The Observer Effect

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Abstract—The observer effect is the fact that observing a situation or phenomenon necessarily changes it. Observer effects are especially prominent in physics where observation and uncertainty are fundamental aspects of modern quantum mechanics. Observer effects are well known in fields other than physics, such as sociology, psychology, linguistics and computer science, but none of these other fields have experienced the same level of publicity and controversy as physics. This may be responsible for the widely held implicit assumption that "real" observer effects are exhibited only by quantum objects and not by classical objects. This misunderstanding may be due, to some extent, to confusing the observer effect with the Heisenberg uncertainty principle and with other quantum uncertainty principles. In fact, observer effects occur in both classical and quantum systems. This article presents a number of examples of observer effects in purely classical processes. It also introduces a framework for understanding and analyzing many of such effects for classical systems. Ignoring observer effects can cause errors in experiments at a macroscopic level where no quantum effects would be discernible. Consequently, there are practical reasons for being careful to address observer effects.

Keywords: observer effect, quantum mechanics, classical mechanics, stochastic processes

I. INTRODUCTION

The idea that simply observing a situation can change it is counter-intuitive. An observer is intuitively assumed to be a passive entity, independent of what is being observed. Physicists were the first to recognize observer effects when quantum mechanics was being developed, and they are a fundamental aspect of modern quantum physics. It was only later that observer effects were recognized in other fields, including sociology, psychology, linguistics and computer science. However, observer effects are much better known in physics than in the other fields.

Within quantum mechanics, the observer effect is commonly confused with uncertainty principles. The first uncertainty principle was introduced by Heisenberg in 1927 [6]. The Heisenberg Uncertainty Principle is a quantitative expression of the inability to measure both the position and momentum of a particle. There are other uncertainty principles that are known, and uncertainty principles are now recognized as arising in quantum mechanics due to the intrinsic nature of quantum objects and is therefore a fundamental property of quantum systems, not just technological limitations of measurement devices. However, it appears that even Heisenberg may have confused his uncertainty principle with the observer effect, although he was careful to make it clear that the observer need not be a human, as he explained,

Of course the introduction of the observer must not be misunderstood to imply that some kind of subjective features are to be brought into the description of nature. The observer has, rather, only the function of registering decisions, i.e., processes in space and time, and it does not matter whether the observer is an apparatus or a human being; but the registration, i.e., the transition from the "possible" to the "actual," is absolutely necessary here and cannot be omitted from the interpretation of quantum theory [7].

Heisenberg was one of the main contributors to the Copenhagen interpretation of quantum mechanics in which the observation of a quantum state causes it to collapse to an eigenstate. This interpretation has been highly criticized and is no longer regarded as acceptable by mainstream physicists, although some variations are still viable. Many other interpretations have been developed, but none is universally accepted, and the problem remains open.

This article is concerned only with classical mechanics, or more precisely, abelian (commutative) probability theory, in contrast with quantum mechanics, or more precisely, non-abelian probability theory. Unlike quantum mechanics, classical mechanics has a generally accepted interpretation. On the other hand, it does not seem to be well known that classical systems can exhibit observer effects. Although classical and quantum systems have many analogies, the proposal in this article for how to deal with observer effects is limited to the classical case. No claim is made regarding any applicability to quantum mechanical observer effects.

Observer effects are an important consideration for situation awareness (SA). SA is the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection into the future [4]. Being a perception, SA ultimately depends on observations which are, in practice, classical mechanical. If the observation of a phenomenon changes it, then SA can be compromised. Consequently, to ensure that SA is correct, it is important to be aware of the possibility of observer effects.

This article is organized as a series of examples that gradually construct a framework for understanding and analyzing observer effects for classical systems. The idea is for the observer and the observed system to be combined into a larger system. Of course, it is a nontrivial problem to model the observer, and the interaction between the observer and the system being observed, so that there is a tractable system

containing them both. This is discussed in Section V. For the sake of completeness, we end the article by surveying observer effects in fields other than classical probability theory; namely, sociology, (classical) physics and computer science.

