Q
is for
QUANTUM

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For Xavier, Aby, Lydia, Jesse and Caleb

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Preface

This book has been written for my 15-year-old self. Well, there is plenty of advice I would give my 15-year-old self that you don't want to hear, and there are very many things I was very interested in at 15 that are not covered here. But one thing I was interested in at that age was science, and I distinctly recall being frustrated by the lack of concrete explanations within "pop-sci" accounts of modern physics. The exciting descriptions I found in them were ultimately hollow. They were vague on details and they came loaded with jargon, questionable analogies, and somewhat mysterious pontifications about the nature of physical reality. Implicitly justifying the lack of explanation were historical anecdotes about how these discoveries confused all the famous physicists who made them as well.

As someone who wanted to tackle these mysteries (perhaps solving them before I left high school!) the situation was frustrating. Having failed to solve the mysteries by 17, I was forced to go and waste years studying physics at university. The failures kept piling up, and I have ended up a professional physicist who is still both confused and amazed by our physical laws.

A fairly recent mathematical breakthrough (not by me) suggested a very different method of presenting some of the most interesting and weird phenomena of modern physics. Through my talks to teenagers I have found it is possible for students who know only arithmetic to quantitatively—not just qualitatively—understand the most important features of many of our deepest confusions about what is going on in the natural world. In fact, my nine-year-old nephew understood why there is a genuine mystery about what could "really be" happening inside the PETE boxes introduced in Part I and a few days later asked me whether I have solved it yet. Perhaps he wanted to solve it himself before leaving primary school.

I eventually decided to write down the method I use, and here it is. Of course it is very much easier explaining this kind of thing in the back-and-forth dialogue of a classroom. It would be awesome if high-school teachers got interested in this approach and felt comfortable enough to explain these wonderful things to their students. I welcome feedback about what other resources I could provide to facilitate this.

Introduction

This is a book about physical phenomena I find deeply mysterious; about how we plan to harness them in amazing new technologies despite not really understanding them; and about where we stand in our attempts to obtain such an understanding.

We use mathematics to help us describe things going on in the physical world around us. This is not only because quantitative statements (which are precise and technical, such as: "If you fall out of a tree twice as high it will take 1.4142… times as long to hit the ground, regardless of the tree height or what size planet you are on") are more useful than qualitative ones (which are fuzzy and vague, such as: "Well, duh, it'll take longer becoz the tree is higher, which planet are you on?"). Rather, to a physicist, the math is an inextricable part of our understanding. Many times we have successfully predicted the existence of new physical objects and new physical phenomena based on the math alone.

The mathematical equations of physics—the "physical laws"—typically provide us with precise and beautifully intricate rules by which we understand how physical things we either observe directly, or otherwise believe exist, connect to each other. This lets us build a story, a narrative, about what is "really" going on. It does sometimes happen, however, that we are uncertain about the exact connection between the useful math and the physical world. For example, prior to the direct observation of atoms, some doubted their existence for this sort of reason.

Modern physics is in an odd situation. Some of our most important physical laws lead to a very strange (many would say completely nonsensical) narrative about what is "actually" going on when we view the mathematical objects in the theory as corresponding to something physically real.

More precisely then, this is a book about the tension between the abstract math, the observed physics, and the inferred story. Along the way the goal is to elucidate both strengths and limitations of some of the very cool new technologies we are currently building based on these incompletely understood laws.

Unfortunately, not everyone is good at mathematics, and most have little, if any, training in physics. So to tell the remarkable story of this ongoing intellectual adventure and the controversy around it, I (and many others) typically have resorted to qualitative expositions. These are very, very limited, and appreciating them alone simply will not let you make a meaningful contribution to the discussion, despite many emails I receive from crackpots suggesting the contrary. It is like only having van Gogh's "Starry Night" described in words to you, by someone who has only seen a black and white photograph. One that a dog chewed.

I recently came to the realization that it is possible to do much better than this. I believe I can help you properly understand most of the mysteries that swirl around our abject failure to take some mathematical equations—which unquestionably describe experiments we can do—and underpin them with a universally accepted physical narrative.

Nominally, the only math required in this book is the arithmetic of positive and negative integers. But in fact the drawings you will see in subsequent pages are mathematics. They are symbols on paper that we manipulate according to fixed rules, which have subtle relationships with each other, and which act as shortcuts for much longer and wordier descriptions. All math is really just this. What I am doing with all these drawings is what theoretical physicists do for a living—play around with numbers and equations and diagrams to try to describe certain things that we observe (or suspect) happen. When we find some that seem to explain the situation consistently, we are delighted if puzzled, and use them to do more complex calculations pertaining to related happenings. As long as the outcomes fit with the observations, we feel somewhat happy with our equations. But ultimately we would like to feel we "really understand" what our mathematics "means" in terms of stuff that actually goes on in the physical world.

I begin in Part I by presenting some simple but amazing experiments we can do, building up the math we use to describe them. From this I will be able to show you how we will soon build new types of computers, ones that think using a logic very differently to ours. We can do this even though we don't have a deep understanding of what is going on inside them at the underlying physical level. In Part II we will tackle the strange phenomena of nonlocality and entanglement; for me these were the gateway drug to physics. In Part III we go on a trip that may make you wonder if physicists are on other kinds of drugs too, as we explore the strong incompatibility between the "physical realism" we simply take for granted, and any sensible narrative about what is actually going on.

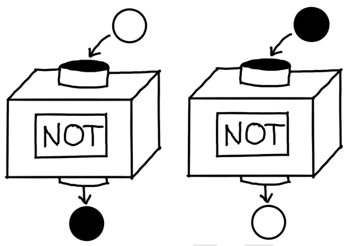
I really should spend a few more pages spouting profound-sounding blather, both to set up the story of this book and entice you to buy it. But while you are mentally fresh I'd rather get you to concentrate on some technical things.

Part I: Q-COMPUTING

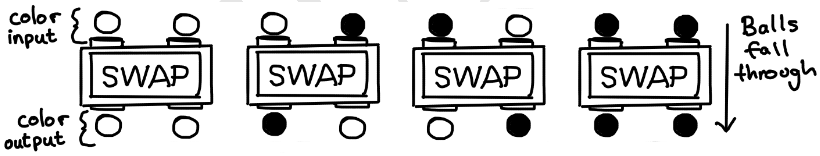
Black balls or white balls?

Imagine you have a box which has a hole in the top and a hole in the bottom. (I say "imagine," but I want to emphasize from the start that what follows is not an analogy, but rather a description of physical devices which we could, in principle, build. They are constructible according to the laws of physics as we know them today. However, the prohibitive cost and engineering challenges of building them means we do not actually try to do these experiments this way—we use other physical setups which are less easy to describe, but which have identical functionality.)

OK, back to your box with a hole in the top and bottom. You can drop either a black or a white ball into the hole in the top, and as it falls through the color flips. If you drop in a black ball, it comes out the bottom hole white. If you drop in a white ball, it comes out black. You could label this box "flip" or "change," but for various reasons it is traditionally labeled "NOT," since a white ball comes out "not-white," i.e. black, and vice versa.

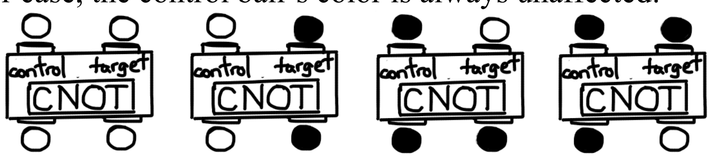


Next imagine you have a different type of box with two holes in the top, and two in the bottom. You discover that if you simultaneously drop one ball in each top hole, then the balls which emerge from the bottom have their color swapped with each other:

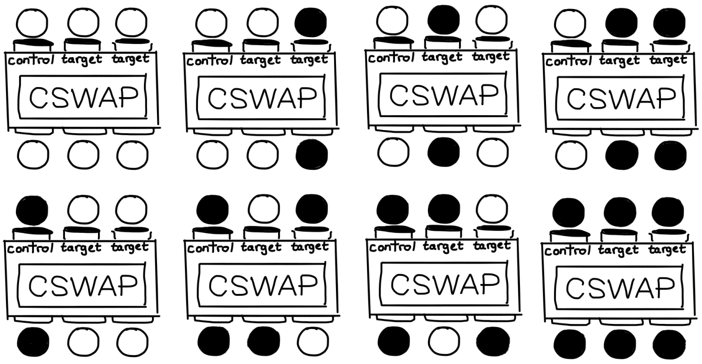


Looking at the balls coming through the first and fourth boxes one might be unsure that a swap had occurred, but it did—white just swapped for white and black for black. Dropping balls of different colors into the second and third boxes makes this clear. We may wonder then if the box is swapping the balls themselves. To check, we can use a plastic ball on the left and a metal one on the right. We find that the ball entering a hole always drops out from the hole directly below it, only the colors have swapped.

