

Chapter 2

The Measurement Problem Is Not a Detail

Leave a detector running in an empty laboratory overnight. It will still register arrivals. By morning, a result may have been stored, copied or used to start another experiment. Nobody needed to watch it happen. Whatever produced the result was already at work before anyone came in to read it.

The word measurement can make this easy to miss. It sounds like something a person does to learn about the world. But first, something physical must happen. The instrument changes in a way that can be read later. PDT is concerned with how that change takes place.

A thermometer gives a simple example. Its liquid expands as it warms, whether or not we look at the scale. Reading it tells us about a change that has already occurred. Quantum instruments make the explanation more difficult, but I want to keep the same question in view. What did the instrument do before we read it?

What happens inside the detector

Imagine a detector with two possible readings, left and right. First we test it with an input that should give left. Then we test it with one that should give right. This is calibration. It checks that the two readings tell us something reliable about the inputs, rather than being arbitrary lights on a display.

Now prepare an input that combines the two quantum possibilities. This is called a superposition. It is different from sending either input and keeping its identity secret. In a superposition, the two contributions can interfere when brought together. That interference is a measurable sign that we are dealing with more than ordinary uncertainty.

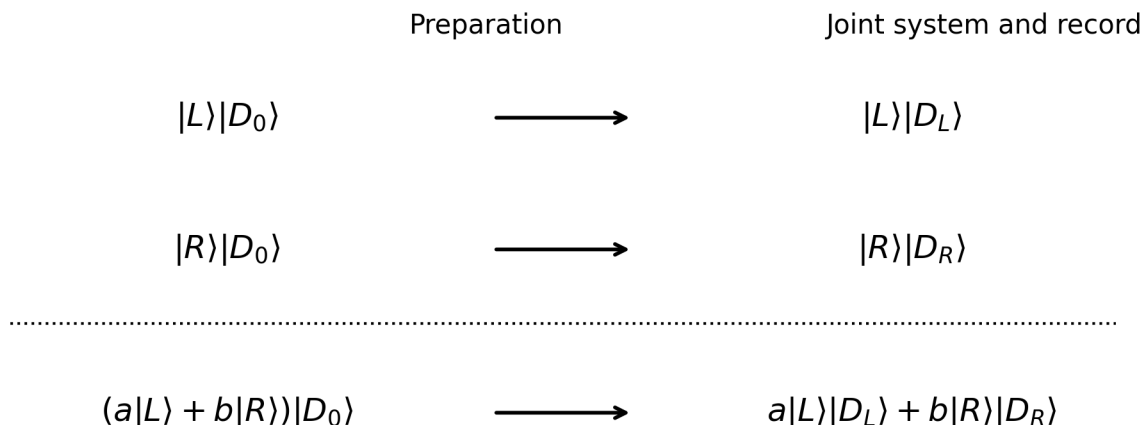
The usual quantum equations tell us what happens when this combined input meets the detector. They link the left contribution with a left reading and the right contribution with a right reading. The detector is now included in the calculation. But the calculation still contains both linked possibilities. [7, 8]

The equation below expresses the rule called linearity. Calculate what happens to each contribution, then add the results. That gives the same answer as starting with their superposition.

$$|\psi\rangle = \sum_i c_i |i\rangle \Rightarrow U|\psi\rangle = \sum_i c_i U|i\rangle$$

The symbol c_i gives the weight of one contribution. U stands for the rule used to calculate its change. The equation says that combining contributions does not make this rule choose just one of them. You can follow the problem without working through the notation.

An ideal linear measuring interaction



Linearity carries both contributions into the joint state

Figure 2.1 The top two rows show the detector responding separately to the left and right inputs. The bottom row combines them. The symbols a and b give their weights. The quantum calculation contains both the left input with its reading and the right input with its reading. It has not selected one overall result.

Making the detector larger does not, by itself, solve this problem. We can add an amplifier and a memory to the calculation. They become linked with the alternatives too. We have described more equipment, but we still need to explain why the experiment leaves the particular result we find.

Textbooks commonly introduce a projection rule at this point. Once a result is obtained, we update the quantum state, our mathematical description, to reflect that result. The Born rule gives its probability. [3, 8] This procedure works extremely well. My question is what happens physically when the possible readings become the recorded one.

That is where I propose phase snap. The detector has its own internal organisation. As it interacts with the incoming system, some possible ways for the encounter to develop may cease to be possible. PDT asks whether that process can account for the result, using the matter already involved in receiving and storing it.

What it takes to leave a record

A tiny disturbance must be amplified to become a useful reading. An arrival might release charge, trigger a larger electrical response and leave a signal in memory. Much of the energy can come from the prepared detector. Think of a small trigger releasing a larger response. The arrival need not carry all the energy used to make the record.