II. THE REFERENCE POINT PARADOX

Suppose that $n > 1$ points are dropped at random on a circle of circumference a. This divides the circle into n arcs or gaps between points. The average length of one of the gaps is easily seen to be a/n. However, there is an unstated assumption that one of the gaps is somehow selected. It is not entirely obvious how one might do this, since the circle may not have a preferred coordinate system and the gaps may not be labeled. One way to choose a gap is to select a point g called the *reference point*. The desired gap is then the one in which the reference point g occurs. Unfortunately, if one performs this experiment repeatedly, the average length of the gap containing g will be nearly twice as large as one would expect. More precisely, rather than an average length of a/n, the selected gap will have average length $2a/(n + 1)$. The reason why the selected gap is so large is that the reference point will occur in a longer gap simply *because* such a gap is longer. In other words, the probability of the reference point being in a gap is proportional to the length of the gap. Note that it does not matter whether the reference point is chosen in some deterministic manner or in a random manner, nor whether the reference point is selected before the n points are dropped or after they are dropped. All that matters is that the n points be randomly dropped on the circle independently of the location of the reference point. As a result, the reference point acts like one more point randomly dropped on the circle. The gap containing the reference point is then actually two adjacent gaps. Consequently, the average length of the two gaps is $2a/(n + 1)$.

This is perhaps the simplest example of an observer effect in a classical system. The phenomenon is the dropping of points on a circle. The observer chooses one gap by selecting a reference point. The observer effect is to change the average length of a gap.

While this is a very simple example, it illustrates how SA could be invalidated by an observer effect. Moreover, the effect is more subtle than the example suggests. The fact that one is using a reference point to select a gap might not be immediately obvious to the observer, as the situation may be embedded in complex data structures and software where the reference point was introduced as a convenience without realizing that it has a significant effect.

III. GIRL OR BOY PARADOX

There are three children in a family, having ages 9, 10 and 11. A friend is visiting the family and meets two of the children, both of which are girls. What is the probability that all three are girls? The friend then asks the girls how old they are. Now what is the probability that all three are girls? Assume that girls are as likely as boys and that each child is independently either a boy or a girl.

The paradox in this problem is that it seems at first that being told the ages of the girls should not have any effect on the probability. It should always be $1/2$. However, being told the ages increases the probability that the third child is a girl by a factor of 2: from $1/4$ to $1/2$. How can observing the ages of the children have any effect?

Assume that the ages of the two girls are 10 and 11. The probabilities would be the same for any other pair of ages, as long as one knows the ages of the three children. The probability space for this problem has 8 points: { GGG, GGB, …, BBB }, where the point GGB means that the two oldest children are girls and the youngest child is a boy. The relevant events are A = "at least two children are girls," B = "the children aged 10 and 11 are girls," and C = "all children are girls." In terms of sample points, $A = \{GGG, GGB, GBG, BGG\}$, $B = \{GGG, GGB\}$ and $C = \{GGG\}$. The probabilities of these three events are therefore $P(A) = 1/2$, $P(B) = 1/4$ and $P(C) = 1/8$. It is then easy to compute:

$$P(C \mid A) = 1/4$$
$$P(C \mid B) = 1/2$$

The disparity between the two conditional probabilities can be explained by considering the relative sizes of two kinds of family, both of which contain families with three girls. If we choose families having three children, subject to the criterion that at least two of the children be girls, we will be choosing among half the families. If we use the second criterion, we will be choosing among a more restricted set of choices, only one quarter of the families. Thus, the families with three girls will seem more probable, not because there are more such families, but rather because there are *relatively* more of them.

This is yet another example of a seemingly innocuous observation that has a significant effect. The original paradox used only two children and was stated more vaguely [5]. Much of the controversy surrounding this paradox is the result of the vagueness. Our purpose here is to give an example of an observer effect, not with the difficulties of interpreting vague natural language statements.