Another two-ball box is the CNOT or "controlled-NOT." This is a box where a NOT happens to one of the balls, the "target" ball, based on whether the other "control" ball is "switched on" by being black. If the control ball is white, nothing happens. In either case, the control ball's color is always unaffected:

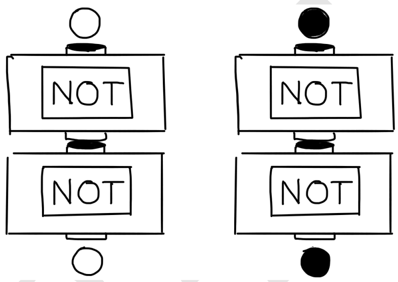


A useful three-ball box is the CSWAP or "controlled-SWAP". Here is how it works on all possible input colors of balls:

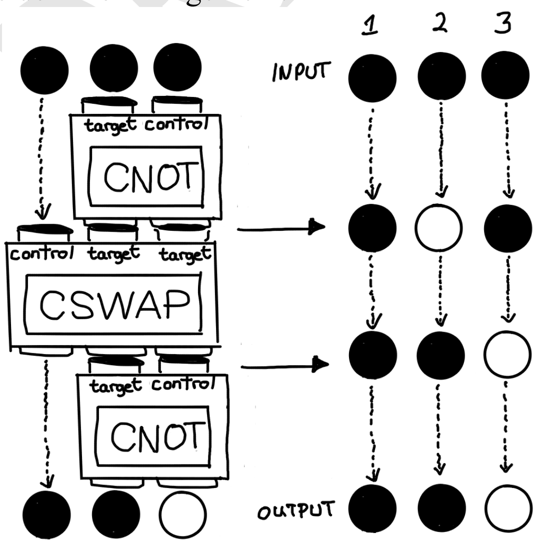


Like the CNOT, nothing happens to any of the three balls when the control ball is white, as you see in the first row of boxes. When it is black, a SWAP happens to the color of the two target balls. In the figure, a SWAP has happened to the colors of all the target balls in the second row of boxes, but you can only see it in the colors of the target balls in the middle of the second row, since the others swapped color with a ball of the same color as themselves.

The next thing to consider is that by stacking boxes on top of each other, we can use the output of one box as the input to another. For example, we can stack two NOT boxes, and the resulting transformation is that the color of the ball stays the same:



We can repeat this stacking trick to execute more sophisticated transformations of balls. For example, consider this arrangement:



On the right, I have shown the calculation of the color of each ball progressing through the boxes, for the case when all three balls we drop in to the physical setup on the left are black. If we do a similar calculation for the other seven possible input configurations of three balls we find: (i) the first two balls always emerge the color they went in, i.e. their color is unaffected overall; (ii) when both of the first two balls are black a NOT is applied to the third ball. In all other cases the third ball is unaffected.

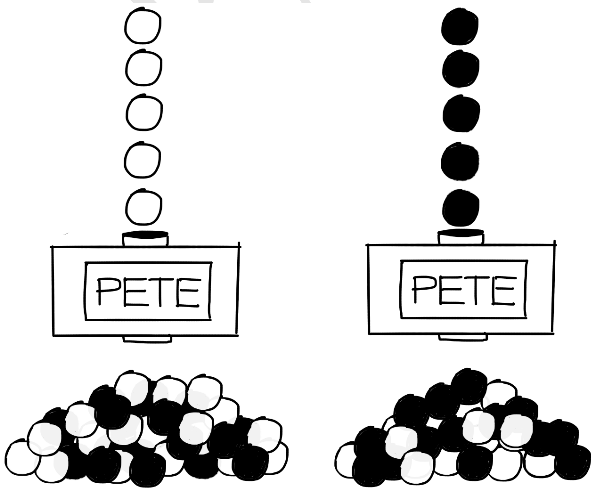
We could combine these three boxes into a new box, which we would call a "controlled-controlled-NOT" (CCNOT) box, since it applies a NOT to the third ball only when both the first two "control" balls are black. Because it is an important box, I recommend you write out a full schematic for the behavior of the CCNOT box much as I did for the CSWAP box a few figures ago. (Don't worry if you cannot, I will do it for you when we encounter it again.)

A twist on the balls

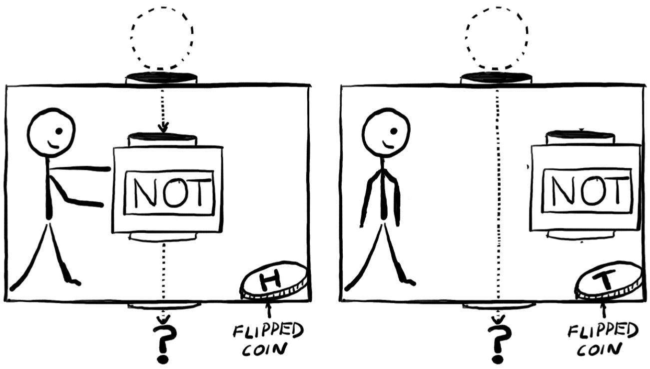
So far you could be forgiven for thinking that all we have seen so far is a bit of a silly game. Yet I'm pretty sure I can convince you, in a little while, that even the simple boxes we have already encountered are actually doing something interesting and extremely important, both practically and philosophically. Before getting to that, however, I want to describe one final box, a box whose behavior is so profoundly mysterious I am really hoping it will, by the end of this book, go much further. I hope it will completely change your views on what is "real" about the physical world around you.

Traditionally this last, very strange, box is named after a person who never built or even envisioned such a device and who has plenty of other things named after him. So instead I will call it the PETE box, after my friend Pete who has spent a significant portion of his life building and testing versions of it. Like the PETE box, Pete often does strange things—for example he put together a machine that enabled a tank of goldfish to browse the internet and control a drum machine. He made the profound discovery that goldfish like seeing humans without their clothes on.

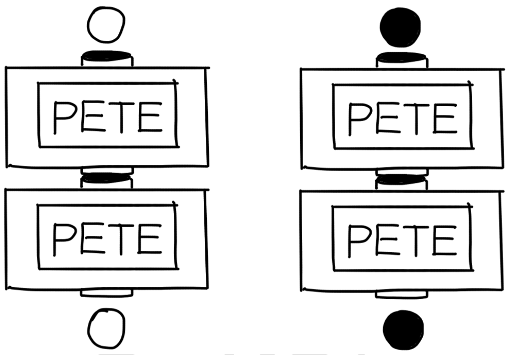
The PETE box has only a single hole in both the top and the bottom. After playing with it for a while, we find that regardless of the color of the ball that we drop in, when it emerges from the bottom it is equally likely black or white; and from one use of the box to the next there is no pattern, no rhyme or reason, about which color the ball emerges:



Is the behavior of the PETE box really so different from the boxes above? Of course the ones above behaved perfectly predictably, while the PETE box is unpredictable—which color emerges is completely random. So far we have deliberately not asked any questions about what goes on inside the boxes we have encountered. All we have considered is what they do that we can actually observe. As described thus far, however, the PETE box's possible inner workings are not necessarily particularly strange. We can imagine building a box with an internal mechanism which flips a coin. If the coin shows tails, it lets the ball travel through directly; but if it shows heads, a NOT box is inserted into its path:

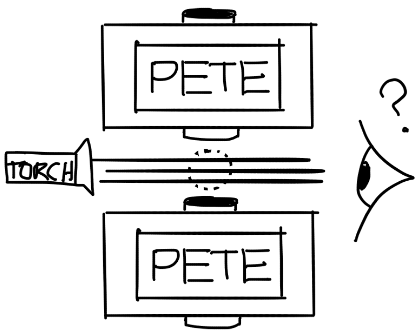


If this was the explanation of the inner workings of the PETE box, it would not be a radical addition to our collection of boxes. However, when we stack two PETE boxes, something remarkable happens: if we drop a white ball in the top of the first PETE box it always emerges white from the bottom of the second box. Similarly, if we drop a black ball in the top box it always emerges black from the bottom of the second box:



Can you see why this behavior is puzzling? It is critical that you do. The second PETE box, regardless of whether the ball entering it from the first box is black or white, should sometimes output a black ball and sometimes a white ball, because inputting a white ball leads to a random color emerging and inputting a black ball also leads to a random color emerging. But that is inconsistent with what is happening when we stack the boxes; stacking them leads to a completely predictable, non-random output.

After checking that each PETE box on its own is behaving properly, what is the next natural thing to do? Well, we get suspicious that perhaps the ball that enters the second PETE box has somehow been messed around with, even though we have exhaustively tested the boxes on their own and they seem to be operating fine. For example, perhaps the PETE boxes detect the presence of each other and change their behavior somehow? To check we do the following experiment. We slightly pull apart the two PETE boxes so we can shine a light through the gap. The light lets us determine the color of the ball emerging from the first PETE box, just before it drops into the second. What do you think we see?



We find that the ball that comes out the first box is half the time white and half the time black, as we know PETE boxes do. So it really does appear to be behaving normally. And now, if we let that ball we have observed keep going into the second box, it emerges from the second PETE box half the time white and half the time black. That is, if we observe after the first box whether the ball is actually black or white, then the second PETE box starts to behave unpredictably (randomly) again. It no longer outputs the ball always the same color as it was dropped into the first box.

We then turn off the light so we can't see the ball in-between the boxes, and immediately the two PETE boxes act perfectly predictably (non-randomly) again—a white ball always emerges white, a black ball always black.

Fine, perhaps the light is screwing things up? Well, we try many, many other less-invasive methods of observing the color of the ball after it emerges the first box, just before it enters the second. We find that no matter how smart a technology we employ, if the method we use is capable of determining the color of the ball emerging from the first box, then it causes the second box to have the random, sometimes-black-and-sometimes-white, completely unpredictable output. If the method we employ cannot tell us the color of the balls (e.g. we use too dim a light), then they behave in the fully predictable way where the color that emerges from the second box is the same as the one going into the first.

