To appear, Proc. of the 13th International Conference on
Language and Automata Theory and Applications, St. Petersburg, Russia
March 26-29, 2019

Observation and Interaction*

Invited Paper

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Abstract. This paper connects three concepts in computer science, zero-knowledge proofs, causal reasoning, and bisimulation, to show that interaction is more powerful than observation. Observation is the use of input data plus, possibly, tractable computation, in such a way that the observer has no effect on the source of the data. Interaction is observation plus action that affects the source of the data. Observation lets the data "speak for itself" and is objective, whereas interaction is first-person and subjective. Zero-knowledge proofs are a strategy for building confidence in some fact while acquiring no additional information other than that the fact is likely to be true. They fall short of absolute certainty and they require interaction. This paper shows that absolutely certainty for such scenarios can be modeled by a bisimulation relation. Causal reasoning has also been shown to require subjective involvement. It is not possible by observation alone, and like zero-knowledge proofs, requires first-person involvement and interaction. This paper shows that bisimulation relations can reveal flaws in causal reasoning.

Keywords: Zero-knowledge proof · causal reasoning · bisimulation · randomized controlled trials.

1 Interaction vs. Observation

A number of researchers have argued that interaction is more powerful than observation [4,18,1,16,10]. What I mean by "observation" here is the use of input data plus, possibly, tractable computation. What I mean by "interaction" is observation plus action that affects the input data. Interaction combines observation with action in a closed feedback loop.

In this paper, which is largely an extract from my forthcoming book [8], I will connect three Turing-Award-winning concepts that I believe have never before been connected in this way. Specifically, I will connect zero-knowledge proofs (Goldwasser and Micali, 2012 Turing Award), bisimulation (Milner, 1991 Turing Award), and causal reasoning (Pearl, 2011 Turing Award) with each other and with the notion that interaction is more powerful than observation. I will

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* This work was supported in part by the National Science Foundation, NSF award #1446619 (Mathematical Theory of CPS).

assume in this paper that the reader is familiar with the oldest of these concepts, bisimulation, but I assume no prior knowledge of the two newer ones. For a gentle introduction to bisimulation, see [7], chapter 14. I will also boldly (and perhaps foolishly) relate these concepts to a treacherous quagmire in philosophy, the notion of free will.

Interaction as a tool is closely related to the concept of feedback, which has a long history. In the 1920s, at Bell Labs, Harold Black found that negative feedback could compensate for the deficiencies in amplifiers of the day [3]. His feedback circuits push on their environment, measure the extent to which its reaction deviates from the desired reaction, and adjust the pushing to get closer to a desired objective.

Norbert Wiener, during World War II, also used feedback for the automatic aiming and firing of anti-aircraft guns. Wiener coined the term “cybernetics” for the conjunction of physical processes, computation that governs the actions of those physical processes, and communication between the parts [19]. He derived the term from the Greek word for helmsman, governor, pilot, or rudder.

Feedback, which is used in many engineered systems today, is a tight interaction between a system and its environment. Turing-Church computation can be used as building blocks, for example to calculate adjustments, but fundamentally, they are just components in a bigger picture. Interactive systems go well beyond what Turing-Church computation alone can accomplish.

To make a connection with the concept of free will, I will rely on current trends in psychology, specifically the thesis of *embodied cognition*, where the mind “simply does not exist as something decoupled from the body and the environment in which it resides” [17, p. 7]. The mind does not just interact with its environment, but rather the mind *is* an interaction of the brain with its environment. A cognitive being is not an *observer* of its environment, but rather a collection of feedback loops that include the body and its environment, an *interactive* system.

