Q
is for
QUANTUM

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ISBN: 978-0-9990635-0-7

www.qisforquantum.org

Cover design by Chris Van Diepen, createwithbodhi.com

For Xavier, Aby, Lydia, Jesse and Caleb

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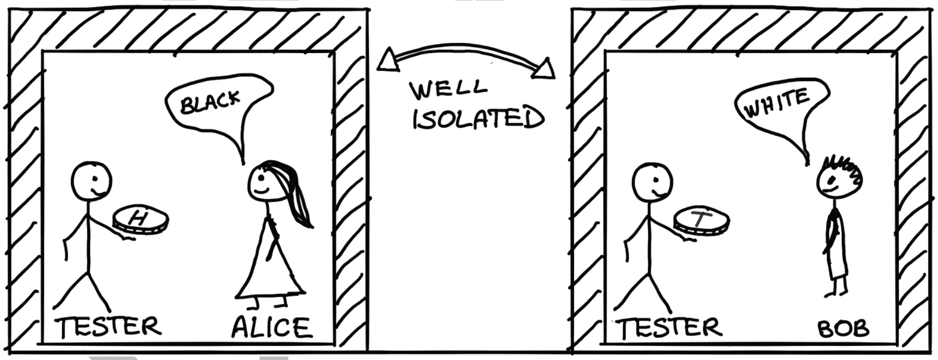
Part II: Q-ENTANGLEMENT

A tale of testing telepathy

Many people—let's call them psychics—claim to have telepathic ability; that is, an ability for instantaneous communication between two separated minds, via means unknown. Whenever asked to evaluate claims of powers that go beyond the laws of physics as we currently understand them, the prominent magician James Randi (who in the past has offered a $1 million dollar prize for any demonstration of such) will insist the claimants first make precise exactly what it is they say they can do. He has found there is no point in designing the test and then challenging the psychics to meet its standards, because the psychics can wriggle out by saying their powers are not compatible with meeting the specific challenge the skeptical tester would like. Rather, it is best to test exactly what it is the psychics claim to be able to do, making sure only to install obvious and agreed-upon safeguards against cheating.

Imagine (as I hope is actually true) that you are skeptical of generic claims of psychic abilities, but you are open to being convinced otherwise by a suitably rigorous demonstration. You are working for Randi when two psychics, Alice and Bob, contact you (by regular means), claiming to be telepathic. You now enter a negotiation as to how they will demonstrate their ability. Unfortunately, and this is quite typical, they do not claim to be able to do something obvious and readily testable, like transmit a simple message. Their powers, they say, are subtler.

Eventually the protocol they propose involves them each being separated in well-shielded rooms, to prevent communication by any regular means. Within each room a tester will flip a coin and tell the psychic in that room the outcome, "heads" or "tails." The psychics will each then have to say to their tester one of two very magical words—namely, either "black" or "white."



Proposed test of telepathy:

The psychics win the $1 million if both coin flips come up tails and they both say "black."

There are two rules:

Rule 1: If both coins are heads, the psychics must not both say "black."

Rule 2: If one coin is heads and the other is tails, the psychic told "heads" must not say "white" when the psychic told "tails" says "black."

If either of the rules are broken, the psychics are severely punished.

There is quite a lot to think about in terms of understanding this proposal.

Firstly, the "game" will need to be played multiple times. If it is only played once and something other than "tails-tails" comes up, then the psychics have no opportunity to win at all.

Secondly, the proposal is that the psychics are “severely punished” if they break either of the two rules. What is something so bad nobody would risk it, even for a million dollars? Think of the worst thing that could happen to someone (head chopped off, pet cat skinned alive until it’s half-dead, ugly selfie posted on Instagram—whatever). Are you confident the punishment is so bad they will not risk it for a million dollars? Less drastic would be to impose a proviso: if any of their answers ever break one of the two rules, the whole game is off, and they definitely lose. If it so happens that every time the game is played and they try to win by non-telepathic means, they also necessarily run some risk of breaking one of the rules, then by playing many times you can make it very, very unlikely (much less than a one-in-a-million chance) that they could win.

Thirdly, if the psychics are isolated and cannot communicate then the testers also are unable to communicate. So, they will need to play a bunch of times, and then the testers get together and compare the coin flips and psychics’ answers in order to check if the psychics ever won (and, if so, did they also always satisfy the two rules?).

But all of this is jumping the gun a little. Why would they need to be psychic to win at all?

I would encourage you to stop now and think about possible strategies for Alice and Bob. To make it easier, here is a summary of the answers that are or are not allowed under the two rules:

COIN FLIPS \ ANSWERS	Alice Bob B B	Alice Bob B W	Alice Bob W B	Alice Bob W W
Alice Bob T T	WIN!	OK	OK	OK
Alice Bob T H	OK	NO!	OK	OK
Alice Bob H T	OK	OK	NO!	OK
Alice Bob H H	NO!	OK	OK	OK

It seems like there should be no problem for them to win the game. But there is. You should try for yourself to prove that they cannot win the game while simultaneously always obeying the two rules (unless, of course, they are actually telepathic). One way to see the issues is to play out what you imagine the conversation between the two psychics will be when they get together to work out what they are going to do.

AN IMAGINED CONVERSATION BETWEEN THE PSYCHICS

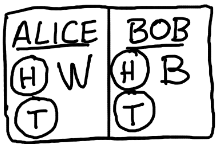
ALICE: Awesome, those suckers accepted our proposed test. Obviously we aren’t actually psychic, but I’m sure we can win this game.

BOB: Let’s work out a strategy. Actually, we both know I’m not the sharpest pencil in the box, Alice—I better let you work it out.

ALICE: Fine. By Rule 1, when we both get heads, we cannot both answer “black.” So how about I will answer “white” when I get heads, and you can answer “black” when you get heads.

BOB: Woah, slow down there, Alice. I think I better write this down, it sounds complicated already.

Bob hunts for pencil and paper, finally finds one and draws a diagram.

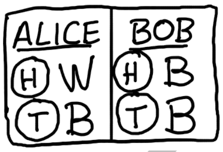


Bob shows it to Alice.

BOB: (*Proudly*) See, I made a table of what we should do. I drew a picture of each coin and its two possible outcomes H or T that the tester could tell us, and I'm putting B to mean black and W to mean white next to each outcome for what color we should answer.

ALICE: Yes Bob, it's very pretty. Let's keep going. Since we only win by both answering "black" when we both get tails, when we see tails we should always answer "black."

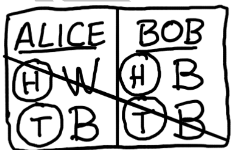
Bob duly makes a note of this as well.



ALICE: So there you go, we have a solution. Now, let's think about what to spend all that money on….

Bob is looking a bit puzzled, scratching his head. Alice has started to daydream.