We conclude from all this that somehow, just by our peeping, we have affected the process. It may remind you of baking a cake: if you open the oven door and peep in while the cake is rising, the cake goes flat; but if you wait patiently until the cake is cooked, it rises as it should. In that case we know the reason our observation changed things—we let cold air in. However, we don't know the reason our observations affect the ball between the PETE boxes. What we are sure of is we cannot be passive observers of the balls exiting a PETE box—and since the balls and boxes are ultimately made up of physical stuff, this becomes a realization that we cannot always be passive observers of the physical world.

This portends a major shift in how we view our interventions in the world. How strange is that? Well it's certainly a step away from the classic scientific view of the universe in which we believe we are not ultimately that important—and so can make sense of things either much bigger or much smaller than us by presuming they conduct their business in (understandable) contempt of our actions.

Later I will explain why, while such "observer dependence" is interesting, the fact that observations have consequences is not necessarily a complete breakdown of the whole intellectual edifice upon which science has stood successfully for centuries. (After all, perhaps everything we do is like baking a cake.) By contrast, such a dramatic conclusion is ultimately where the PETE box will try to lead us by the end of this book.

Another conclusion, almost as dramatic as the first, is that the PETE box's behavior portends a failure of the very logic that underpins how we think. This has exciting consequences. For example, it lets us envision radically new types of computers and other technologies—although in return it is hard to understand the full potential of these technologies, precisely because they don't sit well at all with our "sensible" logic.

Now it takes a few steps to justify this second conclusion. The first step is to try and express what we think is "happening" to the ball—what do we think is "really going on"; what do we think the "facts of the matter are"; what is "the status"? Or, to use language that is meant to capture all of these: what is the "real state" of the ball when it exits the first PETE box?

The word "state" is itself pretty loaded jargon to physicists, and later we will discuss some more precise notions of the state of a physical system. So far all we can be sure of is that the balls that we observe come in at least two distinct states, black and white. Other colored balls are possible to build, so to be cautious we try yellow, red, and grey balls (which are arguably something in between black and white). We find that PETE boxes simply don't work at all if we input any color other than either black or white: nothing drops out the bottom at all. So it is natural to expect that, even if we don't observe the ball when it exits the first PETE box, it actually is either black or white. However, if the state of the ball exiting the first PETE box really is black "or" white, then we have a black "or" white ball entering the second PETE box, and in that case the ball exiting the second box would randomly sometimes be black and sometimes be white. But it is not—this is the whole conundrum!

We are forced to conclude that somehow the logical notion of "or" has failed us. The other natural logical notion when faced with only two possibilities is to say perhaps the ball is black "and" white. Now intuitively this is nonsense—a single ball which is black "and" white is as ridiculous as a cat which is both fat "and" skinny. It is trying to combine two things that are mutually exclusive, while using a logical notion which requires the possibility that they are not.

Confronted with this conundrum, physicists simply invented a new word to describe the ball after it exits the PETE box. We say the ball is "black superposed with white," or more colloquially it is "in a superposition of black and white."

Superposition is a completely new possible state of physical being, and a completely new state of logical being, for two distinct alternatives. Sometimes you will loosely hear a superposition referred to as "black and white," but this is either ignorance or laziness. You know better now.

I will now step away from talking only about experimental observations, to explain precisely how our current physical laws describe such experiments. The first step is to find a way to represent superpositions—these new possible states of physical/logical being. The way we do it seems very arbitrary when you first encounter it, so first a small aside to motivate you to try and learn the details, rather than just skipping over them:

What follows in this book is the only option we know

What I will explain from now on is the only way that we have found to quantitatively describe what is going on with the balls and the PETE boxes. I cannot stress this point too carefully. Many people (myself included) have tried to devise alternative explanations, and often succeed in finding something that looks very different. Once we examine it more deeply we find, however, that it is either exactly (though non-obviously) equivalent to the description I will teach you, or it is in conflict with experimental observations and therefore worthless.

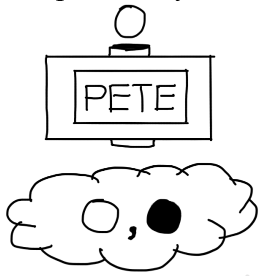
More precisely, what follows in the rest of this book is the only method known to work once we consider experiments that involve multiple balls passing through arbitrary combinations of the PETE boxes together with the CSWAP, NOT, CNOT and other boxes described above.

For the case of a single ball falling through stacked PETE boxes you can actually find other potential explanations which are quite simple. Here is one. Perhaps both black and white balls can have a small sticker on them that we cannot see, but which a PETE box can see. This means there are four possible balls: white, with or without a sticker; and black, with or without a sticker. Perhaps when we create a white or black ball it also, randomly and with equal likelihood, either does or does not have a sticker stuck onto it as well. A PETE box changes the color of a ball if it has a sticker, and not otherwise. This means two PETE boxes either both change the color or both do not change the color—either way the output is the same as the input. To explain what happens when we observe a ball, perhaps our act of observation causes the sticker (if it is there) to be removed, and then randomly, with equal likelihood, a new sticker either is or is not added onto the ball.

I wouldn't waste too much time trying to understand how this simple single-ball model works, I am just telling it to you because it is possible, and so when you find something equivalent on your own please don't send me lots of emails telling me you've solved everything. Yet.

Representing superpositions, the new state of physical/logical being

To represent a superposition of black and white—and capture this new type of ambiguity between the ball being black and the ball being white—we draw a cloud into which we list both possibilities, separated by a comma:

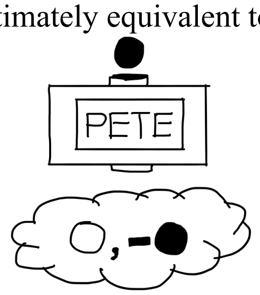


Because the terminology "cloud computing" is already used for something well-known (and irrelevant to our discussion), let me call this new state a "misty" state. (My father would say it's very *mist*-erious.) We could say, colloquially, that the white ball "splits" into a superposition, i.e. misty state, of both white and black.

Although the misty state seems to contain two alternatives simultaneously, we already know if we observe (look at) the ball, it reveals itself as only one of the alternative colors in the mist—and importantly, it does so completely at random. Thus, if we do observe the ball's color, the mist disappears and we get left with just a regular black or white ball. The ordering of the two color configurations in the mist is irrelevant, just like the ordering is irrelevant when you list all the possible things you might get given for lunch.

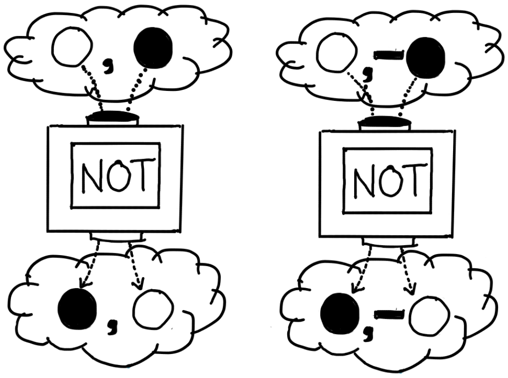
It may seem that we should use exactly the same ambiguous representation for the state which emerges from a PETE box when we have dropped a black ball through it, because it also equally likely appears black or white when observed. But it must somehow be represented differently, because it must capture the fact that after a second PETE box the ball always emerges black. This means there must be some difference between a mist originating from a white ball and a mist originating from a black ball.

You could probably come up with many alternatives to distinguish the two possible mists diagrammatically. But, as mentioned in the preceding section, any method that works in general is ultimately equivalent to the following:



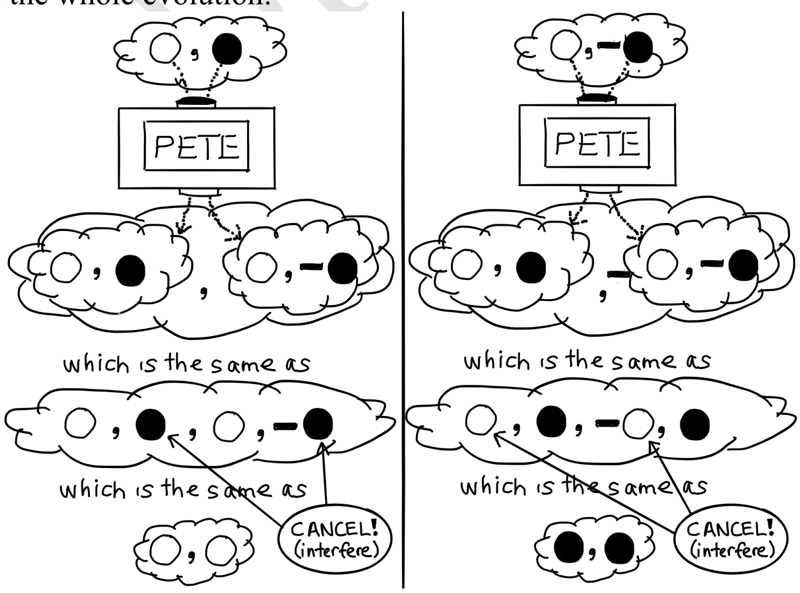
Here the black ball in the mist has a "−"(a minus, or negative) sign in front of it. I think of it as a "−1," a negative 1, somehow associated with, or labeling, this configuration within the mist. But it isn't a "physically different" type of black ball; if we looked at the ball at this stage we would just see it as randomly either white or black. No matter what we do, we won't be able to see anything to tell us that when it we see it black it is actually "negative-black."