IV. THE INSPECTION PARADOX

A Geiger counter is set up to examine a small radioactive sample which produces one click every hour on average. In addition, the machine has a timer which shows how long it has been since the last click. The Geiger counter has been running unobserved for some days when you start observing the timer. You wait until the next click and then note the time shown on the timer. It would seem obvious that the time that you note will be one hour on the average. Yet, it paradoxically seems much longer, indeed two hours on the average. Since your

situation awareness of this phenomenon is ultimately based on observations, and there seems to be no reason to suppose that your presence in the room observing the timer should have any effect on the radioactive sample, this represents a loss of SA.

To understand what is happening, suppose that there is a reset button on the timer. The timer now shows how long it has been since the last click or since the timer has last been reset manually. Using the reset button should not have any effect on the radioactive sample. Now, instead of simply starting to observe the timer, you push the reset button and write down what the timer indicated (call this T_0). As before, you then wait until the next time the Geiger counter clicks, and you also write down what the timer indicates when this happens (call this T_1). If you did not push the reset button, then when the click occurs the timer would show $T_0 + T_1$.

There are two ways to compute the expectations of T_0 and T_1. First, $T_0 + T_1$ is the total waiting time between two successive clicks of the Geiger counter, so that $E(T_0 + T_1)$ should be 1 hour. Since your arrival may be regarded as randomly dividing in two the total time between the two successive clicks, $E(T_0)$ should be the same as $E(T_1)$, and hence, $E(T_0)$ and $E(T_1)$ both should be 30 minutes. The second analysis begins by noting that because the exponential distribution is memoryless, the waiting time T_1 is itself exponentially distributed with mean 1 hour. Therefore, whatever the distribution of T_0 is, we have $E(T_1)$ = 1 hour and $E(T_0 + T_1)>$ 1 hour. Thus, the two analyses disagree.

In fact, the second computation is the correct one. $T_0 + T_1$ does not have an exponential distribution with intensity 1 click/hour even though it is the time between two clicks. The problem is that the randomly chosen reset time is more likely to occur during a longer time interval than a shorter time interval simply because there is more time in the former than in the latter. This is what happened in the reference point paradox in Section II above. In fact, both T_0 and T_1 are exponentially distributed with intensity 1 hour so that $E(T_0 + T_1)$ = 2 hours. It should be clear that T_1 is exponentially distributed because of the memorylessness of the exponential distribution. It is less obvious that T_0 is exponentially distributed. To see why this is true, note that the probability $P(T_0>t)$ is the same as $P(N(t) = 0)$ in the Poisson process; and, in the Poisson process, the parameter t is the size of the region. This region need not have any relationship to time. For example, it could be an area or volume. Thus, the probability is the same whether we are observing a click that occurred in the past or one that will occur in the future.

Actually, this analysis is an oversimplification. It assumes that the process has been running forever backwards in time, when in fact we only know that it has been running for "some days". We give a more accurate analysis in the next section below.

V. Stochastic Framework for Observer Effects

The examples discussed so far all involve an observer O and a stochastic process P being observed. In addition, there is an relationship between O and P that is typically unstated. To resolve the effect of the observer O on the process P, one models O as a stochastic process and then explicitly specifies the relationship between O and P. Together these define a process OP.

For example, in the Reference Point Paradox in Section II, the P is the process of randomly dropping n points on a circle. The observer O is the process of selecting one point on the circle. It does not matter how this is done so long as it is independent of the process P. The relationship between O and P is the selection of the gap of the process P in which the point of O occurs. The paradox arises from mistakenly interpreting the process OP as being P, ignoring the process O.

The Girl or Boy Paradox of Section III begins with a probability space with 4 elements, each equally likely; namely, the families with three children with ages 9, 10 and 11 at least two of which are girls. This is the process P. The observer O is the friend who is visiting. The observation is the ages of two of the girls. The combined process OP has only two elements.

