Does chance really exist?
Hugo Duminil-Copin

Hello everyone, thank you very much for this introduction, it puts a little stress on me ...
always the little moment when everyone is a little stressed because you tell yourself you are
say “ouhlala, 40 minutes of math, it's going to be horrible!” and I tell myself that you are
many so it is horror for many. I also see a lot of physicists so it's
people who probably could give the presentation better than me and I warn you, I do not give
not the briefing for you, I'm giving the briefing for the rest of the world.
So there you have it, don't panic and I know that when a mathematician tells you not to panic
quer, this is the moment when you have to panic, I know it very well since I am a mathematician, but
there, I nevertheless made an effort: there will be no formula, no mathematical formula,
do not worry; no sweet childhood memories, or rarely to be honest, and no no
no more surprise quizzes at the end ... or maybe ... I don't know, we'll see!
So what are we going to talk about? We are already going to talk about chance and I want to stop immediately
everyone's enthusiasm, I'm not going to tell you about all the ways we can define
chance, I'm not going to talk about philosophy, contingency, all these things like that, I
I'm going to focus on a notion of chance which is the scientific notion of chance. I define it
in a few moments but if there are philosophers in the room, don't blame me, I won't
not enter into debates of this type. Chance, let's say that etymologically, it comes from the word ...,
in Arabic, and what does that mean, does it mean the cause of a phenomenon that does not fit
within the framework of a determined process and which escapes any form of forecasting escapes any
forecast form. And that's what I want you to remember, I'm not saying that
this is something that I, personally, Hugo Duminil-Copin, cannot predict, no,
I say that whatever tools I use, that the entire scientific community uses, that
all humans use, we won't be able to predict what's going on; this is an event
really hazardous; it fits, for people who were already bored of what I said and who
were reading the quote, it really matches a very small part of the quote that was written
just before “... which thwarts the most careful calculations”.
You see, I don't pretend to remake the world we're just gonna focus on those few words from
this long quote; very well; so chance is what escapes all prediction and in fact,
when the random word into common usage almost in the seventeenth th century, is in the middle
of a revolution, it is the Newtonian revolution, therefore classical mechanics is in the process of being
built and find all the applications we know. And so in particular, a fantasme
of mathematicians, physicists, of all scientists of the time, is that perhaps
that every effect actually has a physical cause.
It is such a revolution that we begin to believe that this is something that is possible, and
suddenly, chance comes from a certain point of view and the events which still remain inexplicable,

we suppose that chance in any case we use the word chance, to say that well finally, it is
the cause of things that cannot be explained. But since there is a revolution, so we are
in motion, one can naturally ask the question “am I also in motion?
is lying ?".
Let me illustrate a little: one can wonder if this chance, it really exists or if ultimately, it is
just something very subjective that is true at some point because we haven't found it yet
the appropriate explanation for the event in question and that ultimately perhaps everything,
every effect does indeed have a physical cause.