After the PETE box outputs a ball in this misty state, what happens when we drop that ball (without looking at it) into another type of box? The basic rule is that you apply the box to each configuration within the mist independently. For instance, here is what happens when we pass the two different misty states we have just encountered through a subsequent NOT box:



The ordering of the ball configurations within a mist does not matter, and so the mist that emerges for the case on the left-hand side is identical to the one which entered. On the right-hand side we see the negative-sign labels can apply to white balls as well. The NOT box does what it always does—it acts on the color of the ball, and it ignores the negative sign, which just comes along for the ride.

To see how the negative-sign label affects things, we need to look at what happens when we drop a ball that is already in a misty state (having gone through the first PETE box) through a second PETE box. Following the dictum that you simply act the box on each configuration within the mist, each ball within the mist splits, depending on its color, according to the precise rules for the PETE box given above. This gives a larger bunch of alternatives within the misty state; a mist within the mist. Somewhat intuitively, we find that a mist within a mist is mist—the boundaries fade into each other. Here is the whole evolution:



In these two figures we see the white ball split into a misty white and black ball, while the black ball splits into a misty white and negative-black ball. In the figure on the right, the ingoing black ball already had a negative-sign label, and when it splits that label is inherited by the whole misty state it splits into, hence the minus outside the cloud. This means it actually splits into a negative-sign labeled white ball, and a negative-negative-sign labeled black ball. Just like when your mother used the logic that if she makes two negative comments about the state of your bedroom she is actually being a positive influence, the two negative-sign labels combine to a positive label, which we depict as no label at all. What we see happen to the balls in the figure on the right is a bit like when we do math of the form:

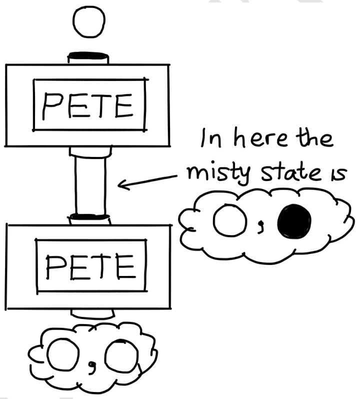
$$-(2 + -3) = (-2 + 3).$$

Now, if it is ever the case within a mist that the configurations of balls (in this example we have one ball; later we will consider multi-ball mists) are such that two of the alternative color configurations are identical, except one has a negative-sign label and the other doesn't, then both of them vanish. We say they "interfere" or they "cancel each other out," like when we do math of the form:

$$+42 + -42 = 0$$

—except that the mist somehow describes material objects, not just ethereal numbers. We can see this happening in both figures above. In the left figure, the two black balls vanish in a puff of interference; in the right figure it is the two white balls that disappear. The only alternatives left in each mist are two configurations of the ball that are the same color, which means if we looked at the ball now we would certainly see it as that color.

Putting together all these rules we can calculate the effect on a white ball falling through two stacked PETE boxes, which yields the "illogical" behavior that it always emerges white:



A very similar figure could be drawn for an initially black ball, to show it always will emerge black. I have drawn a tube to connect the two PETE boxes. This is because our act of observing the color of the ball burns away (destroys) the mist, so in practice when we connect many boxes we must use something like such tubes to prevent us looking at the balls before we want to.

Do not be distressed if the negative-sign is mysterious. My own mother, commenting on an early draft of this book, wrote: "I cannot get into the Why of that minus applied to a black-misty, seems so unfair but I am bashing on with the reading in rebellious acceptance, believing it can somehow be justified and maybe even explained!" Being confused by all this runs in the family.

Is the mist really a "state of physical being"?

Before moving on to examine the exciting power of misty states, a word of caution. The mist itself is never directly observed. I have called it a "new state of physical/logical being". However, amongst physicists these days the extent to which the misty state is "physically real" is very contentious. Everyone agrees that writing the mist on a piece of paper and using it to work out what we will observe in our experiments (performed with actual physical objects) is valid. So, in that sense, the mist is definitely a new state of "logical being" that somehow relates to a state of "physical being." But (a few? some? many?) physicists believe that the mist should not be thought of as "physically real" in and of itself. They would say it is only a tool for calculation—it is something we humans use to make predictions about experiments, and the PETE box should not be thought of as spitting out or responding to a physical misty state itself.

To perhaps labor the point, the mist in the diagrams above can be thought of as either (i) representing an actual physical process of some real stuff (drawn as a mist, but obviously not made of tiny water droplets) passing through the boxes; or (ii) "just diagrams describing an experiment" where the only physical thing is the color of the balls entering and exiting the boxes (once observed).

It is fascinating that we have this incredibly precise theory, which, as we shall see, is going to let us build marvelous new useful devices, and yet we are still arguing about what it all really means. My goal in this book is not to bias you on which side of the argument to sit. In Part III, by which time you will have understood all the key points of the theory, I will introduce you to some of the arguments for and against both viewpoints.

In Part I we will stick to investigating its awesome potential within devices that do not care about our philosophical consternations regarding how they work.

Computers without mist

Obviously our lives have already been revolutionized by computers and the many related technologies all based upon the same basic principles of micro-electronics. Pause and count the number of objects within ten meters of you which contain such electronics. In fact, in the interests of science, I recommend you grab a hammer, smash your TV or computer or phone, and dig out some of those little black "computer chips." Inside those tiny devices electric currents run around and combine together to produce the movies you watch, the game worlds you immerse yourself in, all the stuff you view on the internet, and so much more.

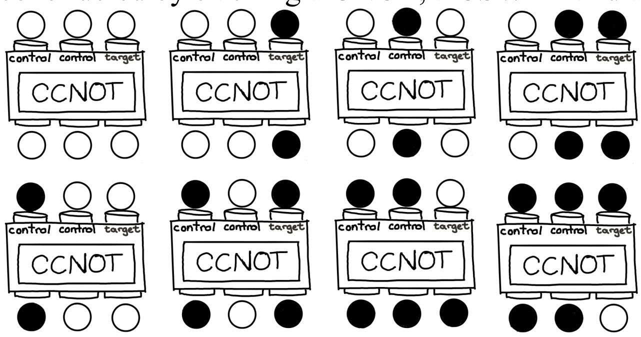
Yet what goes on inside those chips is actually just an electrical version of dropping black and white balls through the boxes we have encountered already—all the boxes, that is, except the PETE box. All the diversity of computational experience arises from electrical currents in one of two possible distinct states (a high and low voltage, but they may as well be called black and white electricity blobs) running through tiny boxes (etched into silicon), and coming out in one or other of the two possible states according to rules like those for the NOT, CNOT, CSWAP, and CCNOT described above. So I am going to call these non-PETE operations the "computer rules." The computer rules are simple to state, but they are what we call "universal"; from just this simple set of rules you can create the inexhaustible complexity of our computer-based technologies.

Seeing complicated larger-scale patterns arise from very simple rules for smaller patterns is neat, but perhaps not a shock to anyone who has dived a coral reef or watched bees work or crystals grow. I suggest to you, however, that a moment's reflection on the essentially unbounded potential of our computerized experiences puts into perspective the much more limited scope of examples of this kind from nature. Moreover, there is a really rather beautiful fact about these small-scale computer rules: as intimated above, they capture primal concepts of logical thinking.

Logic from the motion of matter

If we replace black and white states of a physical material with our ethereal mental notions of "true" and "false," then these simple computer rules capture all the pertinent rules of logical reasoning. The simplest example is that if something is NOT-true it is false, and we have already encountered the NOT box which negates "true" (a black ball) by changing it to "false" (a white ball) and vice versa.

For the next simplest example of logical reasoning, we need the CCNOT box, which we first saw constructed by stacking a CNOT, a CSWAP and another CNOT:



(In the Summary of Part I is a diagram recalling how every box works in case you find it difficult to remember them).

The CCNOT box's logical specialty is AND: If two statements are true, we can say "statement 1 AND statement 2 is true" but not otherwise. The CCNOT box computes the AND of the first two balls as follows: if we input a white ball into the third hole, then it emerges black (i.e. true) if and only if both ball 1 *and* ball 2 are black (i.e. true). This matches/computes the logical notion of "and" perfectly.

Another simple logical construction is that if one or the other or both of two statements are true we can say "statement 1 OR statement 2 is true." The CCNOT—with a black ball input into the third hole, and NOT boxes placed above the first and second holes—will also compute the OR of balls 1 and 2 onto the third ball. That is, the third ball will emerge black if either, or both, of the first two balls are black.

Slightly more complicated constructions give us ways of computing crucial logical elements like "IF statement 1 is true THEN statement 2 is true." Almost everything we ever try to explain or discuss or argue about is built from applying these sorts of basic logical constructions to facts/assertions/propositions we take to be fundamentally (or self-evidently) true or false.