To understand what is happening in this example, it helps to "think probabilistically." In other words, observations and measurements should always be regarded as being probability distributions rather than exact values. Indeed, in the case of continuous probability distributions, it is impossible to observe an exact value. For example, if one selects a point x of the unit interval $[0, 1]$ uniformly at random, then x has an infinite amount of information. While one can develop mathematical models in which one selects such a point exactly, in reality one can only determine x to some finite number of decimal places, and sensors will measure some variable with a known error distribution (usually a normal distribution). However, even for discrete distributions, it is better to think in terms of probability distributions. In particular, the answer to any question about a stochastic process will be a probability distribution. For example, the answer to the question "What is the result of flipping a fair coin?" is the probability distribution that assigns a probability of $1/2$ to each of the two possible outcomes.

Now return to the so-called Girl or Boy Paradox. In this case, one starts with a model in which one only knows that there are three children in the family and that each child is a boy or a girl, equally likely and independently. One then makes a series of observations that successively change the probability distribution. The initial probability distribution assigns $1/8$ to every sample point of the probability space. After meeting two of the children, one assigns $1/4$ to four of the sample points and 0 to the rest. After asking their ages, one assigns $1/2$ to two of the sample points. If one thinks of the probability distribution as being a state, then the observations are "collapsing" the state. Nothing is happening to the children, of course, so it is the observer's perception of

the children that is collapsing. Note that all of these states are "mixed states" (or "superpositions") rather than "pure states" which would assign a probability of 1 to a single sample point.

Next consider the Inspection Paradox of Section IV. We can now understand what is missing from our analysis of this problem: we have not specified the stochastic process of the observer O. Clearly, one could have different results if the reset button is pressed in a periodic sequence (e.g., once a day) rather than in a random sequence (e.g., a Poisson process). The simplest assumption is that the observer is an independent Poisson process in which α resets are performed every hour. Combining the Geiger counter process with the observer process produces a combined process that is Poisson with intensity $1 + \alpha$ clicks or resets per hour. The random variables T_0 and T_1 are in the combined process.[1] They are both exponentially distributed with intensity $1 + \alpha$. So they both have the same mean, $\dfrac{1}{1 + \alpha}$ hours, and their sum has mean $\dfrac{2}{1 + \alpha}$ hours. We were not given the exact value of α, but we do know that the Geiger counter was "running unobserved for some days," which suggests that α is no more than about 0.02. Consequently, the combined process is only slightly different from the Geiger counter process alone, and the average total time between clicks or resets will be between 1 hour and 57 minutes and 2 hours. As α approaches 0, the combined process converges to the Geiger counter process, and the average time between clicks or resets will approach 2 hours.

The behavior in this example is common to any Poisson process or more generally any renewal process. To incorporate the observer into the process, one must combine the observer process with the renewal process. The relationship between the two processes is the sum of two gaps in the combined process.

More generally, the observer effect can be analyzed by combining the process P being observed with the observer process O, together with a relationship between O and P, to form a new process OP. The process OP can be analyzed in itself, or it could be observed by a meta-observer M by forming a process MOP, and so on.

The lesson for the SA of an observer is that the observer should be regarded as part of the process being observed. The combined process could then be observed (for example, as in [2]), and this higher-level observer may also be regarded as part of the combined process, and so on.

VI. The Prisoner

Armed with this framework, we now analyze another observer effect and some variations. The basic observer effect is called the Three Prisoners Problem.[2] Three prisoners are

informed by their jailer that one of them has been chosen at random to be executed and that the other two are to be freed. They are told they will learn their fate in one week's time. Prisoner A asks the jailer to tell him privately the name of a fellow prisoner who will be set free, claiming that there would be no harm in divulging this information, since he already knows that at least one will go free, and he cannot inform the prisoner in question about his good fortune. The jailer refuses to tell prisoner A, pointing out that if A knew the name of one of his fellows to be set free, then his own probability of being executed would rise from 1/3 to 1/2, since he would then be one of two prisoners; and this would be cruel. Does this make sense?