So it is not at all a trivial question to ask if chance really exists.
So what is hazardous? If you are asked, normally the population divides in two parts: those who answer you a coin toss and those who answer a dice roll; these are the two typical things that for people are hazardous, random; I will also use random instead of chance in a somewhat interchangeable way, I'm sorry, I'm a probabilist, it's kind of my group, sorry, it's like that, I use random or chance, do not blame me.
And so, for coin tossing what is needed? It takes a coin you need gravity, basically those are the two things you need, so don't try to do that in the space station, it does not work, but here there is no problem, coins and gravity, we flip the coin, it falls on a toss, we have a fair return, there is just as much probability to fall on one and the other and it is typically random in the sense that we cannot predict what's going on.
We use it all the time in popular culture, we use it in sport of course, these famous toss, now I use the toss; well I am a mathematician, I have to pass a geek reference. There will only be one, I reassure you, it's yes I see the mathematicians who do “Oh no, not just one”.
So there will be one, it's Double-Face, the villain of Batman, who decides with a throw of coin of the fate of these victims; it's quite creepy, yes, that's my geek reference.
So in the collective imagination, throwing coins is by definition chance.
Why do we think it is chance? We think it's chance because we can't seem to predict the result, that is to say that there, if I run ...
Okay, already I'm not going to do it because I think I'm not going to catch up with her, or I will slide on it; in short, if I threw this coin, you agree that neither I who will type in it to start it, I can't exactly type the right way to be sure I have a result and neither you who look at me will be able to know when I shoot what the coin falls. So, in the end, it is almost a synonym to say that for our human brains, we cannot predict the behavior of systems in real time when I toss the coin what a lot of people say is a problem where there is too much parameters, we cannot predict, but if you think about this system, it is not so complicated that that; what is there to say? I have a coin. At the start, when I will type in it, it will give it a speed of rotation, a speed too, I'm starting from a certain place, well well gravity we know very well how to describe what it is, what it has as an impact on this piece ; so we will know how to predict exactly what is its movement there is a moment when it will get to the ground she will type in a certain way there we have physical laws that predict what are
the ways the coin is going to bounce, hop, it's going to bounce first, maybe a second, a third, and finally, the laws of physics, we do not know everything but we should to know, and ultimately it allows us to predict quite correctly what will happen to this piece. There is nothing random about it. But hey that's the theory but even at the level practice with supercomputers, today, in fact, we even manage to make simulations; we are able to predict very well what will happen to the behavior of this part so in fact, it is not a system that has so many parameters: there are few forces exerted on it, there are has many forces which are negligible, moreover few forces which are exerted on them, few conditions, and in the end we still can't predict so that was the first thing I maybe wanted to mention is that we always refer to the fact that there are too many parameters, oh there there there, it's complicated, but in fact relatively simple systems already seem to us random and to perhaps caricature even more what is happening with this coin, I going to talk to you ... I want to take the time to tell you about something that I could have skipped, but I'm going to tell you about a theory that's wonderful called chaos theory.I'll give you an example: chaos theory; in a way, it's a caricature of what happens for the part, in the sense that these are systems which are very, very simple but which are

ultra-sensitive to initial conditions; so these are systems that are going to look completely random while ultimately they are very very simple to describe and I will give you an example and I hope you will agree with me that this is not such a complicated example.
So we're going to do a little thought experiment, all of you, close your eyes, well you're not forced to close our eyes, but we will close our eyes and we will imagine ourselves in our favorite bar in
playing pool, okay, everyone imagines that; well, people who have never played
at pool, I'm sorry for the next five minutes.
But before then we play billiards and we play billiards well so we are winning
and if you've ever played, well remember that at the end of a game of pool there is
this extremely frustrating moment because you are ahead of the opponent but there is still a blow to play which is that it is necessary to return this damn white ball after 3 rebounds in a hole; that's clearly a rule that was invented by someone who didn't want to lose because
that in general, suddenly, we spend hours trying to do that, it's completely random and
people are catching up with us.
So I want you to imagine that moment: you typed that white ball and there,
i would like you to be honest with yourself and admit the thing i am going to you
say which is that ultimately our brain understands pretty well what is going to happen; our hand, she doesn't know how to do what you want to do at all, but our brain knows very well that when we are going to hit this white ball, it will go in a straight line, it will hit the edge
billiards; there, it will bounce while forming the same angle, and that, in fact, we understand quite well
intuitively what she does, we calculate it, we are even ready to imagine what she will do next, before going to type this second edge, the third, and finally, we try to calculate the right angle to be able to hit the ball so that after the three bounces, it reaches the hole.
Why did I make this little aside? It is to try to convince you that finally, we
understands this physical system quite well even intuitively, we understand it very well the brain human understands what is going on and yet, we can create from this very simple system something that looks completely random, this is what I'm going to show you right now because that a mathematician, when he understands a situation, he likes to complicate it, okay? ! So a thing that we can do, if we want to have fun, is to draw billiards that are not
rectangular, why not eh? ... So a billiard table for example circular and a billiard, there, I
Grant it to you, this is really a mathematician's idea, he looks weird, okay you go
understand why we drew it like that, why my mathematician colleague drew it
like that.