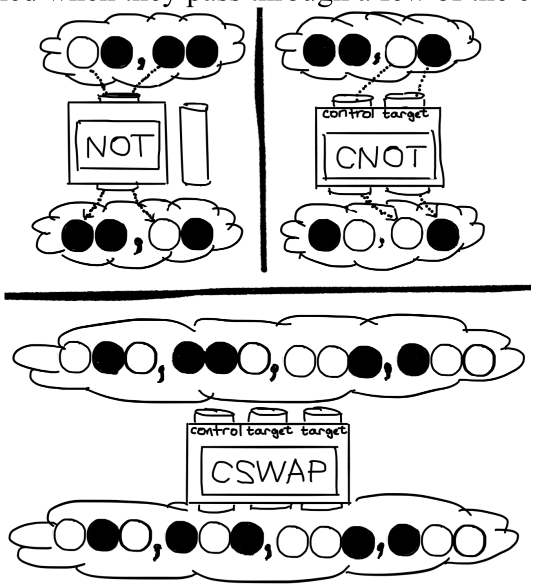
We have very briefly seen then that both our (dumb?) computers and our (intelligent?) logical thought processes share a common set of fundamental rules, rules that can be captured by simple motions of matter such as balls passing through the computer-rules boxes. The power of computers that can make use of misty states by incorporating the PETE box is precisely that they go beyond our standard logic. They bring a radically new element into the computers—a radically new logical alternative that is not a natural part of our reasoning. As exciting as this is, it makes it very tricky for us humans to comprehend, encumbered as we are to think "computer-logically."

Mist through computer-rules boxes

Once we allow the strange logic of the PETE boxes—or equivalently the strange possibility of creating misty states—into our computers, then our whole description of a computation changes dramatically. Computers operating without PETE boxes I will refer to as "regular."

Without any PETE boxes, a regular computer made from balls is always in a single physical configuration of black and white balls. This configuration evolves to a single new configuration as the balls drop through boxes obeying the computer rules of logic. Given the input configuration of ball colors we can readily deduce the output configuration by applying the computer rules.

So far the only misty states we have considered were comprised of a single ball, but it is possible to create multi-ball misty states. The first step to understanding misty computation is to learn what happens when we use the computer-rules boxes with multiple balls in a misty state. To determine how they transform, we work out independently how each configuration within the mist transforms, and add the output into a combined final mist. Here are some examples of how misty states of two or three balls are transformed when they pass through a few of the computer-rules boxes:



There are several things to note in these three examples. In the first, there are two configurations of two balls in the mist. I have indicated with dotted arrows that it is ball 1 of each of the configurations that drops through the NOT box. Ball 2 from each configuration drops through the "pipe" on the right (not indicated with arrows). That is, you take each of the two input configurations WB and BB (where "B" and "W" mean black and white) in the mist and act the NOT on the first ball to find the output misty state. I drew in the pipe, which does nothing to the second ball, to re-emphasize that no ball should be observed in transit or else the mistiness will be lost.

Now look at the misty state that is entering the CNOT box in the second example. In this mist there is also a BB and a WB configuration, but listed in different order to the first example. As mentioned previously, the ordering of the configurations is irrelevant, so this input misty state is exactly the same as the one in the first example. In this second example I have drawn arrows to indicate the path of both of the two balls within the second configuration; similar paths are taken by the two balls in the first configuration.

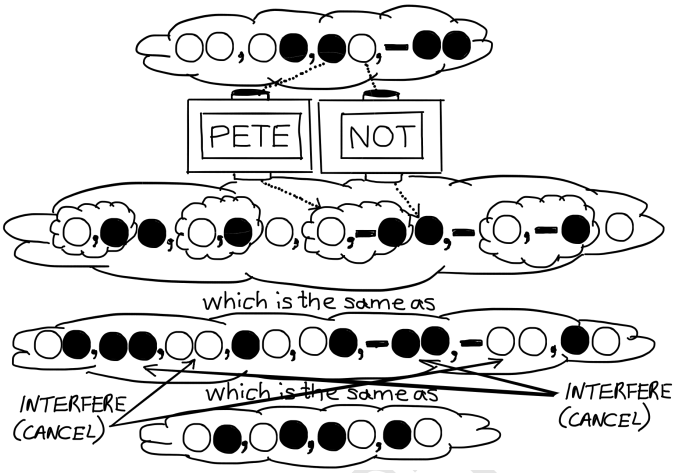
While the ordering of *configurations* (separated by commas) within the mist is up to you to choose, it is not the case that the ordering of the *balls* within each configuration is irrelevant. A WB configuration means the first ball is white, the second black, and this is not the same as the configuration BW. When we have multiple balls in a mist we always know which ball is which—this is the first (e.g. plastic) ball, this is the second (e.g. metal) one, and so on.

The third example shows three balls dropping through a CSWAP box. The CSWAP only affects the ball colors if the first (control) ball is black; if it is, then it swaps the colors of the second and third (target) balls. Remember it swaps the colors, not the balls themselves. In this example, this only changes the second of the four configurations within the original mist.

We see from these examples that passing a mist through any of the boxes obeying the computer rules does not change the total number of different configurations within a mist—it changes only the colors within the configurations that make up the input mist. Things are very different once the PETE box enters the picture.

Mist through both computer-rules and PETE boxes

Recall that every time a ball goes through a PETE box you split it into some mist. If a ball is already within a mist when you do this, then it splits up within the mist into more mist, potentially interfering (i.e., the negative configurations cancel with positive configurations). Here is an example to give you a picture to keep in mind. Don't worry at this stage if it's all a bit foggy and you can't follow the evolution through exactly; although if you can, that's great—you then can understand the rest of this book no problem:



Within the text I will use square brackets to denote "edges of the mist," so the input mist in this example can be written [WW,WB,BW, −BB]. In this example, the first ball goes through the PETE box and splits into a mist of two configurations, [W,B] or [W, −B], while the second ball, which goes through a NOT box, does not split. Note that we then "expand out" the possible configurations. So [W,B]B becomes WB,BB for example. This procedure is explained in more detail in the next section.

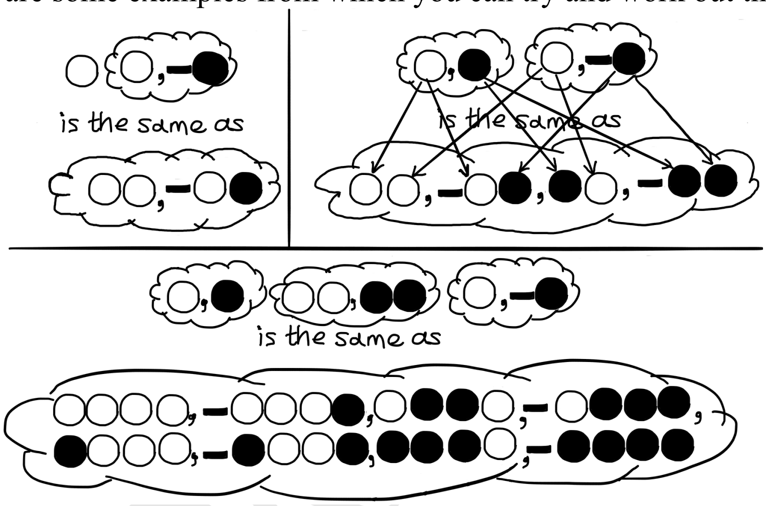
In this particular example, if we observed the two balls prior to them dropping through the PETE and NOT boxes we would find any of the possible combinations of black and white with equal likelihood. However; if we do not observe them until after they come out the bottom we will only ever observe the two balls to have opposite colors—the configurations BB and WW of the initial mist were destroyed by interference. In the output mist, the configurations WB and BW are each repeated twice. This would be physically indistinguishable from a mist containing BW and WB each just once, since in both cases you have equal likelihood of seeing either color configuration, but I leave in the repetitions for pedagogical reasons to do with calculations we make later in the book.

Can you work out for yourself what the output mist would be if the input mist was [WW,WB,BW,BB]—that is, if there was no negative-sign label on the BB configuration of the initial misty state? You should find that one of the balls will always be a single color, while the other might be found either black or white. Note that it is only configurations of ball colors that can be destroyed by interference, not the balls themselves—if you ever find yourself with a mist containing no balls at all, or more balls than entered the boxes, then something has gone wrong in your calculation.

At any time in the middle of a misty computation, we may choose to look at the color of a single ball. In Part II, I will give the precise rule for how the misty state changes when we do this, as it is generally considered very strange and disconcerting. For the moment, however, imagine a computer which operates via a mist cascading down through many stacked boxes until, at the very bottom, we observe the color of all the balls. The outcome will be a random one of the configurations which remains in the mist (i.e., was not destroyed by interference). If all configurations remaining are repeated the same number of times (as in the example just given), then every configuration which remains in the mist is equally likely. I will explain the case of misty states where some configurations are repeated more often than others when we need it much later. At this stage the most important takeaway message is that, just as for a single ball, repeated configurations within multi-ball mists will interfere if one of the copies has a negative-sign label and the other one does not.

Collisions within a fog

The last important ingredient we need to understand about the misty states before we can see a concrete example of a computer enhanced via PETE boxes, is this: What happens when we bring together, or combine together, *sets* of balls—each of which are already in a misty state? How do we describe the larger mist that encompasses them all? Here are some examples from which you can try and work out the rule:



Can you see the pattern? The rule is that when you combine two separate mists you match up every configuration of balls in the first mist with every configuration from the second one and simply append those from the second mist onto those of the first, making sure to keep track which ball is which.