BOB: Uh, Alice, I think there is a liiiiiittle problem. By Rule 2 if I get tails and you get heads I am not allowed to answer "black" when you answer "white." See, I put a line through the combination that breaks the rule:



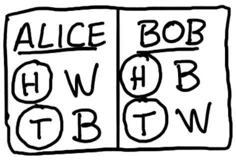
Alice slowly refocuses her attention.

BOB: And because you won't know whether the coin in my room came up heads or tails, there is a risk we will break this rule.

ALICE: (*Impatiently*) Yes, Bob, I see the point. Let me think for a second.

Both Alice and Bob enter deep concentration.

BOB: (*Eagerly*) Oh, wait, I have an idea—we can make sure to not break Rule 2 by using almost the same idea as you had Alice, except that I will say white when I get told tails. See, this is what I propose we answer, it clearly satisfies both Rule 1 and Rule 2:



ALICE: (*A little sarcastically*) Sure Bob, that's great. We will obey both the rules. But don't you see a problem with that?

BOB: Uh, no, looks fine to me.

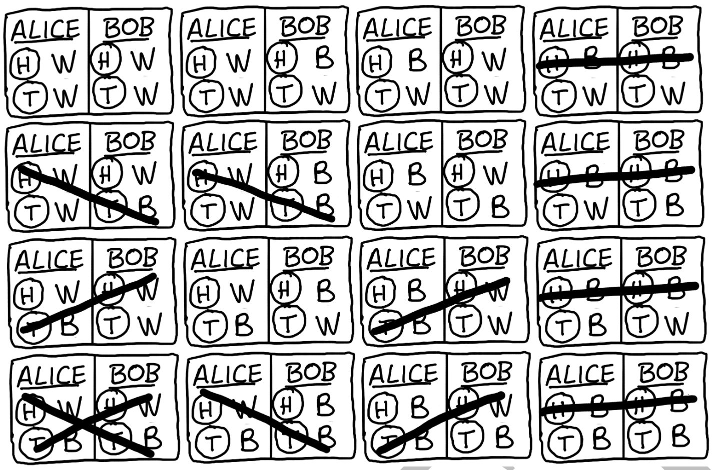
ALICE: Think, Bob, think. If we give those answers, then we will never win. When we both get told "tails," you will be answering "white"—and we only win if we both say "black" when we both get told "tails."

BOB: Oh, yeah, um sorry Alice.

ALICE: (*Muttering to herself*) For tails we both answer "black," but by Rule 1 at least one of us needs to answer "white" for heads, and Rule 2 rules out the other person saying "black" for tails, which rules out winning….

BOB: I can’t think through logical stuff like you, Alice. So I’m going to draw out every possible way we can choose to answer, and then put a line through every combination that violates one of the rules.

Bob starts drawing and after a few minutes produces his diagram:



BOB: Nooooow I see the problem. There are some answers we can give that don’t break any of the rules, but the winning combinations are the ones in the bottom row for which we both answer black when both coin flips are tails. All of those have at least one line through them because they disobey one or both of the rules.

ALICE: Damn, what have we gotten ourselves into? If only I were actually telepathic, then I would just telepathize the coin outcome my tester gets to you, and even *you* would be able to make sure we win. But I’m not telepathic, and I’m sure you’re not, Bob, since it presumably requires having more than three brain cells.

BOB: Hey, no need to get nasty now. Even a three-brain-celled person can lead a nuclear weaponized country, you know.

Scene ends with two grouchy “psychics” not talking to each other, at least not verbally.

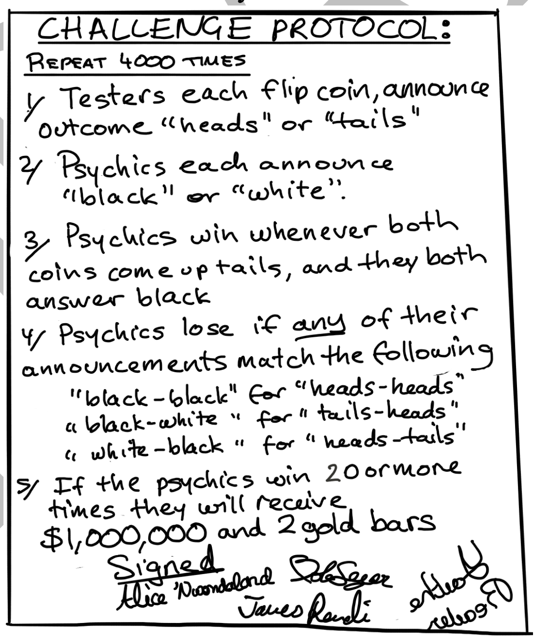
Let me harp on a little longer about the psychics’ options if they are not telepathic. Perhaps it is a mistake for them to pre-determine their strategy? Maybe they should only decide on a “black” versus “white” answer once they know the coin flip they are told by their tester? For example, they could use a coin flip of their own and base their color choice partially on the outcome. Can you see why such a “non-deterministic” (i.e., not pre-determined) strategy won’t help? It makes the other psychic even less sure what their partner is answering, and that cannot help them win. Even if their strategy is chosen randomly in this way, it will still amount to one of the sixteen diagrams Bob drew above, and so will either not have any chance of winning, or will run some risk of breaking a rule. Once again we see we need to test them multiple times to be sure they didn’t just get lucky.

If the psychics are not telepathic and rather employ some combination of the strategies in the diagram Bob drew above, then whenever they cheat (by deciding their colors based on the last row in the diagram, which are all the possibilities where they both answer black for tails) they run at least a one-in-four chance of breaking one of the rules. You can see this in the diagram: for each of the enumerated potential cheating tactics in the last row, at least one of the four possible coin combinations makes them answer colors forbidden by the rules. They also have a one-in-four chance of winning, since this is how often both coin flips would come up tails. Finally, they have a one-in-two chance that nothing happens: they don’t win (because the coin flips did not come up both tails), but at least they don't break a rule and get caught.

You and Randi don't really care what cheating strategy they would optimally employ—you just want to pick a number of times they must win, such that you and he can be confident that they would have less than (say) a one-in-a-million chance of winning unless they really are telepathic. Calculating odds like this is a bit tricky. They will need to cheat many times, and each time that they cheat and don't win they need to get away with it. Intuitively their likelihood of doing so decreases rapidly, much as the chances of you playing roulette and it landing on red over and over and over again decreases rapidly the more times you play. Fortunately, you have your friend in the bank, the same one who gave you inside information when you were robbing it in Part I. Unlike most people who work in banking, your friend understands this kind of thing. He tells you that if they win twenty times using any of the strategies from the last row in the table above, the probability they get away with cheating is less than one in a million. (If you want to see the calculation go to the webpage for this book).

You explain to the psychics that you want to play the game multiple times, both to give them a chance to win and to safeguard against cheating, and you require at least twenty wins. They come back and say that if the game is played four thousand times—so that by the law of averages the coin flips will both come up tails about a thousand times—they will definitely win more than twenty times, and will never break a rule in any of the four thousand games.