This problem has generated quite a few debates, some very heated. Unfortunately, much of the controversy surrounding this problem lies in translating the vague language of the problem into the language of probability theory. Since our purpose is the observer effect, we will use a precise formulation of the problem. Accordingly, let A, B and C be the events that prisoners A, B and C are set free. These events are *not* independent. For example, $A \cap B = \overline{C}$. There are four points of view in this problem corresponding to the following probabilities:

$P(A) = \frac{2}{3}$ Prisoner A before being told anything

$P(A \mid B) = \frac{1}{2}$ Prisoner A after being told that B will be set free

$P(A \mid C) = \frac{1}{2}$ Prisoner A after being told that C will be set free

$P(A) = 0$ *or* 1   Jailer's point of view

Now the prisoner is right that his probability of being executed will not change no matter what the jailer says, because $P(A) = \frac{2}{3}$. However, it seems clear that the jailer is referring not to $P(A)$ but to $P(A \mid B)$ or $P(A \mid C)$, since the jailer refers to the respective probabilities. The prisoner, on the other hand, is referring only to $P(A)$ for himself, although he does seem to recognize that if he could somehow inform the other prisoner about his fate, then that would affect the other prisoner. The fact that he cannot do this is part of prisoner A's argument.

Let us now try to look a little more deeply at the problem. Suppose that the jailer agrees to the prisoner's request. If A is going to be executed, the jailer has a choice: either tell A that B is going to be set free or tell A that C is going to be set free. One naturally assumes that the jailer will make one of these choices at random with probability $\frac{1}{2}$. Is such a model reasonable? In practice, one would expect some bias (the jailer being human after all). So assume that the choice is made to say B with probability p and C with probability $q = 1 - p$. If we make this assumption, our whole model changes. We now have four events to consider:

$\overline{B}$ = "B is executed"

$\overline{C}$ = "C is executed"

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[1] Note that one or both of the gaps T_0 and T_1 could be bounded by two resets. If α is large, then most gaps will be between resets, not clicks.

[2] Note that this problem is very different from the Prisoner's Dilemma.

D_1 = "A is executed and the jailer says that B will go free",

D_2 = "A is executed and the jailer says that C will go free".

By assumption:

$$P(\overline{B}) = P(\overline{C}) = P(D_1 \cup D_2) = \frac{1}{3}$$
$$P(D_1 \mid \overline{A}) = p$$
$$P(D_2 \mid \overline{A}) = q$$

Hence,

$$P(D_1) = P(D_1 \mid \overline{A}) P(\overline{A}) = \frac{p}{3}$$

and similarly,

$$P(D_2) = \frac{q}{3}$$

The event that the jailer tells the prisoner that B will be set free is now $D_1 \cup \overline{C}$. The probability that A is set free given that the jailer tells the prisoner that B is set free is now:

$$
\begin{aligned}
P(A \mid D_1 \cup \overline{C}) &= \frac{P((A \cap D_1) \cup (A \cap \overline{C}))}{P(D_1 \cup \overline{C})} \\
&= \frac{P(A \cap D_1) + P(A \cap \overline{C})}{P(D_1) + P(\overline{C})} \\
&= \frac{0 + \frac{1}{3}}{\frac{p}{3} + \frac{1}{3}} \\
&= \frac{1}{p+1}
\end{aligned}
$$

Similarly, the probability that A is set free given that the jailer tells the prisoner that C is set free is

$$P(A \mid D_2 \cup \overline{B}) = \frac{1}{q+1}$$

Now consider some cases:

Unbiased jailer This is the case in which $p = q = \frac{1}{2}$. For this case the two conditional probabilities are:

$$
\begin{aligned}
P(A \mid D_1 \cup \overline{C}) &= \frac{1}{\frac{1}{2}+1} = \frac{2}{3} \\
P(A \mid D_2 \cup \overline{C}) &= \frac{1}{\frac{1}{2}+1} = \frac{2}{3}
\end{aligned}
$$

So if the jailer agrees to be fair, the probability does not change!