Zero Knowledge Proofs

Zero-knowledge proofs were first developed by Shafi Goldwasser and Silvio Micali [5,6]. They were a first instance of a more general idea, interactive proofs, which bring randomness and interaction together. An interactive proof, developed independently by László Babai, [2], can be thought of as a game with two players, a prover (named Merlin by Babai) and a verifier (named Arthur by Babai). The verifier, Arthur, has limited ability to compute. Specifically, Arthur is assumed to be able to perform only computations that can be completed in a reasonable amount of time on a modern sequential computer. The prover, Merlin, is allowed to perform more difficult computations, but I will not make use of that feature in this paper.

Zero-knowledge proofs are easy to understand using a story developed by Jean-Jacques Quisquater and Louis Guillou, [14]. Assume that Merlin knows something important, like a password, and wants to prove to Arthur that he knows this. Merlin is a very private person, so while he wants to convince Arthur that he knows the password, he does not want Arthur to be able to convincingly tell anyone else that he knows the password. His objective is only to convince Arthur and give him exactly zero additional information. Note that Merlin's objective cannot be accomplished by simply telling Arthur the password because then Arthur will then also know the password.

In this story, there is an oddly shaped cave (see figure 1), where the entrance tunnel forks into two tunnels labeled A and B. Both tunnels are dead ends, but there is door connecting the two ends. The door can only be opened with a password that only Merlin knows.

One way that Merlin could prove to Arthur that he knows the password is to enter the cave together with Arthur, and while Arthur waits at the mouth of the cave, go down tunnel A and come back out through tunnel B. Arthur will be convinced that Merlin knows the password, and Arthur will not himself know the password. But if Arthur surreptitiously records the event with a video camera, then Arthur would be able to convince anyone else that Merlin knows the password. This makes the information that Merlin knows the password available to a third-person observer. The goal is that the information be available only to the first-person interactor, Arthur.

So, instead, Arthur waits outside the cave while Merlin goes in and picks one of the tunnels to go down. Suppose he picks tunnel B and goes as far as the door. Then Arthur comes into the cave as far as the fork and randomly calls out either A or B. He cannot see which tunnel Merlin went down. If he calls A, then Merlin has to use his password, open the door, and come out through tunnel A. Arthur is not yet *sure* that Merlin knows the password, but he can conclude that it is equally likely that he knows it as that he doesn't know it.

Arthur and Merlin then repeat the experiment. If Merlin successfully comes out of the tunnel that Arthur identifies a second time, then Arthur can conclude that the probability that he knows the password is now 3/4. It would have required quite a bit of luck for him to not have to use the password twice in

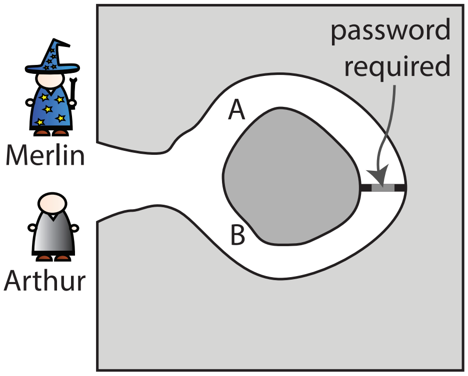

Fig. 1. Ali Baba's cave, illustrating zero-knowledge proofs.

a row. Repeating the experiment again will raise the probability to 7/8. After 10 repeats, the likelihood that he didn't need the password drops to about 1 in 1000. By repeating the experiment, Merlin can convince Arthur to any level he demands short of absolute certainty.

Unlike the previous experiment, where Merlin just went in one tunnel and came out the other, this new experiment does not give Arthur the power to convince a third party, say Sarah, that Merlin knows the password. Arthur could videotape the whole experiment, but Sarah is a savvy third party, and she suspects that Arthur and Merlin colluded and agreed ahead of time on the sequence of A's and B's that Arthur would call out. Only Arthur and Merlin can know whether collusion occurred. So Sarah is not convinced that Merlin knows the password the way Arthur is convinced. Merlin retains plausible deniability, and only Arthur knows for sure (almost for sure) that Merlin knows the password.