Once you understand all this you and Randi agree with the psychics that this is a fair test. You even get a bit carried away, and offer to also throw in a couple of genuine gold bars you came across recently.



Playing the games

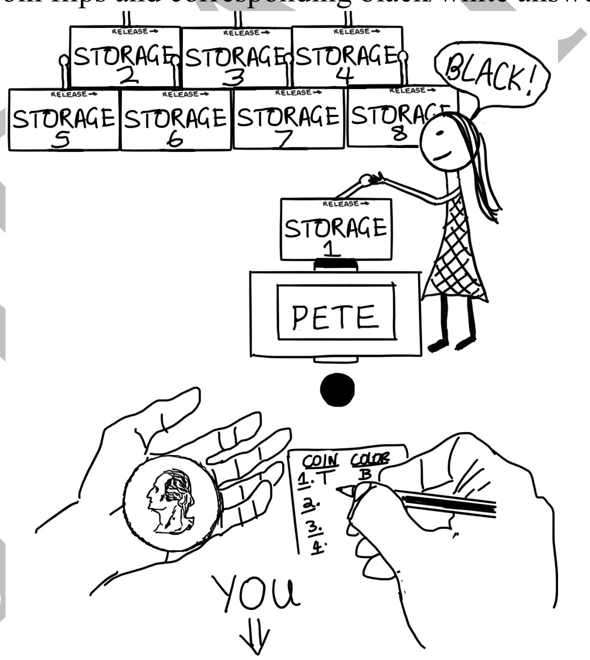
The day of the test comes, and there is much fanfare as the world's media descends. Alice and Bob show up. Hang on, what is going on? They are both carrying a large number of boxes that they each want to take into their isolated room. They say that there is nothing in the rules preventing them having "telepathic aids."

Now, given more time and without the glare of the media, you would hopefully realize that you should contact me or some other scientist just to be sure you haven't missed something. But here is the thing: You and Randi are fully convinced that you have managed to completely isolate the two rooms that each psychic/tester pair will be closed into. What could it really matter if Alice and Bob bring some stuff in with them? Even if they bring in powerful supercomputers to help them do complicated calculations that might somehow help determine the color they should announce to each coin flip, you are sure from the arguments presented above that they cannot simultaneously obey the rules and ensure a win, and so they run a risk of being caught cheating. Of course, you do understand from your bank escapade that a misty computer can do some calculations faster than any supercomputer, but all the computing power in the world isn't going to change the fact they ultimately need to answer "black" or "white" according to some simple constraints that are easily shown to not be consistently achievable. So you decide to let the test go ahead.

Since you and Randi are the ones with serious money at stake, you have decided, as an extra hedge against possible cheating ("Hey skeptical tester friend, want half a million bucks and a gold bar?"), that you each will act as a tester.

When you get into the room with Alice you find that she has brought in a huge pile of boxes, each labeled STORAGE and numbered from 1 to 4,000. You get a slight sinking feeling when you see that she also brings in a box labelled "PETE."

The test begins. You flip your coin and it comes up "tails," which you call out to Alice. Alice then takes the small box labeled STORAGE 1, holds it above the PETE box, pulls some kind of lever and almost immediately a black ball falls out from it. "My first answer is black," Alice tells you. You write it on the piece of paper you brought to record the coin flips and corresponding black/white answers:



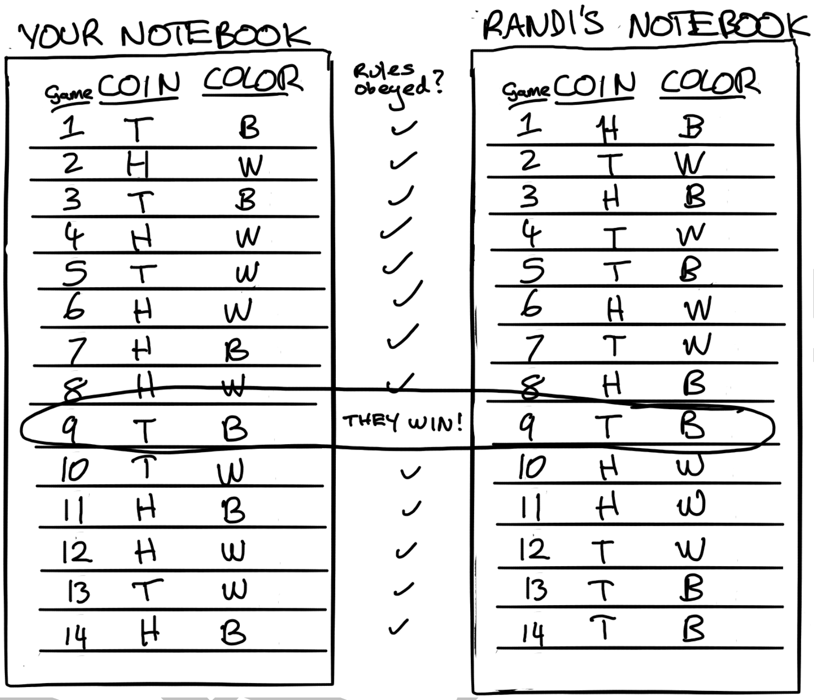
The second time you flip it the coin comes up heads. Alice takes the box labelled STORAGE 2, but this time she does not hold it above the PETE box, she just pulls the lever, and a white ball drops out the bottom of the STORAGE box. Alice says, "My second answer is white." For someone supposedly being telepathic, Alice is acting quite brusque and business-like. "Next!" she says impatiently. "There are a lot of games to play."

After a full day, with the test drawing to a close, you have seen the same procedure repeated thousands of times. Each time you play, Alice takes the next unused storage box from the stack. If the coin you flipped shows heads, she just pulls the lever, while if it is tails, she holds it above the PETE box and pulls the lever.

Either way, she announces “black” or “white” according to the color of the ball that drops out.

After the end of the four thousand repetitions of the game you and Randi meet up and exchange stories. He had the exact same experience with Bob as you had with Alice—Bob also based his black/white announcements on the color of a ball which fell out of a storage box, one that was first held above a PETE box if the coin flip showed tails.

You and Randi now sit down and start the laborious process of counting up how many times the psychics won. That is, how many times did they both say black when you two both flipped tails? You also need to check that their other answers obeyed the two rules. The first pages of your notebooks might look like this:



When you add it all up, you find that the psychics have won eighty times—which far exceeds the minimum twenty times you agreed on. They will win the cash and the gold bars! A bit panicked, you (not Randi, he’s chilled about everything) do the comparison again—maybe having that overly-strong American Pale Ale while you were doing it wasn’t a great idea, and you messed up counting? (For that matter, are you old enough to drink a beer yet?) You find that you were correct the first time, the psychics have exceeded the requisite twenty wins by a long way without ever breaking either rule.