Totally biased jailer For example, assume that $p = 1$ and $q = 0$. Now the conditional probabilities are:

$$
\begin{aligned}
P(A \mid D_1 \cup \overline{C}) &= \frac{1}{1+1} = \frac{1}{2} \\
P(A \mid D_2 \cup \overline{C}) &= \frac{1}{0+1} = 1
\end{aligned}
$$

This looks paradoxical until you realize that the only way for the jailer to tell A that C is going to be set free is if B was going to be executed. So in this case the probabilities do change, possibly very dramatically.

This example illustrates the fact that even in a simple classical probability model, one can have complicated observer effects. In this case, the original model of one prisoner being selected at random to be set free is essentially trivial. The complexity arises when this model is combined with the prisoner and jailer, regarded as stochastic processes.

Many variations of this problem exist. This simplest is to change the problem from one randomly chosen prisoner to be set free to one randomly chosen prisoner to be executed. Another variation includes the prisoner specifying that the jailer should choose the other prisoner to tell him about randomly if there is a choice. Still other variations allow the prisoners to communicate with each other, either in just one direction or in two.

Yet another variation is the Monty Hall problem. While this problem is an interesting puzzle, it is not actually an example of an observer effect. It was included because it is similar to the Three Prisoners Problem[3] and variations of it do have observer effects. The Monty Hall problem is posed as a game show with three doors, one of which has a valuable prize. The contestant selects one door but is not shown what is behind it. The game show host then opens another door which is shown not to have the prize. The contestant is then given the option to change their choice. Note that the game show host must always open a door that does not have the prize, must give the contestant the option to change their choice, and the contestant knows all of this in advance. The best strategy is to exercise the option and change the choice to the other door. Indeed, exercising the option increases the probability of winning the prize by a factor of 2. The reason is quite simple. The probability that the prize is behind the selected door is $1/3$ and the probability that the prize is behind one of the other two doors is $2/3$. The option to change is effectively giving the contestant the ability to open two doors. This analysis seems to require that the prize be randomly placed behind a door. This is not actually necessary for the analysis. What matters is that the contestant has no knowledge of a bias in favor of any door.

The Monty Hall problem would have an observer effect if some of the requirements were relaxed, such as not requiring that the game show host must always open a door and must always give an option to change. This would dramatically change the problem since now the game show host could choose to give the option only if the contestant selected the door with the prize, or could do so with some probability. One can only surmise that it is some variation like this that many people are assuming when the problem is presented to them.

VII. SOCIOLOGICAL OBSERVER EFFECTS

We now consider observer effects in sociology. The earliest example was a research study on working conditions at the

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[3]Indeed, there are variations of the Three Prisoners Problem that are mathematically equivalent to the Monty Hall Problem.

Hawthorne Works of Western Electric in Cicero, Illinois, where it was found that individuals appeared to modify their behavior as a result of an awareness of being observed rather than any changes in the working conditions. It seems clear that there was an observer effect, but there is little agreement on exactly what the effect was. One interpretation is that the increased attention was the cause of the increase in productivity. This interpretation is now referred to as "The Hawthorne Effect" [9].

The observer effect also occurs in sociolinguistic research. The problem is that subjects may modify their behavior when a field worker is attempting to capture linguistic speech patterns. When attempting to observe the daily vernacular of a language, the speaker is aware that their speech is being used for scholarly research, and as a result may adopt a more formal pattern of speech. This produces data that is unrepresentative of the speaker's typical speech [8, p. 209].

A more significant sociological effect is the *secondary observer effect*.[4] This effect is concerned with how researchers select and process data to produce scientific results. Unlike the Hawthorne effect, this is not an effect on experimental subjects. Rather, it is a secondary effect on the observers. Different researchers will have their own techniques for selecting the data for a study and for analyzing it. Even relatively innocuous differences in the analysis steps can cause significantly different results on the same data. Different software packages that supposedly perform the same analysis may produce small but significantly different results. The use of data downloaded from the Internet leads to yet another problem. Online sources are often updated over time, so it need not be the case that the same source data remains the same [3].