As the ordering of balls within a configuration matters, we must keep the mists all in the right order. In the third example, you can start by combining the first two mists, then combine the resultant mist with the third one, to yield the eight configurations you can see. Writing this third example out in detail:

```
[W,B][WW,BB][W,-B]
is the same as
[WWW,WBB,BWW,BBB][W,-B]
which is the same as
[WWWW,-WWWB,WBBW,-WBBB,BWWW,-BWWB,BBBW,-BBBB]
```

As you might imagine, the number of configurations can grow rapidly—every time you bring in a new mist containing two configurations, you double the total number in the combined mist. In the figure, the combined mists contain two, four, and eight configurations; continuing to bring in new mists each containing two configurations would keep on doubling the total: 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024,… and these numbers grow very fast.

Interestingly, we see in the above figure that a negative-sign label applies to a configuration and not to a particular ball. That is, if you are appending one configuration to another and one of the configurations has a negative-sign label, you can put the negative-sign label on the whole joint configuration. For example, combining WW with −BB yields −WWBB. You do not need to keep track of which particular ball, or even which of the two configurations, the negative-sign originated from—it is a holistic property of the combined configuration. This is similar to when we do math of the form:

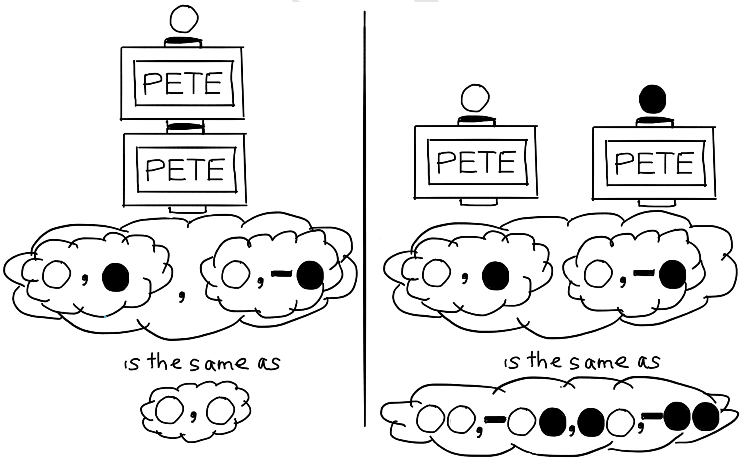
$$2 \times (-3) = -(2 \times 3).$$

If you are appending two configurations that both have a negative-sign label, then, as we have seen already, the two negative-sign labels become a positive (i.e., no label). For example, combining −WW with −BB yields WWBB.

Although it sounds like combining mists is a physical process (grabbing the outputs of some boxes and smashing them together) in fact it is not. It is more like a bookkeeping device. It is completely optional if the balls you are combining are never going to both go through a box like the CNOT, for which they have to interact somehow. That is, if we have two balls in their own mists at widely separate locations we could keep them in their own mists, or we can choose to write down the combined mist. It is only strictly necessary to use the combined mist when the two balls are brought together and something happens to them where the color of one is affected by the color of the other.

Good grammar, is essential

A word of warning: a comma makes a big difference. It distinguishes a superposition (which lists different configurations of *the same ball* or balls), from a combination of mists of *completely different balls*. Here is a subtle example—compare these two very different scenarios, for which the output mists differ only by a single comma:



On the left we have one ball, which is in a superposition of [W,B] and [W, −B], and by interference it ends up in [W,W]. On the right we have two balls—the first ball is in [W,B], while the second ball is in [W, −B]; combining these misty states yields the two-ball mist depicted.

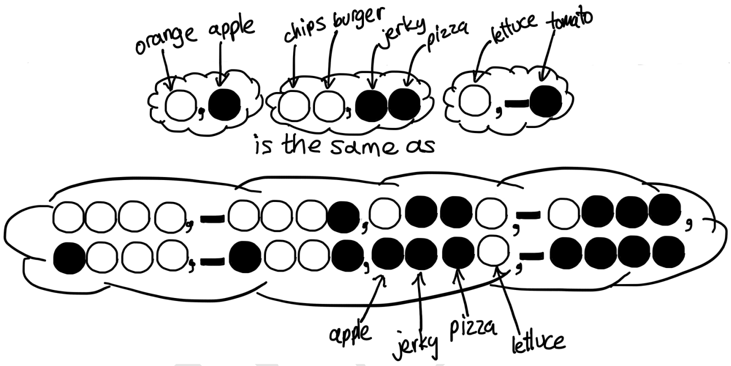
Lunchtime lesson

Should we find the rule about combining mists strange? In fact, it is pretty natural. Imagine you are going on a hike with two friends, and your mother packs you a lunchbox which contains either an orange or an apple. You don't know which; you only know your lunch options are "O" or "A." You now meet up with your first friend, whose mother clearly loves him more: she packed him lunch of either a packet of chips and a burger, or some jerky and a slice of pizza. Your friend doesn't know whether he has "CB" or "JP." (Yes, I know which lunch you want…concentrate please).

You decide to only carry one backpack between you, and so you put the contents of both lunchboxes into it (without looking). The possible contents of the backpack are now OCB,OJP,ACB,AJP.

Finally, you meet up with the second friend. Her mother packed her a lunch which consists of either lettuce "L" or a tomato "T." And you thought you had it bad. After combining her lunch (still without looking) into the backpack, the possible contents you would all agree are now OCBL,OCBT,OJPL,OJPT,ACBL,ACBT,AJPL,AJPT. Note that, analogous to misty states of balls, the order I have listed the possible lunch configurations is irrelevant to the description of the backpack contents. But, sadly for you, the order of each possible foodstuff within any configuration is important—the first letter always refers to your particular lunch, for example.

Compare the eight possible backpack contents to the final example in the previous figure. The configurations match up if you do the following: identify the physically distinct alternatives of the first ball (white/black) with the physically distinct alternatives of your fruit (orange/apple). Similarly, identify white/black of the second ball with chips/jerky, of the third ball with burger/pizza, and of the fourth ball with lettuce/tomato:



I described combining the lunches as a physical process—tipping the contents into a backpack without looking. But what if I had just said, "You each keep your own lunch; just list all the possible lunch combinations"? The list you would make would still be OCBL,OCBT,OJPL,OJPT,ACBL,ACBT,AJPL,AJPT. No "interaction between the foodstuffs" is required for the combined list to be the correct description of the full set of possible lunches. If your lunches were never to interact then it would be your choice whether to use the combined list or just list them separately. Imagine, however, tomatoes had the magical ability to convert an apple into an orange and vice versa. It then makes a difference whether the lunches get mixed together or not, because for something to happen (the killer tomato to attack your fruit) the foods would need to be in the same location (the backpack). The description of the (potential) ensuing mess—depending as it does on whether your friend actually has been packed a tomato—would first necessitate listing the combined contents. We could then describe the action of the (possible) tomato on the fruit much like a CNOT gate acting on the lunch list. This is all very similar to the case for the balls, where the combining of two misty states is not a physical process per se; it is, however a necessary description once the balls interact via one of the multi-ball boxes and we change a color of one ball in the mist dependent on the color of another.

As yummy as this whole lunchbox analogy is, there are limitations—there is no such thing as a "negative-sign-labelled tomato," for example. Moreover, we already proved (by stacking two PETE boxes) that there is no way to think of the misty state of a single ball as "the ball really is either black or white"; whereas the contents of your lunch box can be understood as "the fruit really is either an orange or an apple."

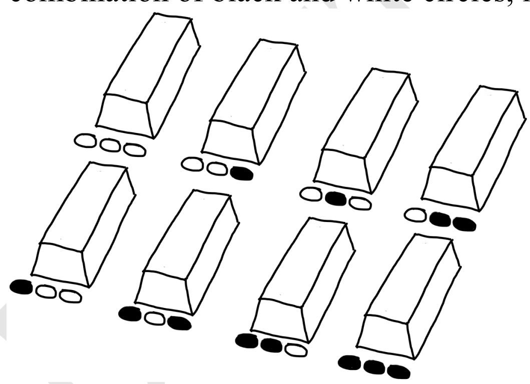
But in terms of understanding how the configurations within separate misty states combine to make a larger misty state, it works perfectly.

Misty computation can be very lucrative

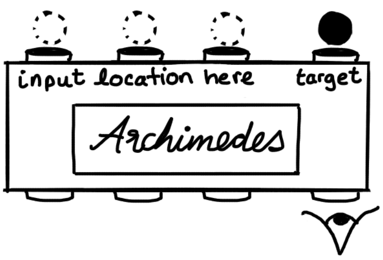
We are now in a position where I can finally give you a concrete example of how the addition of PETE boxes to a computation can be a huge advantage. This example is a little contrived, but it exhibits all the core principles that underpin the computational power of the PETE boxes. (We will incorporate misty possibilities into computers of the future to do much more interesting things than this.)

To set the scene, imagine you are trying to rob a bank. When you finally tunnel into the vault, you find yourself in a room containing eight giant gold bars. You have inside information that this bank has many vaults, and, in any given vault, either all eight of the bars are fake, or four are fake and four are genuine. The fake bars are very good, you cannot tell them apart from the genuine ones without extremely sophisticated laboratory-scale equipment, which of course you cannot just carry around.