The probability of eighty wins following a strategy where you risk a one-in-four chance of being caught every time you cheat, according to your friend in the bank, is absolutely and utterly, mind-numbingly ridiculously small. It is so small that you have a much better chance of winning a game where I take one grain of sand, mark it somehow, and hide it anywhere on any beach in the whole world, or anywhere in the Sahara desert as well. You then walk around the whole world blindfolded, sifting through all those sandy beaches, dragging yourself through that lovely desert, and at some point you grab a single grain of sand. The chance that you grab the same grain that I marked is still much greater than the chance the psychics can win the game eighty times and not be caught cheating, if they really are using one of the strategies discussed above and just gambling on not being caught each time they play.

I don't know about you, but if it was me I would be very, very suspicious at this point. Randi you can likely trust, although maybe given what is at stake even he should be suspect. Because remember, what is at stake is not just money and gold, it is something far more important: it's the possibility of some kind of psychic connection that defies common sense. Something at least as strange as telepathy.

But, in fact, stranger.

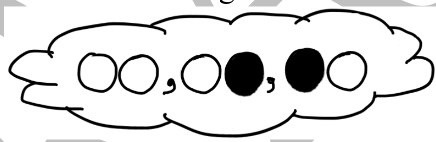
What went wrong?

Assuming for the moment you trust Randi, your suspicions will first fall on the isolation rooms. All it takes to win the game every single time is for information about the coin flip outcome in the other room to be available. For instance, perhaps hidden inside the STORAGE or PETE boxes is a cellphone of some form, which sends a message to the other room? While you have completely shielded the rooms to all known types of signals, there could be ones you don't know. In fact this type of cheating is not how they do it, and a bit later I will explain how we try to take extreme measures to ensure that it is not what they do, but first let us see how they really are doing it.

The answer, as you may have guessed already, involves misty states of balls somehow.

A tangled question: how did they do it?

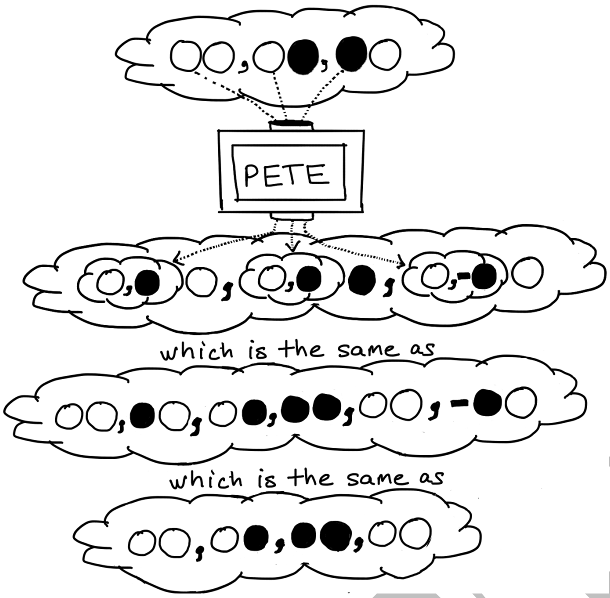
Alice and Bob each have a pile of four thousand storage boxes (numbered 1, 2,…, 4000). Inside each storage box is a single ball. Each ball in each correspondingly numbered box—the one in Alice's room and the one in Bob's room—has been carefully prepared to already be in this misty state, where the first ball is in Alice's storage box, and the second is in Bob's storage box:



The storage boxes are very carefully designed so that they don't (even inadvertently) observe the color of the ball they contain. As we know, looking at the color of the ball will destroy the mist. Toward the end of this part of the book I will explain how this particular misty state can be prepared. One of the remarkable features of the mist is that, although the balls need to be brought together in order to create a mist like this, once it has been created they can be separated as much as we like without the mist being affected (as long as we keep all balls safe inside storage boxes).

Alice and Bob both get heads: When both coin-flips in both rooms result in heads, Alice and Bob each simply release a ball from its numbered storage box, observe its color (destroying the mist), and use that as their answer. As a result, they will answer WW, WB or BW with equal likelihood. They will never answer BB, since that is not one of the configurations within the mist. This ensures they will always obey Rule 1. They need a new pair of storage boxes/balls for each time the game is played, because the mist gets destroyed by the observation.

Alice gets tails, Bob gets heads: If Alice gets told tails, she passes her ball through a PETE box before she observes its color. Calculating what happens is simpler than some of the calculations in Part I:



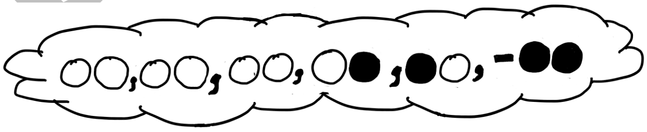
From this we can see that Rule 2 will be obeyed when Alice gets tails and Bob gets heads: the forbidden configuration BW does not appear in the misty state—it disappeared when it was cancelled out by interference. This means that when they now observe their respective balls, regardless of which answer they give (WW,WB or BB), it will be valid under the rules.

I will leave you to do the calculation for the opposite case—where Bob gets tails and Alice gets heads. It is very similar, and for this case you should find that the forbidden configuration WB does not appear in the misty state.

Both Alice and Bob get tails: The most interesting case—the "winning" case, so to speak—is when both of them get tails. Writing out all the steps is a bit long and messy, but what happens here is the heart of Alice and Bob's "telepathy." Here it is written in our more compact notation from Part I:

```
The mist inside the two storage boxes initially:
[WW,WB,BW]
Passing each ball through a PETE box:
[[W,B][W,B],[W,B][W,-B],[W,-B][W,B]]
which is the same as
[[WW,WB,BW,BB],[WW,-WB,BW,-BB],[WW,WB,-BW,-BB]]
which is the same as
[WW,WW,WW,WB,BW,-BB]
```

That is, after both Alice and Bob have passed their ball through a PETE box, the final misty state is:



We see that the BB configuration is there in the misty state. This means sometimes they will observe both balls are black and win the game.

I have shown only the calculation for one pair of storage boxes, but the pairs of boxes are all the same and so, when the game is played many times, eventually some BB outcomes will be observed. Even just seeing the BB outcome once is amazing, given the fact the two rules are always obeyed.

In the above two-ball misty state, it would seem that the likelihood of seeing the BB outcome is one in six, because there are six configurations in the mist. It is not—there is a subtlety to do with computing probabilities in cases where some configurations appear more often than others (as here, where WW appears three times while WB, BW and BB each appear only once). At the end of this part of the book I will show you how to do that type of calculation and we will find it is a one-in-twelve (about 8%) probability of seeing BB, given two balls in the misty state above. For the moment, let us just be amazed it happens at all, because we couldn't come up with a strategy to win the game, and so just saying, "Oh, well, the psychics use magical misty states of balls," only defers the question: How do the balls actually manage to do it? Unless, of course, the balls themselves are telepathic—that is, they somehow know what is happening to the other ball?