Both primary and secondary observer effects can be modeled by analogy with the framework in Section V. In other words, the observer should also be considered as an experimental subject by a meta-observer. The combination of the scenario being studied and the observers who are studying it then forms the subject of the meta-study. A whimsical example of this appears in "The Hitchhiker's Guide to the Galaxy" [1] in which the Earth is actually a computer or laboratory created for and run by mice, and the researchers who are experimenting on mice are the actual subjects. This is not very much different from studies of primary and secondary observer effects, making Douglas Adams quite far ahead of his time; indeed, nearly 40 years before secondary observer effects were first considered by researchers.[5]

VIII. Schrödinger's cat

In quantum mechanics, a popular example of the observer effect is the Schrödinger's cat thought experiment, sometimes referred to as a paradox. The usefulness of this example is

[4]This could also be called a meta-observer effect.
[5]Alternatively, in the spirit of Douglas Adams' book, a copy of a paper on observer effects was sent backward in time...

that it furnishes a simple framework for distinguishing the various interpretations of quantum mechanics. Although the thought experiment was formulated in the context of quantum mechanics, it is unclear how it is actually quantum mechanical. One has a cat in a sealed container together with a mechanism that will kill the cat with probability $1/2$. Schrödinger was explicit that the mechanism was a radioactive sample, and even gave details about how the cat would be killed. None of this is especially relevant to the thought experiment, which could easily be regarded as being purely classical. One aspect of the paradox is that it does not seem to make intuitive sense for a macroscopic entity like a cat to be in a mixed state of being half alive and half dead. However, if one accepts this, then the other aspect of the paradox is that when one opens the sealed container, the mixed state somehow instantly collapses into a pure state; namely, the cat is either alive or dead at that point, not a mixed state of both. How does the observer cause this effect by simply observing the state of the cat?

While the quantum mechanical version of this problem is far from being resolved, from the classical point of view, there is no paradox at all. Mixed states are commonplace in probability. Indeed, as discussed in Section V, it is the essence of thinking probabilistically to view *every* measurement as being a probability distribution rather than to require that every measurement be a single value. Classical states (i.e., probability distributions) can evolve (as a result of new information), and there is no need for arbitrary, unexplained state collapses to occur. Unfortunately, this does not resolve the quantum mechanical problem.

IX. Software Monitoring

Complex mechanical and electronic systems can be prone to observer effects. These effects are called *probe effects* for electronic systems, and *observer effects* for software systems. Complex multithreaded applications are especially vulnerable to observer effects. Threads can have subtle thread coordination errors (commonly called "race conditions"). When a multithreaded application fails, the usual approach for dealing with the problem is to add additional software to monitor the behavior and isolate the cause. Unfortunately, such monitors can affect the functioning of the software so much that the failure no longer occurs. When this happens, the error is called a "Heisenbug." This name was inspired by the Heisenberg uncertainty principle. Unfortunately, while the name is very clever, it is also inappropriate. As was pointed out in Section I, the observer effect is not the same as an uncertainty principle, and a Heisenbug is clearly an observer effect, not any kind of uncertainty principle.

Software monitoring can have other effects as well, even when it is not being used to find a thread coordination error. Monitoring can invalidate the effects one is attempting to observe, and it can even cause its own errors and failures. For example, monitoring software to determine its performance

can be invalid due to the impact of the monitoring as a result of effects on caching and pipelining.

Needless to say, adding monitors to a software system will produce a different software system, and the modified system may have very different characteristics. The observer effect for such systems is a complex problem.

X. Conclusion

A number of examples of observer effects for classical systems have been presented. The main purpose was to make the case that observer effects are not exclusively a quantum mechanical issue. To analyze such effects for classical systems, it was proposed that the observer should be modeled as another stochastic process and a relationship between the observer process and the process being observed. The process being observed should be combined with the observer process to form a new process. The relationship between the two processes is a key part of the combined process. This approach may be useful for situation management as well as in other fields.

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