There are several fascinating aspects to this story. First, for Merlin to prove to Arthur that he knows the password while not giving Arthur the power to pass on that knowledge, interaction is required. If Arthur simply watches Merlin, observing but not interacting, then anything Merlin does to convince Arthur that he knows the password gives Arthur the power to pass on that knowledge, for example by making a video. He can then convince Sarah that Merlin knows the password by simply showing her the video. But by interacting, Merlin is able to convince Arthur and only Arthur. No third party observer will be convinced. You have to actively participate to be convinced. Interaction is more powerful than observation, but for interaction to work, you have to be a first-person participant in the interaction. This is what interaction means! Arthur's first-person action, choosing A or B at random, is necessarily subjective. Only he knows that no collusion was involved.

Another fascinating aspect of this story is the role of uncertainty. Using this scheme, it is not possible to give Arthur absolute certainty without giving Arthur more than Merlin wants to. The residual uncertainty that Arthur retains can be made as small as we like, but it cannot be reduced to zero, at least not by this technique.

A third fascinating aspect is the role of randomness. Arthur has to know that the sequence of A's and B's that he calls out are not knowable to Merlin (with high probability), but that fact has to be hidden from anyone else. Arthur could choose A or B each time using his free will, if he has free will. Actually, all that is required is that Arthur *believe* that he has free will and believes that he has chosen randomly between A and B. Given this belief, he will be convinced that with high probability Merlin knows the password. It makes no difference whether the choice is made by Arthur's conscious mind or by some unconscious mechanism in his brain.

Suppose that Arthur chooses instead to rely on an external source of randomness rather than some internal free will. He could, for example, flip a coin each time to choose between A and B. But this could result in leaking information because now he could videotape the coin flipping, and the resulting video would convince Sarah and any other third party as much as it convinces Arthur. It will be evident to any observer that Arthur is not colluding with Merlin. Observers could easily imagine themselves flipping the coin, so Arthur is just a proxy for their own first-person interaction. I will later leverage this strategy to explain why randomized controlled trials work to determine causal relationships. But for the goal of preserving Merlin's privacy, Arthur has to generate the choices between A and B in a hidden way, and by hiding this, he gives up the ability to convince any third party.

Even Arthur's knowledge, however, is not certainty. Some background assumptions are needed. Arthur has to believe in his free will, and dismiss ideas like that Merlin is somehow manipulating his subconscious brain to make colluding choices. Ultimately, a little bit of trust is required to get past all the conspiracy theories. Once we open the door to trust, we have to admit that a third person may decide to trust Arthur and assume that he is not colluding with Merlin, in which case, despite Merlin's wishes, his secret will be out.

Merlin and Arthur Bisimulate

Merlin and Arthur's interaction in figure 1 can be modeled using automata, as shown in figure 2. The model for Arthur is shown at the top. It shows that Arthur enters the cave in the first time instant, then nondeterministically calls out A or B, ending in one of two possible states, *endA* or *endB*. The second model shows Merlin under the assumption that he does not know the password. He also enters the cave in the first instant, but nondeterministically goes to one of two locations, *insideA* or *insideB*. Once he is one of these locations, he has no choice but to come out the same way he went in.

The third model in the figure shows Merlin under the assumption that he does know the password. One way to understand the difference between the second and third models is that, in the second, the decision about which tunnel to exit from is made earlier than in the third model. To make the decision later, in the second reaction of the state machine, Merlin needs to know the password. To make it earlier, in the first reaction, there is no need to know the password.