And now, what I did, the little blue and red squares. So I was told that I could
to do something that, it's hard, you see why I became a mathematician, so there, here,
the little blue square, in fact, are small dots that represent billiard balls; Okay
they are next to each other and we will imagine that someone is banging in these marbles a whole a little differently, in two almost the same directions, the balls start almost from the
same place and we will see what happens, let's go!
Little moment of rest for the brain, here it is, unfortunately, what we see is that it does not happen quite the same way: we see that on the right, in red, finally the balls have gone close
from each other, and they keep coming eventually, coming and going, staying in one form.
relatively orderly while on the left, conversely, the balls, excuse me for saying it but a little

the mess, on the left, it's nonsense, the trajectories of the marbles seem completely random
and if i started the video at that point i think no one would say to me “oh but listen,
it's fair, it's very simple, we send balls in one direction, they bounce at an equal angle
against the walls and then there you go. ”
I make them go right next to each other and I get this ... There, this is a typical example
of randomness in a way in the same sense ultimately as this random coin which
so much of something that is almost deterministic, we had a very simple system, we created
disorder.
For this game *(denoting circular billiards)* , have you all seen the circle in the center here?
in which the balls never fit ... I give you the video, just because in fact, like
that, you can stop listening to me in general, it attaches very well, there you are, it is completely
hypnotic.
There you have it, it's a chaotic system on the left, while on the right it's not chaotic, no I see
that everyone is fixed on the circle, the red one, in short ...
Why is this type of chaos important. Well because in fact, deep down, maybe it's
be this way the easiest way to create randomness. So not real randomness since we
saw that everything was deterministic: if I give you the initial condition, we know very well how to
predict the
behavior of the ball but overall, we create randomness due to the sensitivity, if you
want, on the initial condition; the fact that the human brain cannot analyze sufficiently
well the initial condition and that in fact is the basic idea of almost all generators. I
will come back to recent improvements afterwards but until recently this was the way
for example, random numbers were generated; we took on functions we call chao-
ticks and created random numbers by iterating these functions, and numbers that we got,
it was considered that these were numbers which were sufficiently ... well incalculable; we'll say
by iterative methods, it is sufficiently random to be able to be used.
The problem is that it was to be able to be used in the very important field that is
cryptography, that is, they were the keys to our encryption systems, then you can
imagine that it is a little embarrassing if an encryption system is based on keys which ultimately
are not random at all, if there is a law, if there is a function that gives you this number;

it's complicated but there is one so imagine someone trying to decipher your
message, or your crypto system, because it sort of guessed the function. And
the existence of this function is something that is very inconvenient, okay?
So there you have it, so just for the record, I did something classic in mathematics.
ciens, it is that I say to you “oh one speaks about throwing of coins, then I say to you ah but
suddenly it makes me think of chaotic systems ”. And you, you say to yourself “ah bah great,
actually
coin throwing is a chaotic system. ”.
Well not at all, this coin is not a chaotic system but let's say
that it is on the scale of the comprehension of our brain

A chaotic system, in fact, for it to be truly chaotic, whatever
the very small disturbance of the initial conditions, if I put the ball just a little bit to
aside, I get something completely different. And that's exactly what happens with
that system; I'm giving it to you just for fun, i know you like it, just don't me

do not hide. So this system, on the left, is really a chaotic system, the coin tossing of currency, it is not chaotic because at the bottom of the bottom, if you disrupt even a whole little bit, well, if you are able to just disturb the way you launch
this part, it will in fact fall on the same side, but we will say that the basins of attraction, the right you have to modify the initial condition, this right is so small the right is so small that you really don't have to change the initial conditions much and this right is small enough that in fact the human mind cannot understand what is happening at all.
past. So basically there is a sensitivity to the initial conditions, that's it.
So at this point I'm sorry there won't be just videos like that, so at this point what I wanted to tell you, is that ultimately everyday chance, chance on our scale, in fact, it is an apparent coincidence; that you may say that it is a subjective coincidence, and that somehow it is me, as Hugo Duminil-Copin who I am unable to predict this chance, is random. It is not chance in the mathematical sense or in the physical sense since we had says that chance in the mathematical sense must resist any form of forecasting. But there, we saw for example with chaotic systems that this is not the case: in a chaotic system, if you know the initial value and the function, you actually have the behavior of the ball of billiards, this is what you imagine, it goes straight, it bounces etc., you can describe any path.
So we'll have to go *a little further* to find real chance, or I should rather say *a little smaller* .
So there, I feel in a situation which is a little complicated because there is a lot quantum physics specialists next door, so I'll be careful what I say, well
I was going to be careful anyway but even more.
So we're going to do what's called a thought experiment. A thought experiment is a experience but who is not in a laboratory, okay? ... So that's typically what we likes to do math and we also really like to do that in physics. This experience of thought will be as follows: we will imagine the following protocol so we will have three walls, until then, everything is fine, they are very very far apart, in the first wall there will be a hole, in the second wall there are two holes and as I am a mathematician, I have a lot of imagination. Call them *Hole 1* and *Hole 2* and on the last wall there are going to be detectors. I haven't drawn any
only one but imagine that they are everywhere in agreement, and we will ...
So I have to say that historically, in fact, we take a submachine gun and fire bullets but I thought it was a little bit violent so we're going to do something a little bit more funny, we will imagine that the transmitter, in fact, it is a frantic player of billiards there are tons of marbles and he hits, he hits, in all directions, all his marbles; so there are balls and balls that are launched launched launched launched and our question is “what is happening?
more specifically, what's going on here? ”