Now you know how the psychics "cheated" you out of Randi's money and your gold. But didn't they do it in a remarkable way? It's worth at least a million dollars to understand this feature of the universe (and if it's the first time you have genuinely understood it, please feel free to post me a cheque!). In fact, the more one thinks about what has happened, the more disconcerted one gets. Let us delve a bit further into the conceptual problems that all this raises about how the world works.

Nonlocality of correlations

We have seen above a demonstration of what physicists call "nonlocality": When we observe a misty state of a ball in one location, the outcome of that observation can depend on what is happening to another ball in a different location.

The words "can depend" in the preceding sentence invoke a notion of causality—what Alice is doing to the one ball is "directly affecting" Bob's ball, or vice versa. For a number of reasons, this description is already controversial and not accepted by all physicists. One of those reasons is that there is no need for Alice and Bob to observe their balls at exactly the same time, and so which direction the cause happens seems to somewhat arbitrarily depend on the timing of who measured first.

A less arguable way of describing the situation would be: the outcome obtained when we observe a misty state of a ball in one location is inextricably linked with what is happening to another ball in a different location. Even the words "what is happening to" in the preceding sentence would make some physicists uncomfortable.

I don't think anyone would argue with this version: the outcome obtained when we observe a misty state of a ball in one location is inextricably linked with the outcome obtained when we observe another ball in a different location. This is purely a statement about the experiments we do. Just re-imagine the combination of Alice+tester and Bob+tester as merely experimental physicists who are choosing randomly between two different experiments to perform on their balls—either to observe them directly, or to put them through a PETE box and then observe them. They see are what are often called "nonlocal correlations" between the colors of the two balls at the separate locations.

Correlations per se are not strange. If someone gave Alice and Bob each a box containing a ball and assured them that the balls were both the same color, then when they open their boxes they will see that the colors are correlated—in this case, both the same color. But in that situation each ball would "really have" a color prior to being observed; it is just that Alice and Bob do not know what it is.

Such an explanation will not work to explain how the colors of the balls can be correlated in such a way as to respect the two rules of the psychics' game, yet sometimes both emerge black when they have both been passed through a PETE box. Can you see why?

To perhaps over-labor the point, you can imagine that if the two balls did "really have" a color prior to observation, then they would need to choose their colors using a strategy that would mirror exactly the kind of thinking that Alice and Bob went through in the imaginary conversation above. Instead of giving black/white answers to heads/tails questions, the two balls are either being observed directly, or being passed through a PETE box and then being observed. But they still have to choose a color "to actually be" once they are observed:

AN IMAGINED CONVERSATION BETWEEN THE TWO BALLS

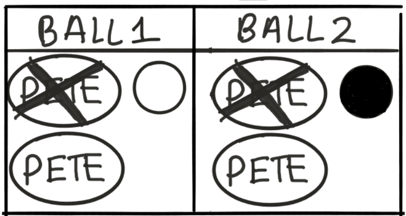
BALL1: Awesome, those suckers accepted our proposed test. Obviously we aren't actually psychic, but I'm sure we can win this game.

BALL2: Let's work out a strategy. Actually, we both know I'm not the smoothest bearing in the barrel Ball 1—I better let you work it out.

BALL1: Fine. By Rule 1 when we both get observed directly, we cannot both be black. So how about I will be white when we get observed directly, and you can be black.

BALL2: Woah, slow down there Ball 1. I think I better write this down, it sounds complicated already.

Ball 2 hunts for pencil and paper, finally finds one and draws a diagram.

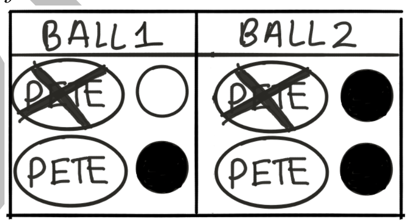


Ball 2 shows it to Ball 1.

BALL2: (*Proudly*) See, I made a table of what we should do. I drew a picture of each possibility—being observed with or without passing through the PETE box first, and I'm drawing a black circle to mean "be black" and a white one to mean "be white" next to each to indicate the color we should be.

BALL1: Yes Ball 2, it's very pretty. Let's keep going. Since we only win by both being black when we both get passed through the PETE box, when we see we are going through the PETE box we should always be black.

Ball 2 duly makes a note of this as well.



BALL1: So there you go, we have a solution. Now let's think about what to spend all that money on?

Ball 2 is looking a bit puzzled, scratching his head. Ball 1 has started to daydream.

BALL2: Uh, Ball 1, I think there is a liiiiiittle problem….

Hopefully you get the idea—if two intelligent creatures cannot work out a strategy to obey the rules but win the game (without being telepathic) then what chance do the two balls have on their own? Let me reiterate that explanations of the form "Well, we already know from experiments with just a single ball and a PETE box that we shouldn't think of a ball as really having a color when it isn't observed" are not particularly helpful in understanding the nonlocal nature of the correlations in the colors we do observe. Sure, the balls do not have to pre-decide which colors they will be, but we implicitly also granted that option to Alice and Bob—they didn't have to try and work out a concrete strategy beforehand, they could have said, "Let's just decide once we know what the coin flip in our room is." In that case, they would have needed even more telepathy to win once they were separated.

Causal nonlocality would have to be weird

Perhaps then we should consider more seriously the possibility that putting one of the balls through the PETE box actually causes, by some mechanism, the color of the other ball to be affected.

In physics, prior to encountering misty states and nonlocal correlations, it was always the case that the causes of things were mediated by "physical stuff." Sometimes the physical nature of the causal mechanism is obvious. When you grab your cat's tail and drag it along the floor, there is a complex story involving atoms and the forces between them that can explain the events that occur, right up to you getting scratched and later bleeding to death. In other cases, the physical stuff that acts as a causal intermediary is not so obvious. When you use your phone to call the ambulance for help (not in time, unfortunately) the radio waves that your phone emits and absorbs are not obvious to your senses. But they can be detected and manipulated—that is what your phone is doing—and they are so physical they can pull and push the molecules that make up a cat almost as well as you can (for example if you had, equally unadvisedly, tried to warm up the cat in the microwave). Radio waves are undeniably "physical stuff."

Events that are caused by physical stuff have certain common features, none of which turn out to be true for a mechanism that could give a causal explanation for the correlations between the colors of the balls:

(i) Causes precede effects, so the ordering of events in time matters.

(ii) If the cause and the effect are separated, then it takes time for the physical stuff that connects them to propagate. (You do not notice the time delay between when you speak in the phone and the person you are calling hears what you have said, but it is there. If you were on Mars it could take up to twenty minutes for what you have said to be received on earth, because radio waves travel at finite speed—the speed of light—and Mars is very far away.)