Here is where I will boldly make a connection with the concept of free will. Arthur has to make one decision, which tunnel to call out, A or B. Merlin has to make two decisions, which tunnel to enter, and which to exit. If Merlin does not know the password, the first decision determines the second, and, once the first decision is made, Merlin has no free will to make the second. On the other hand, if Merlin does know the password, then the second decision remains free, and Merlin is free too exit from the tunnel called out by Arthur. Here, "knowing the password" is a proxy for an ability to exercise the choice to pass through the door. If Merlin does not know the password, there is no such choice, and the tunnel by which he exits has been preordained. This lack of free will illustrates the incompatibilist interpretation in philosophy, where free will is incompatible with determinism. On the other hand, Arthur's free will in choosing to call out A or B illustrates the compatibilist interpretation, where it doesn't really matter whether the resolution of alternatives is predetermined or not. If Arthur's brain

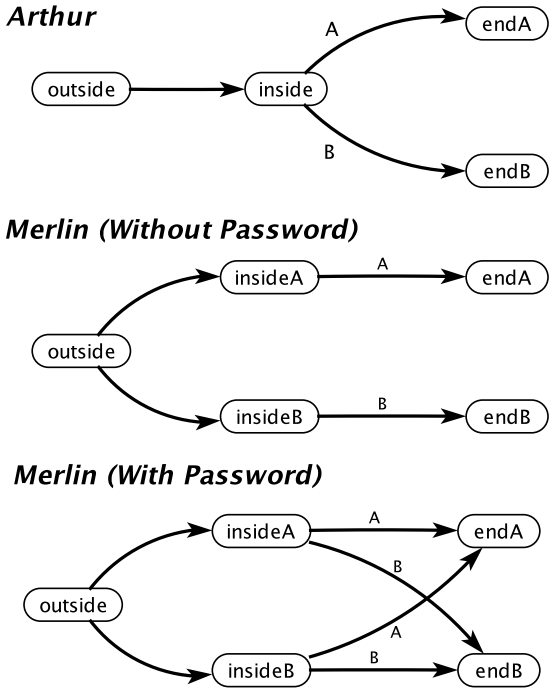

Fig. 2. Automata models of Arthur and Merlin, with and without the password.

internally uses a deterministic pseudo-random sequence generator, the outcome is the same as long as he believes the choice was free.

Given the many trajectories that the game can follow, we can ask *why* one trajectory occurs over another, *how* the determination of a trajectory is made, or *when* the determination between alternatives is made. If, for example, the determination between alternative trajectories is made early, then according to the incompatibilist interpretation, later in the game, there is no free will. If on the other hand, the determination between alternative trajectories is made as late as possible, say, just before the selection of alternatives has any effect on anything else, then there remains at least a possibility of free will. In any case, the questions of *how* and *why* a determination is made can only really make sense after we answer the question of *when*.

How can we determine whether the selection between alternatives is made early or late? I will leverage insights first exposed by Robin Milner, who showed how to compare automata using simulation and bisimulation relations. In automata theory, a passive observer of a system *cannot tell* whether selection is made early or late. In order to be able to tell, an observer must *interact* with the system. It is not sufficient to just observe the system. Interaction is required to determine whether there is free will, and first-person interaction yields more than

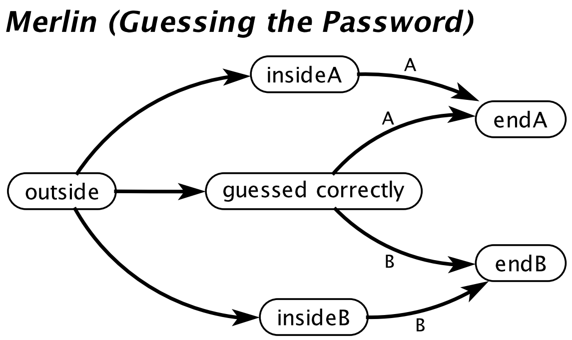

Fig. 3. Automata model Merlin where he guesses the password.

observation. This theory, in fact, helps to explain why first-person interaction is so different from third-person observation. It may even help us understand what we mean by "first person."