So there are a lot of balls which bounce, which do not go through the holes, but because flow, there are those who finally manage to pass through the holes and who will arrive in our detectors. Imagine that the detector is a sandbox for example. The balls are stopped when they reach the 3rd wall and we try to see what happens so this is a simulation, they are not billiard balls and what we see is that the balls appear one by one.
one of course since the balls are pulled one by one very very quickly; the shots are distributed a little
uniformly while being random, well, we will not see quite well formally, but they are distributed according to the following bell. We are going to make a blue bell so here, what is it that this curve? This curve, in a way, is the arrival frequency of the balls, that is to say that there are places for example a little whiter, here the center, typically, where there are more

balls arriving only in other places; this means that the frequency of arrival of the balls at these places there is larger, there are more marbles arriving in a given time and the blue curve, it represents these frequencies; so you must have said to yourself “there, we can guess what's going on;
very clearly, what will happen is that we expect that there will be marbles passing through the hole 1, they will arrive roughly in the axis, as well; I draw a line roughly in the axis between the emitter and the hole then they bounce their balls a little on the edge of the holes and therefore they
do not all arrive in exactly the same place and then also the shooter sends them a little in all directions so it makes a kind of little bell like that; and the marbles that pass by hole 2 creates a second bell which looks more like this; so if I decompose by closing a hole for example, what I get is that the balls arrive according to this frequency bell rather upwards, this frequency curve excuse me. When I close hole 2, they arrive rather down and one thing that is completely obvious is that if I open hole 1 and the hole 2, of course, the frequency curve is the sum of the frequency curves of the balls which go through hole 1 and balls that necessarily go through hole 2.
And when I open the two holes, the balls go either through hole 1 or through hole 2 so there are a certain quantity arrives from hole 1, a certain quantity from hole 2 so the frequency of arrival balls is the sum of the two frequencies, OK.
Until then I believe that I have not revolutionized the world and I agree that you could ask yourself what this has to do with sauerkraut.
So the relationship comes when you change the game a little bit.
So let's play a little more subtle: we go down the ladder and we are not going to launch billiard balls, we're going to throw electrons. So there, normally you have to say to yourself “ouh there there, there it is, he really begins his thought experiment: it is not possible ”.
So it may be prehistory for many of you but there is a system that corresponds exactly, if you will, to the electron submachine gun, it is the cathode ray tube. It was exactly the concept of old TVs, we send electrons, that is quite feasible and in fact, we can even send them one by one it's something quite admirable, it's not that simple than that but it is doable.

So imagine our transmitter now is an electron submachine gun, it sends the electrons, *(turning around to see the projected slide)* ah well alright, fine, no, so this is not what was planned, hop, you did not see anything, so we forget!
We take out the detector, poc! 1.
Ok, so, we're going to start the same experiment, we're sending electrons but we're already shutting down
one of the holes, we just open only hole 1 okay, and we look at what happens and there, when we look at what happens, well the same thing happens as for the marbles so until then, it hasn't really changed, it's still the same story; in fact, if you opened hole 2 and if you closed the 1, you would also get the same, the same type of distribution as for billiard balls. So now, the next step, we're gonna watch what happens when we open both holes; there, normally, we can make a kind of bet on what is happening but the problem is that if I give you a qcm and that I give you two solutions you will all go look at the physics section here who knows the answer and you're going to copy them so I won't not do that; I had planned but I will not do it. So we're not gonna ask how it is going on, we're just going to show you ... a little bit of suspense, so something already admirable there