The employees of the bank also cannot distinguish genuine bars from fake ones. Rather than give them a list of the genuine bar locations, which could be copied or stolen, the witty bank manager has installed in the corner of the vault one of our black and white ball computers, labelled *Archimedes*. Every bar in the room has a location uniquely identified by a combination of black and white circles, like this:



To check whether a particular bar is genuine or not, a bank employee drops three balls, with colors corresponding to that bar's location, into Archimedes, and a fourth "target" ball which starts off black:



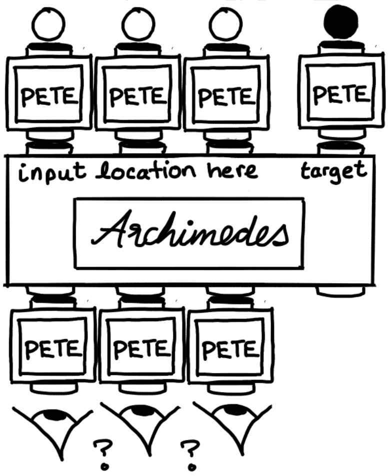
Archimedes works in such a way that if the gold bar at the location corresponding to the input balls is genuine, then a NOT is applied to the target ball. So, if the target comes out white then the employee knows that particular bar is genuine, if it remains black it is fake. The three location balls just emerge the same color they entered - similar to the control ball(s) of a CNOT or CSWAP or CCNOT box.

Imagine you know that this is how Archimedes works, but there is a snag. The time it takes for the balls to fall through Archimedes is very long—let's say an hour. Perhaps this is an extra layer of safety for the bank to thwart people like you, or perhaps it is because inside Archimedes are a huge number of boxes executing some very complicated computation (otherwise possibly you would just smash Archimedes open to see if the information you need is easily accessible!). You definitely do not have time to check more than one bar before you had better get the heck out of the vault. To make matters worse, you are part of a gang, which has busted open many of the vaults. The gang leader has declared that anyone who steals only fake bars will be executed, as they will have wasted valuable space in the getaway truck.

It would seem the best thing you can do is pick one bar location at random and check if it is genuine or fake. If it is genuine, that's great—you know you are in a vault with four genuine bars, and so stealing all eight bars is worthwhile. If it is fake, however, you will still be unsure which type of vault you have entered, it could be of either type. Without PETE boxes this really is the best you can do. Using Archimedes only once you can never be sure that you will be sure in an hour about which type of vault you are in.

Fortunately for you, and also for me (if you paid for it—though given your current escapade this seems unlikely), you have read this book and came prepared with some PETE boxes. This is going to let you determine for absolute sure which type of vault you are in, using Archimedes only once—that is, in just one hour.

The method to achieve this little piece of magic is as follows. You place four PETE boxes above all four entrance holes to Archimedes, and three PETE boxes at the bottom where the first three location balls emerge (there is no need to put a PETE box below the target hole). You drop into the first three PETE boxes a white ball, and into the fourth PETE box above the target hole, you drop a black ball.



One hour later, when the balls emerge, you check the color of the first three location balls. If all three balls are white then you are 100% guaranteed that you are in a vault containing only fake bars. If any (or all) of the first three balls are black, you are 100% guaranteed that you are in a vault containing four genuine bars and four fake bars.

To see that these last two assertions are true is a little bit of a messy calculation, I suspect it will be the messiest in the whole book, and so you should definitely skip it on a first reading if you're not yet comfortable with these misty-state manipulations. Although the calculation is messy, it does not use any new rules beyond those I have already introduced you to.

Before you skip ahead, here is the intuitive description of how it works. The three PETE boxes above the location holes create a large misty state, in which all eight possible gold bar locations appear (all without a negative-sign label). The target ball enters Archimedes in a misty state of white and a negative-black. Archimedes performs a calculation in the mist that acts on all possible location configurations at the same time. This is one part of the magic—a regular computer cannot do anything like this. The last three PETE boxes at the bottom of the computer are there to cause interference—the adding and subtracting of some of the configurations in the mist because of the negative signs. The interference is carefully tailored in just the right way such that the only possible way the first three balls end up white (the same color they went in) is if all the bars are fake; if four of the bars are genuine then at least one of the three location balls will come out flipped to black.

You didn't have to initially use three white balls at the location holes. If you begin with a different initial color configuration then you will find those three balls definitely emerge the same configuration they went in if all bars are fake, and definitely emerge in one of the many other color configurations if four of the bars are genuine.

The Archimedes calculation (consider this an aside)

We drop a white ball in the three PETE boxes above the location holes, and a black ball in the one above the target hole.

Case 1. All bars fake: If you are in a vault that only contains fake bars then Archimedes does nothing to the misty state; its effect is the same as if it was not there at all. After an hour the three location balls that exit Archimedes then each go through another PETE box. As we have seen, the combination of two PETE boxes in succession is the same as doing nothing—a white will emerge white, a black will emerge black. Since we input three white balls, we conclude that if you are in a vault containing only fake bars, you will definitely see the first three balls come out white.

Case 2. Four genuine bars: After entering the first line of four PETE boxes the balls are in the misty state:

[W,B][W,B][W,B][W,-B]

By the rules for combining mists, this is the same as a single large mist of 16 configurations.

The mist after 4 PETE boxes, but before Archimedes:
[WWWW, WWBW, WBWW, WBBW, BWWW, BWBW, BBWW, BBBW,
-WWWB,-WWBB,-WBWB,-WBBB,-BWWB,-BWBB,-BBWB,-BBBB]

This misty state now goes through Archimedes, which applies a NOT whenever the first three balls correspond to the locations of genuine bars. To illustrate, let me just pick four such locations at random. Let's say the four genuine bars are at the locations labelled WWB, WBW, BWB and BBB.

The mist after Archimedes, before the final PETE boxes:
[WWWW, WWB**B**, WBW**B**, WBBW, BWWW, BWB**B**, BBWW, BBB**B**,
-WWWB,-WWB**W**,-WBW**W**,-WBBB,-BWWB,-BWB**W**,-BBWB,-BBB**W**]
which is the same as
[WWW,-WWB,-WBW,WBB,BWW,-BWB,BBW,-BBB][W,-B]

To make it easier to see what's going on I used bold font to indicate the target ball colors that Archimedes flipped by applying a NOT. We see that the configurations corresponding to locations which contain a genuine bar now have a negative-sign label. Unfortunately, the negative signs cannot be observed, and so if we destroyed the mist by observing the balls now we would learn nothing useful. The final three PETE boxes are going to help cause interference so that these negative-sign labels have some useful effect.

It is a fortunate happenstance for this particular problem that the full mist of sixteen configurations can be split back apart into a mist of the location balls containing eight configurations, and a mist of the target ball containing just two. This will simplify the analysis, but in general this kind of thing does not happen in a misty computer (although for this particular problem it would happen no matter which four locations I had chosen to contain genuine bars).

We now take this mist of the eight configurations for the location balls and send each ball through another PETE box. Can you see what a giant mist this is going to produce? For example, just the BBW configuration in the mist will break up into eight configurations like this:

```
                 BBW
   evolves through 3 PETE boxes to
          [W,-B][W,-B][W,B]
          which is the same as
[WWW,WWB,-WBW,-WBB,-BWW,-BWB,BBW,BBB]
```

Thus the total mist of the location balls, after evolving through the second set of PETE boxes, potentially has 8x8=64 configurations in it—although many of these will disappear due to interference. Here then is then a calculation of the full set of final configurations in the mist. Don't say I never do anything for you (and if you are reading this electronically you may want to resize the font to make this palatably line up):

```
[WWW, WWB, WBW, WBB, BWW, BWB, BBW, BBB,
-WWW, WWB,-WBW, WBB,-BWW, BWB,-BBW, BBB,
-WWW,-WWB, WBW, WBB,-BWW,-BWB, BBW, BBB,
 WWW,-WWB,-WBW, WBB, BWW,-BWB,-BBW, BBB,
 WWW, WWB, WBW, WBB,-BWW,-BWB,-BBW,-BBB,
-WWW, WWB,-WBW, WBB, BWW,-BWB, BBW,-BBB,
 WWW, WWB,-WBW,-WBB,-BWW,-BWB, BBW, BBB,
-WWW, WWB, WBW,-WBB, BWW,-BWB,-BBW, BBB]
```

In the large output mist the first line originates from the WWW, the second from the −WWB and so on. If you look at the 64 configurations in the final mist, you see that there are exactly the same number of WWW configurations with a positive label as a negative-sign one. This means they all disappear by interference. Which in turn means when you observe the three location balls you will definitely *not* see all three of them white. At least one of them will be black.

Even if you raced through all that (as I would do on a first reading) and didn't really follow it, that's OK. The final claim is that the only way to see all three location balls emerge white is for you to be in a vault containing all fake bars. Conversely, if any or all of the balls come out black when you observe them, then you are in a vault containing four genuine bars.

If you have the fortitude, it would be a good idea to redo this calculation for yourself, picking a different four locations for the genuine bars than the ones I chose.

Before leaving this complicated aside aside, let me remark that it is just as annoying for me as it is for you that I have had to describe this whole Archimedes problem and its solution in terms of the individual boxes and what they do on specific ball configurations. It is much like if we wanted to play a computer game but first needed to specify how each individual transistor within the computer should be set. In practice, for regular computers we have programs built via programming languages which let us determine what the computer should do by giving it a set of instructions that we ourselves can understand quite naturally. Unfortunately, we have no good programming language for a misty computer. This is not because we don't want one. So why haven't we made one? Well, if you have ever written some computer code you know that a program is just a set of logical instructions for the computer to follow; instructions of the form "check IF this thing AND NOT that thing are the same, and if they are THEN do the following." But that is all just a phrasing of regular logic, amenable to boxes obeying the computer rules—rules that we cannot use naturally to describe a misty computer!