Notice that all three automata in figure 2 are language equivalent. Each is capable of producing the output A or B and nothing more. But language equivalence is not enough. Milner's notion of simulation captures the difference between Merlin (without password) and Merlin (with password). Specifically, Merlin (with password) simulates Arthur, but Merlin (without password) does not. Merlin is unable to make some of the moves that Arthur may demand.

The fact that Arthur simulates Merlin is what makes it possible for Arthur to collude with Merlin. Arthur can match the decisions Merlin has already made. Equivalently, Merlin can anticipate whether Arthur will call out A or B. If Merlin *does* know the password, then Merlin is bisimilar to Arthur. They can perfectly match each other's moves regardless of who moves first at each time instant. No collusion is needed.

Simulation relations, however, are not quite enough. Suppose instead that Merlin does not know the password but rather guesses it each time he needs it. This can be represented by the automaton in figure 3. Here, if Merlin correctly guesses the password, he is able to fool Arthur no matter how many times they perform the experiment. This gives Merlin's automaton the ability to simulate Arthur's automaton. So Merlin (with guessing) simulates Arthur, and Arthur simulates Merlin (with guessing). But Merlin (with guessing) is still not fundamentally equivalent to Arthur. The possibility of guessing incorrectly remains.

A bit of history may be helpful here. In the 1970s, Milner had introduced the idea of simulation relations between automata. In 1980, David Park found a gap in Milner's prior notion of simulation. He noticed that even if two automata simulate each other, they can nevertheless exhibit significant differences in behavior when they *interact*. Milner's prior notion of simulation was unable to distinguish Merlin (with password) from Merlin (with guessing).

Milner and Park together came up with a stronger notion of modeling that they decided to call "bisimulation" [11,9]. Milner then fully developed and popularized the idea.[1] He showed that the difference between Merlin (with password) and Merlin (with guessing) becomes evident only if the two automata interact with one another. It is not enough to just observe each other, as he had done previously with his simulation relations. Interaction is more powerful than observation.

How is bisimulation about interaction whereas simulation is only about observation? To construct a simulation relation, the automaton being simulated moves first in each round, and the automaton doing the simulating must match the move. To construct a bisimulation relation, in each turn, either automaton can move first and the other automaton has to be able to match the move. The ability in the game to alternate which automaton moves first makes this fundamentally an interactive game rather than a one-way observation.

It is easy to verify that there is no bisimulation relation between Merlin (with guessing) and Arthur, nor between Merlin (with guessing) and Merlin (with password). The lack of a bisimulation relation reveals the mismatch. But there is a subtlety. To know that there is no bisimulation relation, we need to know the structure of the automata. If we know that Merlin's automaton has the structure shown in figure 3, then we know that he does not know the password, even if the possibility of a lucky guess remains.

This subtlety lends insight into why zero-knowledge proofs do not yield certainty. Arthur is never absolutely certain that Merlin knows the password, though by repeating the trial, be can reach any level of certainty he desires short of absolute certainty. If Arthur were instead given the bisimulation relation, he would have a proof that Merlin knows the password. No uncertainty would remain. But constructing that proof requires knowing the structure of Merlin's automaton, or equivalently, knowing that Merlin knows the password.

What really does bisimulation mean in this case? The two automata, Arthur and Merlin (with password), have different structure, but they are fundamentally indistinguishable. Arthur's automaton represents what he demands from someone who knows the password. Merlin's automaton represents the capabilities he acquires by knowing the password. The fact that these two automata are bisimilar shows conclusively what Arthur is able to conclude with repeated experiments, that Merlin knows the password. Hence, the repeated experiments may provide evidence of bisimilarity that does not require knowing the detailed structure of the automata. Such evidence will only be provided if the repeated experiments are fair in the sense that all of the possible nondeterministic transitions occur in at least some of the trials (or infinitely often in an infinite experiment).

Causal Reasoning

Pearl has argued that interacting with a system enables drawing conclusions about causal relationships between pieces of that system, conclusions that are

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[1] Sangiorgi gives a nice overview of the historical development of this idea [15]. He notes that essentially the same concept of bisimulation had also been developed in the fields of philosophical logic and set theory.