there is a lot of suspense, we see nothing at all so it's beautiful, it's an admirable thing already which is that the electrons, they arrive one by one, that is something incredible but it is due to the fact that electrons are particles so we can really measure them one by one, and the second thing which is much more admirable is that we do not get at all at all all the same as in the case of billiards because there, if you look, I don't know if I can stop hop, there, I can stop, perfect, if you look at what is going on well there are zones completely black which do not receive any electrons and there are areas on the contrary white yes very
white now *(explanation: having inadvertently manipulated the slide sorter, we can see a white screen)* that one, I would have liked to do it, I would not have succeeded. So very white areas,
I let you imagine ... Now I raise, just so that you see white areas where it there are a lot of electrons coming in.
But imagine what just happened, it is something extremely astonishing,
maybe I sell it very, very badly but when you close one of the holes, hole number 2, there is electrons which arrive almost everywhere, in particular exactly at the places of the black zones, there, but when I open the other hole, then these areas do not receive any more electrons. In fact the frequency curve, in this case it does not look at all like the sum of the curves when I'm only opening one of the holes, it looks like something like this.
So you will have noticed, I think, that everyone will have understood it, I am bad at computers, ok so i didn't know how to rotate this video to match
better at the curve, but of course this image you should imagine it with a rotation of *$\pi/2$*, like that, I am a mathematician (90 degrees for those who do not like radians).
All right, so we get something completely different, we actually say that there is interference, okay, and that is something that may seem super weird to you because we have this interpretation of electrons which are particles and which come one by one. And so suddenly,
1. (imitating a man in black erasing the memory of the listeners)

these electrons, they go through hole 1 or hole 2, so normally we should get the sum frequencies but you get something completely different, you actually get something something that we see very frequently with the waves of agreement, if you take waves, so there, we is happy, in saint-jean-de-luz they gave us the gift of giving us two holes and so there, we has waves and we have interference; here it is the light that interferes with us and very famous physics experiment which is the experiment of the two slits of Young which allowed in showing that light behaves in a wavy fashion and we actually get the same type interference than here.

Okay, but then that says something anyway and because what we can do, at the stage according to, it is to ask oneself, well, ok, very well, one to these interferences but where do the electrons? Did the electrons pass through hole 1? Have the electrons passed through hole 2? It's a natural question and to do that, Richard Feynman, Nobel Prize winner fact has democratized this thought experiment, it is not mine, proposes the following:
he says “electrons react to light, so what we're just going to do is we're going to put a lamp." Sometimes things have simple answers, so we put a lamp, and this lamp basically when the electrons pass, bing, if it went through hole 1, it will light up, there is a little a little light spot, and if it is hole 2, it will be at hole 2, and so like that, we can record whether the particles pass through hole 2, paf, paf, hole one, hole one, hole one, hole 2, hole 2, hole 1 etc.
The problem is that what we get in this case is exactly the same curve as for billiards, the fact of having lit these electrons, finally, that completely changed them, main-holding, they behave exactly like billiard balls and we get the sum.
So that is something that we know well in quantum physics, it is the fact that when we measure a system, we modify it, we cannot measure a system without impacting it and.

But what does this have to do with alea? The relationship with the hazard, it comes from there. Now imagine that he there is a way to measure whether the electron goes through hole 1 or hole 2 before it has passed through the hole, that is to say imagine that for example we can land near the transmitter here and at each output of electrons, we can measure physical quantities linked to this electron and which tell us, that one, for sure, is hole 1, that one is hole 2, etc.
Imagine we could do that; it's easy to imagine that in this case, in fact, the presence of the light source to tell you if we go through hole 1 or hole 2, you could put it or do not put it, that would not change anything in fact, because you have the information that we pass under the hole. Besides, or suddenly, what does that tell us? Well that tells us that if there is had no light source, we should still fall on the blue curve. From a certain point of view, if we are able to tell before the electrons pass if it will pass through the hole 1 or hole 2, in this case, the frequencies should add up, we should have the sum the frequency of what goes through hole 1 alone and the frequency of what goes through the hole 2 alone so we should not fall on interference, we should fall on the sum of frequencies or we come across interference. What does that tell us? it tells us that it does not exist no way to measure something on the electron, no way to predict if it will go through the hole 1 or through hole 2 and in particular for example when we measure here if it goes through hole 1 or 2 eh well, with this light, they actually go through one hole or the other in a completely random fashion. There is no predictive way using physics that allows, finally, quantum physics in any case, which allows us to say if we go through hole 1 or hole 2. That is a real hazard, then it's a thought experiment, it's not that easy to do. In fact, it is an experience that has was introduced for educational purposes because there I crashed you, very bad probably, moreover, a crash course in quantum physics because we have seen a lot of phenomena. bizarre quantum physics nomenes.