Follow the signal and we find a chain of physical changes. Charge affects an amplifier. The amplifier changes a memory. We later read the memory. There is no obvious point where the equipment stops obeying physics and begins to act simply because somebody wants to know the answer.

The detector and the particle belong to the same world. The detector's size makes its reading easier to use, but does not explain why one result occurs. I want an account in which the encounter and the changes in the equipment explain the result together.

How the detector is prepared matters. One arrangement can let contributions interfere. Another can leave separate records that distinguish them. These instruments interact with the incoming system differently. Changing the apparatus changes what is physically done, as well as what we can learn.

We can choose which arrangement to build. We cannot then choose whichever individual result we would like it to produce. The equipment and the incoming system have to obey their physical rules. Preparing an experiment is different from instructing nature to give a preferred answer.

Suppose a left result opens one shutter and a right result opens another. The next experiment receives light through whichever shutter actually opened. It now depends on the first result. We may copy that result to a computer or send it to another room, but each use requires another physical change. In the one history account I am seeking, the result becomes part of the conditions for what follows.

Erasing the original memory will not close a shutter that has already opened. Nor will it recall a signal sent elsewhere. A record can disappear from one place while its effects remain in others. This is how a small event can matter long after its original trace has gone.

The surroundings are involved

The detector also interacts with its surroundings. Light scatters from it and heat passes out of it. Information about its possible readings becomes linked with surrounding matter. This can remove the interference we could otherwise observe between those alternatives. Quantum theory calls this process decoherence. [9]

Decoherence helps explain why a detector gives us a stable, everyday sort of record. Once information has spread into many parts of the surroundings, gathering it all back and reversing the process becomes extremely difficult. The record can then survive long enough to be read or copied.

But there are two questions here. Why can we no longer observe interference between the readings? And why did this particular reading occur? In Figure 2.2, the middle panel loses the terms that describe interference, while both possible readings remain in the description. The right panel describes a left result that is already known.

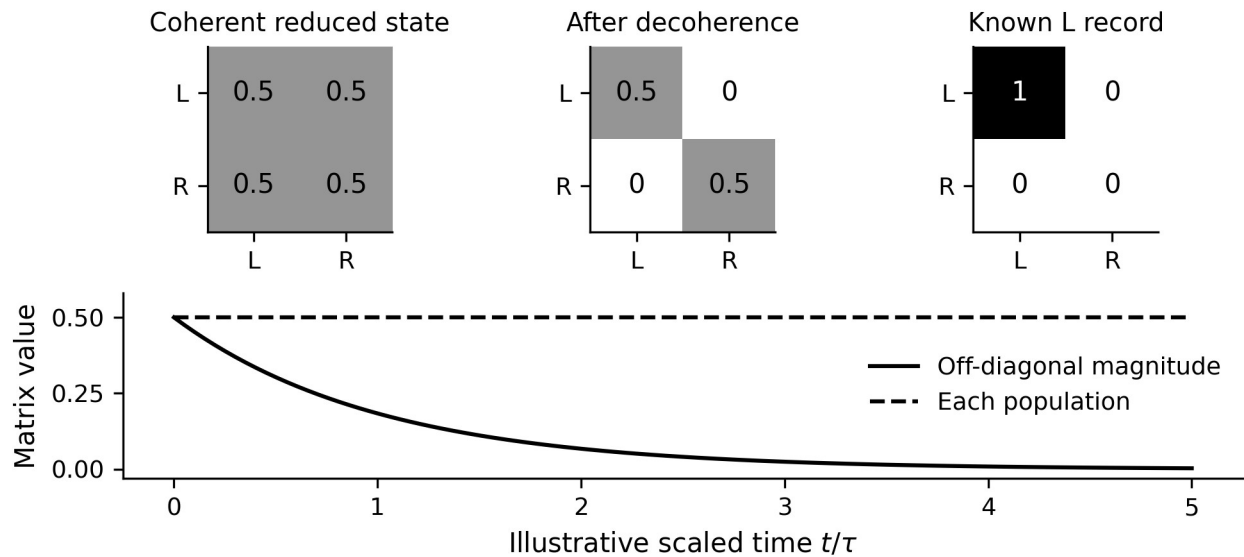


Figure 2.2 The panels show three descriptions of the experiment. First, the alternatives can interfere. Next, decoherence removes the accessible interference. Finally, a left result is known and the description is updated. The lower curve shows interference fading while both populations remain equal. Fading interference does not itself select one result.

Decoherence answers an essential part of the problem. It does not, by itself, establish one actual outcome for the whole experiment. PDT adds the question of whether an interaction can physically rule out alternatives, rather than merely make their interference difficult for us to observe.

Here, ruled out means that the physical rules no longer allow that development. A hidden interference pattern is not enough. PDT then adds the principle introduced in Chapter 1, that a unique surviving possibility becomes actual. These are additional claims, and the explanation must show where they enter.