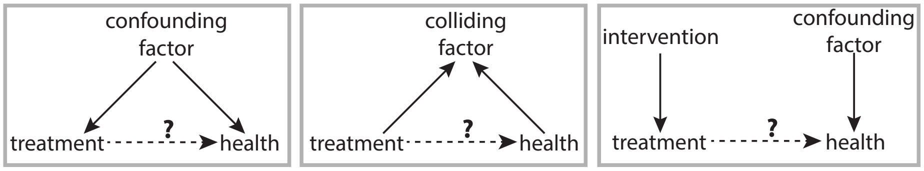

Fig. 4. A causal diagram on the left guiding the evaluation of a treatment's effectiveness that requires controlling for a confounder on the left and *not* controlling for collider in the center. On the right, intervention removes the effect of a confounder.

much harder to defend without interaction [12,13]. Specifically, consider the classic problem of determining whether administering an experimental drug causes a patient's condition to improve. The gold standard for making such a determination is a double-blind randomized controlled trial (RCT), where a subset of patients from a population is chosen at random to receive the drug, and the other patients in the trial receive a placebo. "Double blind" means that neither the medical staff administering the drug nor the patients know whether they are using the real drug or a placebo. "Randomized" means that the selection of patients to receive treatment is not causally affected by anything other than chance.

Why does an RCT work so well? Pearl explains this using causal diagrams, which represent the ability one variable in a system has to cause perturbations in another. Consider the causal diagram on the left in figure 4. The solid arrows represent an assumed causal relationship between a "confounding factor" and both the treatment and health of the patient. For example, suppose that some treatment, when made available to a population, is more likely to be taken by males than by females, and males are also more likely to recover than females. In this case, a statistician will tell you that it is necessary to control for the sex of the patient. Otherwise, you may derive erroneous conclusions from the data. But the challenge, in many practical cases, is that the confounding factors are not known or data about them are not available.

Consider instead the scenario in the center of figure 4. Suppose for example that the "colliding factor" is whether a patient ends up in the hospital. Taking the treatment, because of side effects, may cause the patient to end up in the hospital. Poor health, where the treatment has been ineffective, could also result in the patient ending up in the hospital. In this case, it would be a statistical error to control for whether the patient ends up in the hospital. An effective treatment could be rejected because, among patients that end up in the hospital, whether they got the treatment and whether their health improved could be uncorrelated, and also among patients who do not end up in the hospital, while in the general population, there is a correlation between patients who receive treatment and those whose health improves.

At the right of figure 4 is a causal diagram representing an intervention, a form of interaction that Pearl calls a "do operator." The intervention in a ran-

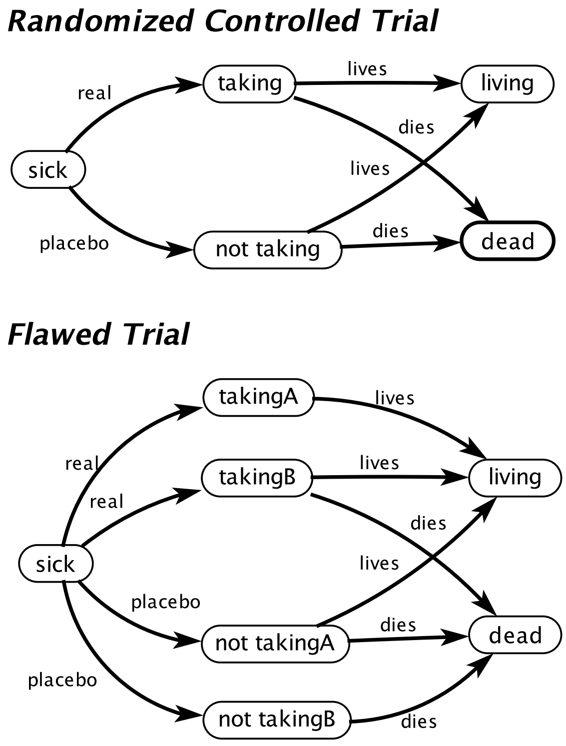

Fig. 5. Randomized controlled trial model and model of a flawed trial.

domized controlled trial (RCT) breaks any causal dependencies on whether the treatment is taken by forcing the treatment to be taken or not taken according to a random outcome. This removes the need to control for any other factors, known or unknown.