The hazard, it was only the icing on the cake because we saw the fact that we impact a system when we measure something on it and this famous intrinsic hazard so you can imagine that, it is blessed bread for a pedagogue and in particular, Richard Feynman was a former pedagogue extraordinary and therefore he used this thought experiment a lot to describe the basics of quantum physics.

There you have it, you've taken a quick quantum physics course. Now you can relate all this in the evening in the bars; so that's perfect. But what I meant was that in fact this thought experiment, it has been reproduced recently and in fact you get this kind of interference so here, this is what we get with the electrons when we have closed one of the holes, that, when we have closed the other hole, and that when we have opened the two holes and we see, or we guess in any case, more general interference there are many other experiences which confirm the alea at the quantum level.
And I would even say that there are much better experiences. It's not such a good experience only that but I think that already gives a good idea of what is happening; there are experiences extraordinary which justify, which show that if one believes in quantum physics, in any case it there is an intrinsic alea, an objective alea, it does not depend on us, it is impossible to predict what is happening.
So at this point normally you shouldn't believe me anymore, no, but that's not possible; necessarily, we can predict the existence of a hazard, it is not possible; it is these physicists, these mathematicians, they are crazy ... So I will teach you something is that you are in

a category of people that is not bad because it is a category of people that includes Einstein and it's always good to be in the category that includes, well almost always good to be in the category that includes Einstein, that is to say that he himself had trouble with this idea: it is this famous quote, I think he himself must regret having said it so much it is reused but "God does not play dice". What he thought was that this probabilistic interpretation of the physical quantum science, it is not that it is false but it is that it is only a step, it is in some so that we do not know enough, and one day we will have better theories that will explain the physical without this alea. First thing, he worked to try to show physicists to time and to those of future generations that indeed, it was not such a good idea to to produce alea and in particular it has developed paradoxes and the best known is the paradox EPR which showed that things are bad if we assume this type of thing.
I want to tell you that there are some really great experiences, especially the ones that use photons so that's what we have, it's a whole discipline called quantum optics and which consists in trying to prove the existence of this alea.
So Alain Aspect, first, in 1983, showed for example that this great paradox which had been stated, in fact, it was not a paradox: no problem, you just have to give up something called the locality. It might not be that easy to give up on this idea, but anyway it is possible, and if we renounce that, it is no longer a paradox.
I mention this experience because this experience has been improved in Geneva precisely and besides we have one of the people who participated in this experience in the room so I won't tell you more because otherwise I will say wrong things and someone will rush on the platform to tackle me; so I don't want to take that risk.
They could say much better things than me, especially on this subject, but these experiences are wonderful because they allow both finally to contradict to say that this paradox is not a paradox and in fact, they also allow to show much more effectively the presence of a truly fundamental hazard in physics. So it's not just a figment of the imagination, this is not just a bad explanation, it is in any case something that is intrinsic to quantum physics, I should say to be more precise to an interpretation that is called the Copenhagen interpretation of quantum physics. There are people who keep on resisting and who try to have different interpretations of quantum physics, which would not be based on chance, but there and this is perhaps the punchline of this presentation, is that when you are a scientist
tific, everything works axiomatically, I am not claiming that there is not a description of the world that is not based on randomness; what I claim is that with mechanical physics and quantum physics, and I believe those two things and I believe that I'm not the only one, with these two physics at our disposal, it's normal to think that randomness rules the world quantum, it's just normal, that's what comes out of theory. Maybe one day we will improve the theory maybe we will make it different and we will realize that there is no randomness but axiomatically, if we condition by the fact that we believe in physics today, the world is random, okay, anyway that's what I think.
So just one thing, because you can say, “So why do scientists spend so much time trying to prove that there is randomness in the world? ”. So apart the fact that it's cool anyway, let's be honest, it also has applications and in particular, the Geneva experience and the work of Professor Gisin in fact make it possible to create rators of random numbers or this time, we do not create randomness from a chaotic system of any given function, we use the quantum world to create this hazard. We know in any case with today's knowledge that it will be perfectly random so there are applications real ideas that may seem crazy at first glance, ok, we're coming towards the money time, we're near the end of it, don't worry.
Should we abandon the principle of deterministic causality, should we completely forget that every thing, every effect has a cause? Well, that's not so much what physics when-tick tells us. Quantum physics tells us something a little more measured: it tells us

