up to date, and so people began to ask whether you can find a calculable model in string theory that can be identified with black holes. Let me simply state here that these collections of effort now point toward very strongly in favor of 't Hooft, and that everything should be consistent with quantum mechanical principles. In case you are wondering, this has nothing to do with his Nobel prize.

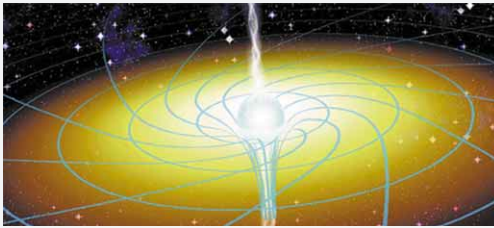


I shall not try to explain why majority of string theorists sided with 't Hooft. Instead let me explain how they managed to evade the above counting of information, which seems to say that surface information cannot possibly be large enough for describing what are inside. In reality, the resolution is pretty simple and come from one very unusual property of the black hole that its radius, instead of its volume, is proportional to the mass of the black hole.

In the above toy example, amount of information you need to specify depends on the number of electrons inside the ball. This is reflected on the small number above. Initially with very few electrons, the bulk information inside could be very small thanks to very small.

As we increase the number of electrons, the density inside the ball grows and so does its total mass. At some point along the way then, gravitational interaction becomes important, and there will appear a critical state where the ball and the gas can no longer sustain its state and have to become a black hole instead.

The point is that the maximum possible value of before the ball turns into a black hole is not a constant but a function of the size of the ball. In particular, as the size of the ball increases, the number ϵ decreases so fast that $c \cdot \epsilon \cdot \text{Volume}$ always remains less than $c' \cdot \text{Area}$ no matter how large the volume is. Thus, the surface information is actually always larger than actual bulk information.



This is because the radius of black hole grows linearly with its mass. The crucial difference gravity introduced here is that, given a fixed volume, there is an upper limit on possible amount of matter that can be put inside.

This unexpected scaling of bulk information is directly related to the nature of gravity. But on the other hand gravity is everywhere. If one strong gravitational body has this “hologram-like” property, then any other strongly gravitating body should exhibit the same sort of behavior. What other examples are there?

One answer to this question might be very surprising: the Universe. Since the radius of black hole horizon grows linearly with the mass

inside, an extremely large black hole could have very small ratio between the mass and the volume. Thus, contrary to the usual characterization, a black hole could be a very low density object if it is sufficiently large. In fact, an extreme case of this is our own universe which is known to be of very low density but at the same time so large.

The upshot is that the Universe can also be regarded as a kind of an extremely large black hole, except that we are surrounded by the horizon rather than being outside of one.

Then, if we are convinced that all information about inside of a small black hole is actually stored on the outermost surface, we might also believe that every single bit of information about our part of universe can be and is stored on its outermost boundary. This would be what one means by saying “the World is a giant hologram.”

What is this outer surface that acts as a holographic plate for the world itself? Do we mean that the Universe has a finite size and surrounded by a wall of some kind? Unfortunately, things are far more subtle than this. An outer boundary comes about, not because space is finite but because age of universe is finite: there has been only finite amount of time (and thus distance) any light could have traveled before getting to us. Anything beyond reach of lights, we have no way of observing, so the outermost distance from which any light could have arrived from defines the horizon for us. To distinguish it from black hole horizon, we call it cosmological horizon.

By the way, a civilization in the Andromeda galaxy, if there is one, would perceive a different cosmological horizon, just as the earthly horizon at Geneva is different from its counterpart at Seoul. This observer dependent nature of horizon

alone would have tipped off Einstein that we are talking nonsense, I would think. Yet, many serious string theorists will stick to the idea nevertheless.

Cosmological horizon usually expands with time because the older the Universe, the longer can lights travel. At least this is ordinarily true. The most startling observational data of recent years indicate strongly that our universe is just about to turn into an “accelerating” one, where distances between adjacent galaxies and clusters will begin to grow with time exponentially fast. In such universes, the size of horizon remains fixed, because anything beyond a fixed distance from us will speed away so fast that lights from it can never reach us. We would be forever surrounded by an a forbidding shell of horizon which does not grow or diminish with time.

Having a black hole horizon keeping information about its inside is one thing. But having a finite sized shell of cosmological horizon knowing everything about our part of universe?

Even worse, cosmological horizon remains the same finite size forever if the universe happens to be accelerating forever. One of its implications is that the world as we see is and will remain a closed, quantum mechanical system with only finite number of degrees freedom forever. This seems to contradict many things that we take for granted.

For instance, one of macroscopic law of nature is that entropy will always increase, which modern cosmology faithfully obeys. Once we believe that our cosmological history can be thought of as that of finite number of, however many, quantum mechanical degrees of freedom interacting only among themselves and somehow reflected on cosmological horizon, this sacred law

of thermodynamics has to be thrown away completely. According to this hologram idea, thus, actual history of early universe could be very different from what we all thought to be true. Yet, modern cosmology is one of most accurate science of all, and we think we have pretty good idea of what happened near the beginning of universe.

When it comes to the universe, this idea of holographic description becomes extremely speculative. Readers should not be fooled into thinking that string theorists really know what they are talking about here.

Yet, theoretical physics is all about unity. It is almost out of force of habit that we try to identify properties of black hole horizons (of which we have a little bit better understanding) with those of cosmological horizon. Maybe in reality, things are completely different, and holographic description is unique to black holes. However, we are yet to find a reason why we should distinguish two kinds of horizons either, and herein lies our problem. Either we find a unity or we should explain the difference.

This is the current state of affairs, confused but also tantalizing. Just as shadow puppetry and hologram are useful metaphors for the fundamental nature of black holes, perhaps black holes will prove a useful tool for understanding fundamental nature of universe. **KIAS**