(iii) You can use the connection between cause and effect to send a message, though it will always be limited to traveling no faster than the speed of light.

(iv) It is harder to maintain the connection between cause and effect the further apart they are (the intermediary physical stuff inevitably "spreads out" in some sense and becomes weaker with distance).

How can we be sure that a causal explanation of the nonlocal correlations does not respect these four common features?

Going back to the story of you and Randi testing the psychics: we concluded that the most obvious explanation for their win would be that you and he have failed to shield the rooms properly, and they have cheated by communicating. On the face of it, there will never be a way to absolutely and completely shield a room. However, all known signals that can carry information also share common feature (ii), namely they travel at a speed no faster than the speed of light. This gives us a way to ensure that the psychics are not signaling to each other: You demand that after you tell Alice the coin flip outcome, she tells you her black/white answer (in effect the ball color) before there is time for a signal travelling at the speed of light to make it to the room where Bob and Randi are.

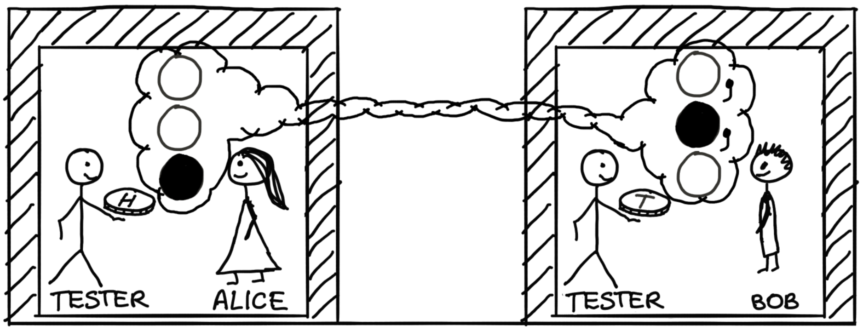
Because light travels so fast, even if you put the isolation rooms at the opposite ends of the earth there are only small fractions of a second during which the whole process must take place. I doubt you can even flip a coin fast enough. For this reason, when we do this experiment we use some electronic mechanism to do the coin flip and a different piece of equipment to insert (or not) the PETE box. That is, we use a mechanical version of both you and Alice. But in principle what we do is identical to the psychics' game—a version of it where and Bob and Randi play their part on the equivalent of Mars, safely too far away to signal to Alice.

The fact that nonlocal correlations do not get weaker the further you separate the two experiments (feature (iv)) and cannot be used to send signals faster than light (feature (iii)) can also be tested experimentally. Both are also fundamental theoretical predictions of the whole misty-state description of the world, and if they proved to not be true it would be an interesting breakdown of the laws of physics as we currently understand them. Testing feature (i), namely that the ordering of the experiments in time doesn't matter, is tricky but has been done. I do not want to go into details, but if you know about the Theory of Relativity, it shows we can set up the experiments so that two different people will not even agree on whether Ball 1 was observed before Ball 2, or vice versa, and yet the misty states still correctly predict what happens.

The conclusion of all this is that if you want a causal explanation of the nonlocal correlations we observe, then it has to be a very strange explanation in its own right. So strange that physicists seriously consider other disturbing options. For example, one way to get around all of these conundrums is to propose that the balls (or the psychics) already know in advance all of the coin flips that you and Randi will flip. This explanation requires that no matter how you and he try to make an independent choice (you don't need to use a coin, you could use any object, or do it purely in your mind) whatever you will choose can be pre-known to the balls/psychics. This way they can easily arrange to obey the rules, yet sometimes win, with no need for telepathy or any other causal link between them.

Such explanations are known as "super-deterministic." They conflict with our psychological feeling of free will (which arguably need not be given much credence in a theory of physics), but more critically, they conflict with the very notion of performing independent experiments to test and verify our fundamental ideas and theories. Without such independence we have to call into question the whole process of science and, at some level, all the scientific understanding we (think we) have gained, because it is so tied up with that process. It is a significant price, but an idea that is considered seriously.

All of which is not to say that a causal explanation is impossible. One such explanation is to consider the mist itself as "real physical stuff." So far, the mist has only played a role of encapsulating rules by which we can calculate what we will eventually observe. It has been part of our mental deduction process—a mathematical object, not a physical one. As is hopefully clear from Part I, we do not see actual mist emerging from the bottom of the boxes. But one option is to take seriously the possibility that the mist directly represents some kind of real physical object, like a radio wave or a bowl of soup, and when we separate the psychics the mist is stretched between them:

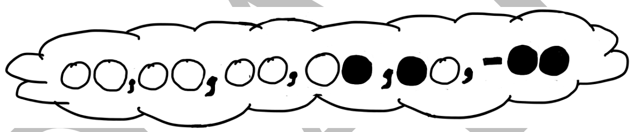


Such a mist would, for the reasons just discussed, have to have many physical properties that differ from any other kind of physical stuff we have ever encountered. It would be arbitrarily stretchable and move instantaneously when you whack it at one end, for example. The whole question of how to interpret the mist—as something physically real? as something which is just mathematics in our heads?—is one of the major schisms between physicists. Some arguments for and against both are addressed in Part III of this book.

Before we turn to these questions, you are now ready to learn a couple more important features of misty states.

Computing the likelihood of observing a particular configuration given a complicated mist

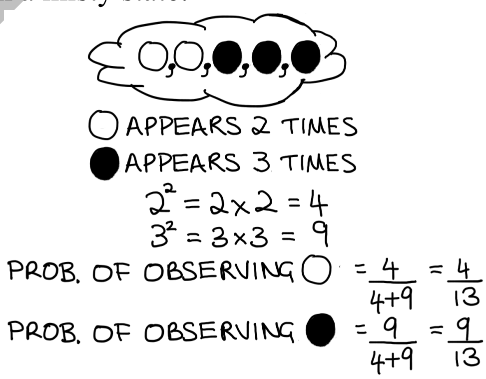
Previously I skipped over explaining why it is that when Alice and Bob observe balls in the misty state



there is a one-in-twelve probability that they see both balls are black (and hence win the game). One would more naturally expect the probability to be one in six, since there are six configurations, but, unfortunately, nature is not quite that kind to us. Nobody really knows why. It's all part of the mystery you are going to solve for us one day.