that we must forget the idea of being able to determine whether an event is taking place or not, of being able to
undermine a quantum system, but it does not tell us that we cannot determine the probabilities that the events take place and finally if we think about it, it is already very good, it is largely sufficient. So quantum physics actually tells us how to compute laws of probability.
bility and these laws of probability, on the other hand, have a causality; quantum physics we explains why it is this probability and not another. So finally, if we forget the fact that we want to determine the state of a system, and we only want to determine its probability linked to quite a well-defined causality, and just because hey, I'm a mathematician, I could not give you a presentation without a single mathematical formula, when even that you come back with stars in your eyes, so just to mention it to you; there is has an equation, the Schrödinger equation, which allows you to calculate the evolution of probabilities in an evolving quantum system, it's an equation, it's not that complicated only that when you see it like that; in general, an equation that looks simple means that it is very complicated; in fact so it is not that simple, don't worry, but it is not so complicated that neither to state. And so, it allows you to calculate the laws of probability.
So we summarize: there is always a principle of causality from a certain point of view. It's just that we are now trying to determine causes of probability and not of reali-
sation of events; when we see that now, there is one thing that becomes natural, it is that what I'm saying here seems to put a new player in the middle of the game, these are the proba-
bilities; it becomes crucial to understand what the probability of something is, I see I see the math students who are there, he is promoting his class, because well of course, when you have a new object that you want to study, you have to understand it yourself and therefore there is a theory which focuses on understanding what probabilities are, how we manipulates them, as we add them, how to control them, and this is the theory of probability and it is in particular the theory of which I am a specialist, hop there! We are just going to make an example to fi-
Finally maybe come full circle and after that I'll have a last slide to just open up a little.

We have spoken of apparent chance, finally objective chance, subjective chance, in a way, small-scale chance is objective; subjective chance is chance on a large scale because it's just our inability to figure things out, okay, but suddenly, sometimes systems are indeed too complicated to really understand the physics involved.
nist of these systems so what can we do instead of saying to ourselves “well, it's only subjective randomness ”, we can embrace this problem and say“ let's model that by the probabilities ”.
It's just subjective randomness, it's okay, we're going to calculate the probabilities anyway and that will allow us to understand a little better what is going on. And that's exactly what we do when we study systems depending on too many parameters.
For example, imagine the behavior of an atom in a gas, of a molecule in a gas, it hits all the other bouncing molecules, etc. : it's like a billiard table with thousands liards of billions of billions of billions of balls, so it seems there for little completely to escape our understanding we will say personal. Well there, we model by the random, it is random, perhaps of a third type, artificial randomness. Maybe the math-
maticist, the physicist model this by the probabilities and there, we manage to describe what is happening very
very well; we therefore generate this subjective hazard, it's not wrong, there is no pejorative connotation,
on the contrary, it is a very useful hazard, it must be studied and understood.
I just end with one thing, which is that the random, there are laws that govern it; that is something

something that is hyper-important to understand and I want to mention one to you because it is a law which at the moment moreover has a certain importance. This law is due to Jacques Bernoulli. Jacques was a member of a family of absolutely extraordinary Swiss scientists, they are all hyper-known, and this theorem says the following, it is even a mathematical theorem: it said if I repeat an experiment once, I haven't said a thousand times, we know I'm counting the number
of times the event takes place, the result is then 1
not
; it will be very very close to the probability
whether the event occurs, the result is *A* agrees. I give you two examples because the examples is always better than theorems. Finally, I do not agree but I was told to say that. So, first example, if the probability that a coin lands on a tails is 1
2
, then if we run
a coin ten thousand times, there will be with a very high probability about half throws that will land on tails; it is intuitively completely obvious thing, we will have about 5000 throws which will fall on tails and about 5000 throws which will fall on heads. Same thing if I take a 6-sided die, I roll it a lot of times, there will be about a third throws that will land on one or two because the probability of a 6-sided die falling on a or two is a third. Until then, I think I haven't revolutionized science, I think I don't you may not have even taught you anything. But I just wanted to show this little video because it made me laugh, I admit, so what is it? What is happening ? it's a toss and there, bang, it falls on the edge. So already, there you have it, I wanted to teach you that a coin toss is not always heads or tails, it can be the slice, you should not be lucky but it happens, there you go!