How one result affects the next

Return to the shutters. Before the reading, either might open. Afterwards, light passes through the one that did open and reaches the next experiment. That experiment starts from an actual physical arrangement. Its input depends on the earlier result, not just on the probabilities that existed before it.

This is what I mean when I say an event enters history. Something later depends on it. Telling the next instrument that each shutter had an equal chance of opening cannot replace the light it actually receives. The probability and the result do different jobs in the explanation.

In PDT, the incoming system meets a prepared detector, and their interaction changes what can happen. A possibility may become impossible because the interacting arrangement can no longer support it. Phase snap names the proposed step in which one possibility remains and becomes actual. The resulting change can then control the next piece of equipment.

These possibilities are ways the encounter might develop. I am not imagining tiny completed readings stored inside the detector in advance. Before a snap, the phase relationships between alternatives may still affect the experiment. Physically removing an alternative is therefore a stronger claim than simply failing to see it.

Many interactions need not produce a snap. We can change a phase and still compare it later. We may undo a disturbance, or leave several possibilities open. PDT needs room for these cases. If every interaction immediately removed all but one possibility, it would destroy the interference the theory must explain.

One result also leaves room for uncertainty later. Once a shutter opens, its light can enter another experiment with several possible outcomes. The first event supplies the starting conditions for that experiment. It does not have to settle the entire future.

We have built this chain deliberately so that it is easy to follow. Nature does not need our equipment to have events. An encounter in a gas cloud can affect later encounters too. I use measurement as a clear example of a process I propose also occurs where nobody is making a human record.

Why physicists disagree about the result

There are several ways to interpret quantum results. Everett's account keeps multiple branches in the description. Objective collapse theories alter the dynamics to produce definite outcomes. Bohr emphasised the conditions of the experiment. [2, 4, 5] They differ over what exists and what happens. Agreement about successful calculations does not settle those differences.

PDT starts with my commitment to one actual history. I can imagine the other shutter opening, but I take the opening that occurred to be a fact about the world. The shutter example does not prove this starting point. It explains why I keep asking how the alternatives become one event.

Across many trials, PDT must still recover the probabilities quantum mechanics gets right. It must also meet Bell's restrictions on hidden local explanations, which we will examine in Chapter 4. [1] A plausible story about one detector is only a start. The story has to work for the less familiar experiments too.

What encourages me is that the signal, the equipment and the record form one connected physical process. Each change helps produce the next. I want the explanation of the outcome to belong within that process as well.

This is why the measurement problem matters. We can prepare alternatives, let them interfere and obtain a definite result. All three occur in experiments we can study. PDT asks whether we can follow a physical explanation all the way through, including the step where a particular result becomes established.

Think again of the empty laboratory. By morning, the overnight result may already have changed the next experiment. Our reading it adds to the story, but does not begin it. How the record formed is a question about the world, whether or not anybody was watching.

Bridge to Chapter 3

We have given the proposed event a name, phase snap. Now we need to understand the word phase. Chapter 3 starts with something familiar, two swings moving back and forth, and shows why comparing cycles matters to the behaviour of light and, perhaps, to the deeper structure of matter.

References and further reading

- [1] Bell, J. S. (1964). On the Einstein-Podolsky-Rosen paradox. *Physics*, 1, 195-200. <https://doi.org/10.1103/PhysicsPhysiqueFizika.1.195>
- [2] Bohr, N. (1928). The Quantum Postulate and the Recent Development of Atomic Theory. *Nature*, 121, 580-590. <https://doi.org/10.1038/121580a0>
- [3] Born, M. (1926). Zur Quantenmechanik der Stoßvorgänge. *Zeitschrift für Physik*, 37, 863-867. <https://doi.org/10.1007/BF01397477>
- [4] Everett, H. (1957). “Relative State” Formulation of Quantum Mechanics. *Reviews of Modern Physics*, 29, 454-462. <https://doi.org/10.1103/RevModPhys.29.454>
- [5] Ghirardi, G. C., Rimini, A., & Weber, T. (1986). Unified dynamics for microscopic and macroscopic systems. *Physical Review D*, 34, 470-491. <https://doi.org/10.1103/PhysRevD.34.470>
- [6] Gibbs, J. W. (1902). *Elementary Principles in Statistical Mechanics*. Yale University Press.
- [7] Schrödinger, E. (1926). Quantisierung als Eigenwertproblem, fourth communication. *Annalen der Physik*, 81, 109–139. <https://doi.org/10.1002/andp.19263861802>
- [8] von Neumann, J. (1932). *Mathematische Grundlagen der Quantenmechanik*. Springer.
- [9] Zurek, W. H. (2003). Decoherence, einselection, and the quantum origins of the classical. *Reviews of Modern Physics*, 75, 715-775. <https://doi.org/10.1103/RevModPhys.75.715>