Is there no limit to the magic?

I phrased the story above in terms of a vault containing eight bars. If there were double this number of bars, then the sixteen location labels would require four circles, and Archimedes would have four location holes. Yet, as long as you had the extra PETE boxes for the extra access into Archimedes you would still be able to determine the type of vault you were in by using Archimedes just once. This remains true whether the vault has 8 or 16 or 32 or 64 or… or 1024, or 2048, or …. or 65536 or… or any such "doubling number" of gold bars. In just one hour you can be absolutely sure of whether you were in a vault of all fake bars, or a vault where half of them are genuine.

Contrast this with the following worst case scenario. You enter a vault with 65,536 bars, and you have no PETE boxes. The gang leader now insists you do not leave the vault until you are absolutely sure which type of vault you are in. Perhaps you have entered a vault of fake bars. You start choosing locations at random and testing them and Archimedes tells you "fake, fake, fake,…." Are you definitely in a vault full of fake bars? No, because you may have entered a vault containing 50% genuine bars and 50% fake bars, but you are just really unlucky and keep testing the locations of fake bars. In that case you would also keep seeing "fake, fake, fake,…" as the answer. Until you have tested more than half of the 65,536 bar locations you could not be absolutely sure of which type of vault you were in. Do you really want to spend half of 65,536 hours (nearly four years) checking? Jail would be way more fun.

This last example brings home a crucial distinction between regular computers and those, like Archimedes, capable of utilizing misty states. Because it needs a much, much smaller number of steps, we see that even a slow ball-based computer using misty states will be better than using the fastest supercomputers around, once the number of gold bars to check gets high enough. The valuable resource that these misty computers can save us, is "number of computational steps"—which in many cases can lead to a staggeringly large savings in the time it takes to get an answer. It is a common misconception that the misty computers will be smaller and operate with a higher speed than regular computers, but in fact we do not expect that at all. The reason we want these misty computers is because, even if their speed of operation is much slower, it is their fundamental logic which is different, and this gives them an unconquerable advantage for certain problems.

Another point to emphasize about the misty computers is that they are much more than just regular computers with some extra fundamental randomness thrown in. In a limited fashion, the Archimedes example shows that: random choices without PETE boxes is not equivalent to PETE boxes. Access to fundamental randomness does make regular computers somewhat more powerful, but they still cannot come remotely close to the power of the misty computers.

Misty computers will be very lucrative, but not because they will help us rob banks. There is a massive worldwide effort to build them because they will vastly outperform our regular computers for certain problems that are major obstacles to technological progress. Examples include calculating accurately the chemical reactions necessary to design important new medicines, or solving the equations that will let us design highly-specialized materials to harvest solar energy better, or speeding up machine-learning so regular computers become more intelligent than ourselves sooner, or … well the list is massive, and I have heard the figure thrown around that over twenty percent of all current supercomputer time is spent solving problems that a misty computer will be able to solve unbelievably more easily and quickly.

However, the really exciting thing is not that misty computers will let us do things we already do a bit faster—rather, it is that they will let us tackle problems that at present we don't even bother trying on our regular computers since we know they are much too hard.

Yet, while the misty computers will solve some problems much more easily, the set of all "in principle solvable" problems is unaffected by the new possibilities of misty logic. This is another point that is often misunderstood about what the misty computers will and will not be able to do. They will not be able to "compute the uncomputable." The set of problems they can solve in principle is no bigger than the set of problems we can solve on our current regular computers. How do I know that? Well, above I have given you the full set of rules for how to compute what happens to the misty state as it evolves through the boxes. So you could just sit down with a piece of paper, and draw out the misty states, and work it out for yourself.

How much paper would you need? If you begin with a problem using seventy balls falling through seventy PETE boxes (and we expect to build much larger misty computers than this) then the number of balls in the combined misty states will be the seventieth term in the doubling sequence: 2, 4, 8, 16, 32, …. Assuming you can draw at most about a thousand balls on a page, you would need so much paper you would be able to completely cover the earth. Use just one more PETE box and your paper stack will be large enough to cover two earths. (And I think *I'm* sick of drawing black and white balls….)

More sensibly, you would write a program for a regular computer to do the calculation for you, and computers don't need paper. They can store huge amounts of data in the tiny chunks of matter that make up their memory. As impressive as this is, in the end it only helps a little—even if we turned every atom in the earth into a bit of computer memory, the computer would only be able to "write down" the misty state produced by fewer than 150 PETE boxes.

While there are some clever programming tricks that will optimize things a bit, and reduce the time and memory requirements from these naïve estimates, the upshot is that even using these tricks you would need an absolutely giant regular computer (as big as the universe for even reasonably sized problems) and very, very long amounts of time (more than the age of the universe) to work out what a small misty state computer will be able to somehow do on its own, inside itself, quickly and easily. In theory you would be able to do any computation a misty computer does, but in practice you cannot. Unless, of course, you happen to be The Spectre (who is immortal) during Crisis on Infinite Earths (so you have lots of space)—and if you are then it seems likely you have many problems of inconsistent logic on your mind; best to work on those.

A final common misconception about misty computers is that this huge growth in the number of configurations is "obviously" the source of the extra power of a misty computation. But some caution is required. If you went on a hike with seventy people, each of whom had a "two options" lunch which you threw in a backpack, the total number of potential lunch configurations in the backpack is just as large as the misty state after dropping balls through seventy PETE boxes. Just as for a misty state, when you look inside the backpack, you will only see one of the configurations. Within the mist, however, interference (cancellation) is possible between different configurations that are somehow all "in there" together, and this is not something that can be mimicked by your lunch.

Well, why can't we buy one of these magical, misty computers yet?

We can build many versions of the PETE box already, and our current computers already contain devices (transistors) implementing the computer rules like NOT and CNOT and CSWAP and so on. So why can't we just join them all up?

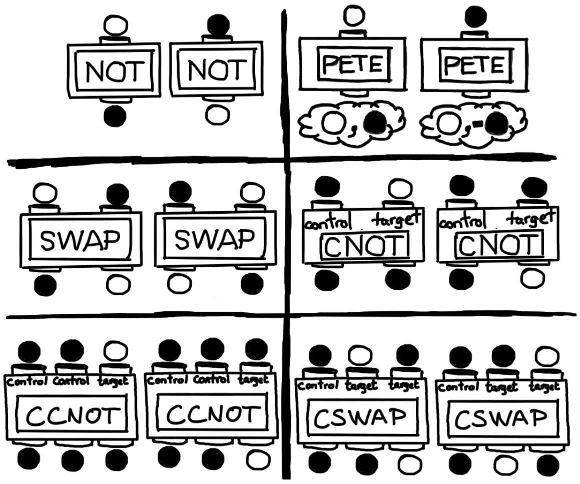
The reason we cannot just grab some components at Fry's electronics and hack up a misty computer is because the computer-rules devices we have built (so far) are all really nosy: they just can't help themselves looking at the color of the ball exiting the PETE box. We try and try to get them to not do it, but they are like a curious cat that desperately needs to see the color, and their observations keep on burning away the valuable mist. Nosiness leads to noisiness.

We are making a lot of progress, however, and I am optimistic we will create large scale, useful misty states very soon.

Many, many words ago I claimed the existence of misty states would profoundly change your whole view of the physical world. But with respect to computers, this now seems to be a bit of hyperbole, as if I was just writing a standard pop-sci book. I mean, sure these new computers will impact your life, they may even help extend it hundreds of years, but the progression of our lives is already marked by the continual increase in computing power we have all witnessed and come to expect. In terms of challenging deep-seated conceptions about how the universe works we are going to have to delve into a more detailed look at the illogical behavior of the misty states. This will show they are completely incompatible with "sensible and obvious" expectations we have about the nature of physical reality.

Summary of Part I

* Two distinct physical properties (e.g., black and white color) of a system (e.g., balls) can be manipulated by extremely simple rules (e.g., NOT, CCNOT, etc.) that nonetheless can produce the profound complexity of computation, and moreover map directly to the basic logic of our thought processes.
* There exist some experiments that exhibit fundamental randomness. The origin of the randomness is subtler than our simple ignorance about what's going on inside the experiment.
* Two distinct physical states can sometimes be in a misty state or "superposition," which is jargon for a new state of physical/logical being.
* Our observations of things cannot be completely passive.
* These misty states are definitely math and possibly physics, but their status is contentious.
* The misty states grow rapidly as you bring in more systems. But the same can be said about your lunch prospects.
* Regardless of what they are, a suitably built computer will be able to utilize misty states to do certain computations in vastly fewer steps than regular computers would require. This means we don't need to care about the speed at which they execute each step: they will win because they use a different logic.
* The excitement about misty computers is not because they will let us solve problems we currently tackle a bit faster, it is because they open up vast new territories of previously unthinkable problems to take on.
* Misty computers do not compute the uncomputable—the set of in-principle soluble problems is the same. They just make previously highly infeasible problems tractable.
* The boxes we have encountered are:



In the diagram, only cases where the output is different from the input are shown—in all other cases the boxes do not change the input.