It's not a big deal because fortunately, the chance that it happens just a second time after is really very small, so you will eventually manage to get out of it. But what is as this video says. And that's what I wanted to finish on, that's a bit the moral of these last two slides: is that when we see events that take place, we tend to think that they have a probability much greater than it actually is. Why? Because we totally forget-
ment the fact that there are a lot of experiments that are carried out. For the coin toss, that's fine sure a very small probability that the coin falls on the edge, I think if we look in room, no one has ever thrown a coin that has fallen on the edge but you can imagine the number of people doing toss, especially now, we see football matches everywhere, so just on football matches, there is already an incredible number of throws and therefore time in time, it happens because the number of times it happens is about *n* times the probability so if *n* is very very large, if there is a lot of coin tossing, even with an event of very small probability, it ends up taking place and there you may see me coming, because in right now, it is a problem precisely these cognitive biases. I think the doctors in the room will confirm: there is very little chance of having a complicated and dangerous side effect of a vaccine but the problem is that today we are vaccinating, finally that's not the problem moreover, it is rather very good, we are in the process of vaccinating all earthlings and there is little nearly 5 billion, 6 billion, so 5 billion when I was born, 7 billion when some of you were born three billion when others were born, but many people get vaccinated and therefore even these effects which have a very small chance of happening, finally, we see them on TV
and our brain, which is a very bad risk calculator, ultimately thinks that the probability looks a lot taller than it is. But we, when we get vaccinated, it's just a experience among all these experiences and therefore ourselves, we are very, very unlikely to have a serious side effect. Fortunately! But now, it was to tell you this law of the great numbers, in fact, it comes from our mind, and in fact, it allows to correct a natural cognitive bias. turel. And in fact, probabilities in general, that's it.

I will give you one last tip: I had spoken of an interro but there will be one anyway; you take 23 students in a class; what is the probability that two of them have the same birthday, it's a qcm, I help you; is it 5% is this 15% or is it is it 50%? Wait, wait, we must give everyone time, there are always the students who want to speak first, we will answer, but then we will do a pool, that would be very good. Thank you for your attention before giving you the answer, just wanted to thank you- to have listened to me and to thank you for having listened to me, I wanted to show you something thing. “What is this video?” You might be able to tell yourself. But in fact, good your hazard, send electrons one by one and those that pass through hole 1, through hole 2, You don't see that, I will never see that in everyday life. So finally, all i see is never random. Well there, this video, it's real random, what is it what is this video? It's fine uranium, uanite so it's uranium ore, so it's radioactive, and since it's radioactive, it emits charged particles when it decreases and these particles, quantum physics tells us that they go in such and such a direction is evenly distributed. It goes in any direction but what happens there is that there has a gas around this uranite and when the charged particles pass it excites the ions in this gas and they leave a trail, much like in the video I showed, when the light it light up the electron and let it tell you, it goes through such and such a hole. In fact, this gas it shows you exactly the direction that the charged particles take and this direction is totally random. That is real hazard.

So that was to end with a little poetry, there you go, it's very pretty I think, it's enough hypnotic, there you go, to sleep at night, and now we're going to finish with the interview. Who thinks these 5%, wow, okay, maybe I gave the wrong talk if everyone ... 15%? Ah when even, a few people, you are obliged to answer, we are not going to replay the game of the primary school. mayor where no one answers the trick. 50%? Well, there are a lot of people who have a good mechanism is 50% and the law of large numbers tells you suddenly that for example, in Ge-nve, in about half of the classes, there are two pupils who are the same age, finally who are really from the same day, that's what I meant, of course, which have the same anniversary date. There you go, and with those fine words, thank you very much for your attention.

[Applause.]

Reference https://www.youtube-nocookie.com/embed/IupY68PJ6iw?autoplay=1&iv_load_policy=3&loop=1&modestbranding=1&playlist=IupY68PJ6iw

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