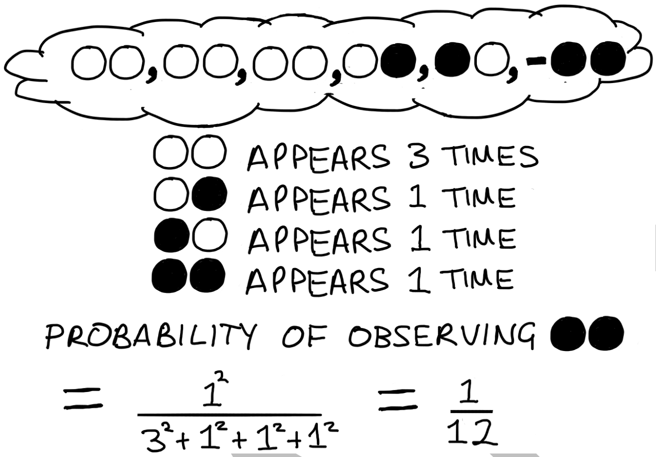
The general rule for computing the likelihood (probability) of seeing any particular configuration is the following: Square the sum of the times the particular configuration appears, and divide *that* square by the sum (over all the configurations that appear) of the squares of the sum of the number of times that they each appear.

Huh? Yes, I do enjoy causing you a bit of mental pain. It is much easier to understand than it sounds, and the best way to work out what is going on is with an example of a single ball in a misty state:



In this example the white ball appears two times, the black ball three times. We first square these numbers. The probability of any given configuration is then the ratio of the squared number of times it appears, to the sum total of all the squared numbers. In this example if you observe the ball you will find it white with probability four in thirteen (4/13=0.3077... so you see it white approximately 30% of the time), instead of the more natural expectation, which would be with probability two in five (or 40%). In these types of calculations, we ignore any negative-sign label—all copies of a given configuration will have the same label, since oppositely labelled copies will have cancelled out by interference already.

We can now work out the probability of the psychics winning the game, by calculating the probability of BB on the misty state that the two balls evolve to when both psychics put their ball through a PETE box:

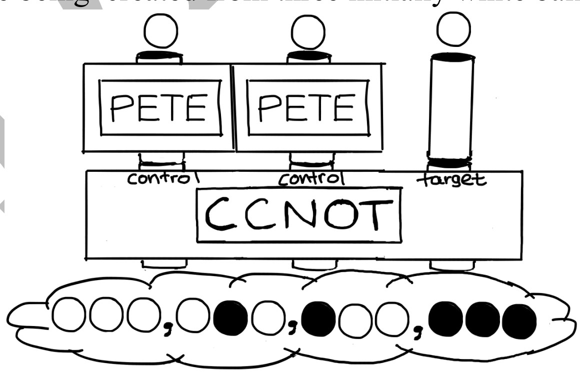


In the event (as always occurred in Part I of the book) that all configurations in a mist appear the same number of times, doing the whole calculation is unnecessary, all configurations are equally likely. Can you prove that for yourself more carefully following the "square divided by sum of squares" rule?

Making observations on a few balls within a multi-ball mist

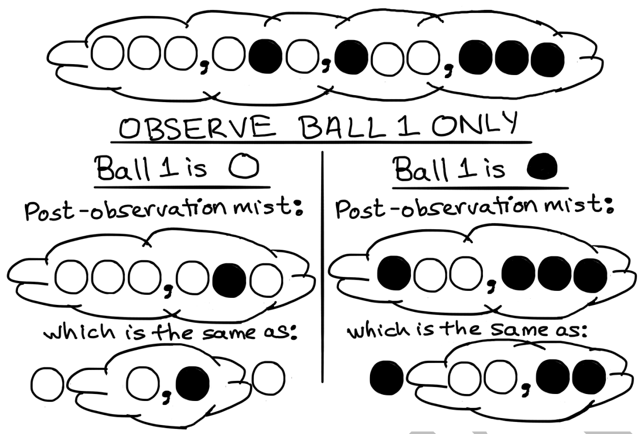
There's one more rule for computing with misty states. Up until this point we have only considered the case where we always observe all the balls at once. The result of that kind of observation is that we completely destroy the mist. We are left with just one of the configurations from the mist, with a probability you have just learned how to compute. But what if we don't observe all the balls?

Here's a misty state being created from three initially white balls:



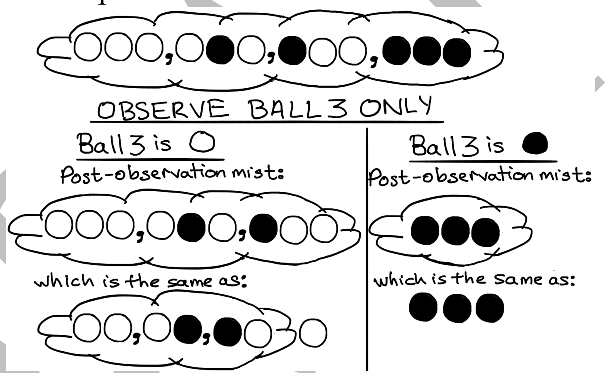
Have a guess at what the final state of the three balls will be if we now only observe the first ball?

As is typical for misty states, we will sometimes observe the first ball is white, and sometimes observe it is black. Let's say we observe it is white. We still will not know anything about the color of the other two balls. It is then perhaps unsurprising that the new misty state just comprises all the pieces from the original pre-observation state in which the first ball is white, in this case WWW and WBW. Similarly, if we observe the first ball to be black then the final misty state of the three balls consists of those configurations in which the first ball is black, in this case BWW and BBB. Summarizing:



We see that by observing only one of the balls it is possible to leave the other balls in a misty state—whereas if we had observed all three balls, then there would be no mist, and no ambiguity about each ball's color.

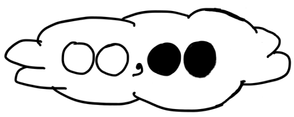
Remember the two-ball state that the psychics used? Of course you do, it's how they cheated you out of your gold bars. One way the psychics can prepare that state is to observe ball 3 of the example above instead of ball 1. Summarizing:



When the third ball is found to be white, the first two balls end up in the misty state that the psychics required. You should really hate that misty state.

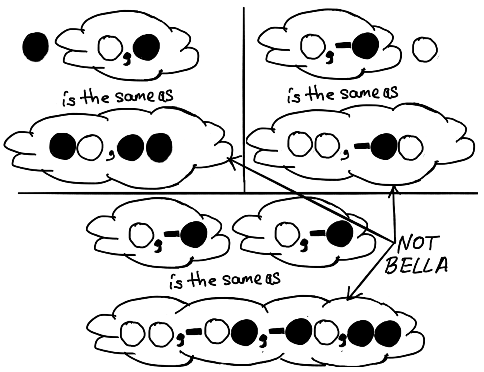
Entanglement

Recall the following misty state that we first encountered in Part I:



This particular misty state has many beautiful features and is considered quite special by physicists, so I will name it the "Bella" mist, after the Italian word for beautiful.