The intervention is analogous to Arthur's calling out of A or B to specify the tunnel from which Merlin should exit. But there is an interesting twist here. The purpose of a randomized controlled trial is to broadcast the information that a drug works or does not work, whereas in the Merlin-Arthur scenario, the goal is to ensure that the information that Merlin knows the password (analogous to the drug works or does not work) is *not* available to a third party observer. Recall that if Arthur visibly flips a coin, as opposed to using free will, to determine whether to call out A or B, then the information that Merlin knows the password becomes available to a third party observer. Analogous, in an RCT, the decision of whether to administer the drug or a placebo should be made by a verifiably random choice, not secretly by someone's free will, in order for the outcome of the trial to be trusted by an outside observer.

A properly constructed RCT can be represented by the automaton at the top of figure 5. The important feature of this automaton is the determination of whether the patient lives or dies is made *after* the determination of whether to administer a placebo or the real drug. In an incorrectly constructed trial, shown at the bottom of the figure, it is possible for a patient who is doomed to die will get assigned a placebo and one that is destined to live will be given the real drug. An unscrupulous researcher could, for example, assign the real drug to younger and healthier patients and the placebo to older and sicker patients, thereby skewing the results of the trial.

The two automata in figure 5 simulate each other, but they are not bisimilar. These automata say nothing about the probabilities of outcomes. They only express possibilities. Hence, it is still possible to construct an invalid trial that is bisimilar to the top automaton. For example, adding transitions from *takingA* to *dead* and *not takingB* to *living* would make the lower automaton bisimilar to the upper one, but the trial could still be skewed. But any automaton that is *not* bisimilar to the upper one will *surely* be invalid.

Humanity Requires Interaction

Interacting components can observe *and be observed* and can affect and *be affected.* Such interaction can accomplish things that are not possible with observation alone. The implications of this are profound. It reinforces Milner's observation that machines that look identical to an observer are not identical if you can interact with them. It reinforces Goldwasser and Micali's observation that interaction can do things that are not possible without interaction. It reinforces Pearl's observation that reasoning about causality requires interaction. It also reinforces the hypothesis of embodied cognition from psychology. If our sense of self depends on bidirectional interaction, the kind of dialog of Milner's model, where either party can observe or be observed, then our sense of self cannot be separated from our social interactions. Our minds cannot exist as an observer of the universe alone. And indeed, our interaction with the world around us has this bidirectional character. Sometimes we react to stimulus in ways that affect those around us, and sometimes we produce stimulus and watch the reactions of those around us. Such dialog seems to be an essential part of being human and may even form the foundations for language and even thought.

Moreover, such dialog has deep roots in physics. Quantum physics has taught us that no observation of a physical system is possible without disrupting the system in some way. In fact, quantum physics has real problems with any attempt to separate the observer from the observed. The observed automaton necessarily observes the observer. Passive observation in the form of unidirectional simulation is impossible in our natural universe. This suggests that simulation relations alone are not a reasonable model of modeling (a "metamodel," if you will permit me). Bisimulation is a better choice.

In an objectivist approach to science, we are often taught to let the data "speak for itself," to avoid subjective bias, where our actions may affect the data. I have collected in this paper several powerful arguments that being so objective has serious limitations. Subjectivity, first-person involvement, and interaction with the sources of data are sometimes essential.

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