The Bella mist has the feature that it is reasonably simple to see there is no way to view it as being obtained by combining separate mists for each ball individually. That is, we saw in Part I that when you combine separate, individual, misty states of different balls you get a larger single misty state. The claim is that the Bella mist cannot be built up in this way. Here are three examples of two-ball misty states that are built up from separate misty states:



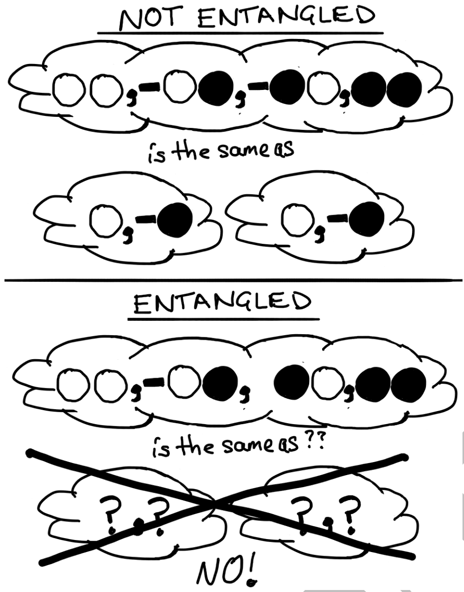
None of these examples are the Bella mist. The top two examples have only two configurations in the combined mist, just like the Bella mist, but one of the balls is always the same color in both. In the bottom example there are too many configurations. You should try several more examples to convince yourself getting to the Bella mist by combining two separate misty states is not possible.

This feature of the Bella mist—that it cannot be built from a combination of individual mists for each ball—turns out to be extremely special and useful, and so we give it a new word. We say the Bella mist is "entangled." As with the word "superposition," saying a misty state is "entangled" is just physicists making up a word to describe a situation which had previously never been encountered in any physical theory. Unfortunately, unlike "superposition," "entangled" is a word that already has colloquial meaning, and that meaning is only vaguely reminiscent of the precise way in which we will use it. This happens a lot in physics and math—common words get adopted for precise usage, and it can be a major source of confusion, so be careful if you ever study these subjects more deeply.

One might have thought that the lesson from passing single balls through PETE boxes was that, if you can't think of the color of a ball as something it "really has"—as a physical property—maybe the mist *itself* is a physical property. Then a single ball could "really have" a "value" of its mistiness. This view might lead one to think of superposition as the only mystery to be explained. The phenomenon of entanglement shows that this is not the full story—we have seen that an entangled misty state of just two balls like the Bella mist cannot be interpreted as arising from balls that are actually in their own individual misty states. In reality, superposition is not the only mystery.

Of course you may want to simply adjust the proposal; perhaps it is misty states of two balls that are the "real thing"? But then we can find entangled misty states of three balls that cannot be built from separate misty states of one and two balls. (Try it). The whole of Part III is about the many questions and issues surrounding the reality (or otherwise) of the mist.

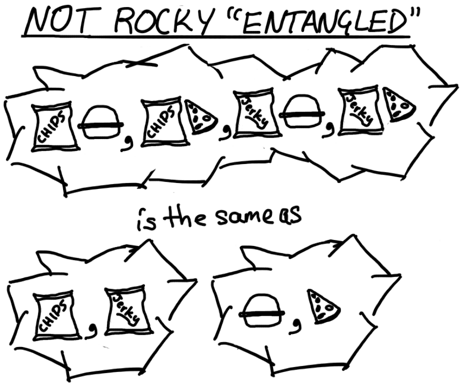
A word of warning, determining whether a misty state of two balls is entangled or not is not trivial. Consider these 2 examples, which differ by only one negative-sign label:



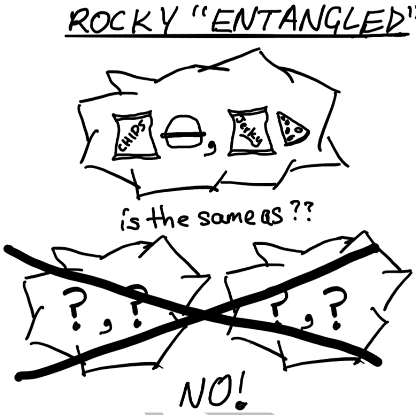
The two-ball misty state [WW,WB,BW] that was repeatedly used by Alice and Bob to defeat you and Randi is also entangled. In fact, entanglement is provably necessary for generating nonlocal correlations. It is not possible to generate nonlocal correlations with a non-entangled misty state, basically because without entanglement the balls behave as if they are completely independent. It is often said that entangled states are special because they are "non-separable." That is, you cannot any longer treat the entangled balls separately.

Again, some caution is required when trying to claim that this non-separability is fundamentally strange. Remember back when you went hiking, and your lucky friend had a lunch packed that consisted of either chips and a burger, or jerky and pizza but none of you knew which was the case? We could invent a way of depicting the state of your friends' lunch box, similar to misty states. Let's depict them in a rock (since they are more down to earth), and call them rocky states:

We see that by identifying foodstuffs with ball colors appropriately there is at least a superficial similarity with the Bella misty state [WW,BB]. The correspondence goes further: this state is "rocky-entangled." Specifically, it is not possible to create a lunchbox in this state by taking two individual lunchboxes that have uncertainty about their contents. More precisely, imagine you are told there are four potential configurations for lunch, namely CB,CP,JB,JP. You would say that is just the combination of two separate lunchboxes, one of which contains either chips or jerky, the other of which contains either a burger or pizza:



However, there is no way to create the rocky state <CB,JP> (using pointy brackets to denote the edges of the rock) by taking two separate lunchboxes in such a manner:



Creating an "entangled rocky state" like <CB,JP> requires some type of coordination, because some configurations need to be excluded. Similarly, creation of an entangled misty state like the Bella mist can only be done by causing the two balls to interact (perhaps via intermediary systems).

Once again, these similarities and analogies are useful, and perhaps (physicists argue about it) they reveal something important about how to understand misty states. But they should be treated carefully. If entangled misty states were really equivalent to entangled lunchboxes, telepathy/nonlocality would definitely not be demonstrated by winning the psychics' game, because Alice and Bob could have just played with their lunch and there is nothing strange about that. Your lunch cannot be negative, it cannot interfere, and it is not telepathic.

Summary of Part II

* We can perform far-separated, well-shielded experiments (observations) on balls in a misty state, the outcomes of which are inextricably linked, in as much as they cannot be reproduced by physical stuff (whatever it is) responding only to what is going on around it locally.

* Such "nonlocal correlations" do not depend on the temporal ordering of the experiments, cannot be used to send messages, and occur even if there is no time for communication at light-speed between the experiments. This puts them in severe tension with the normal type of causal explanations in physics.

* Misty states of two or more balls can be "entangled," by which we mean they cannot be treated as if they have independent colors, or independent misty states for that matter. Entanglement underpins nonlocality.

* Given misty states with unequal numbers of repeated configurations of ball colors in the mist, the rule for computing the probabilities of observing any particular configuration involves squaring numbers and dividing them. All a bit messy, but still just basic arithmetic.

* Beginning with misty states comprising many balls, observing only some subset of the balls can leave the remainder of the balls in a misty state.