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THE BEGINNINGS OF A MODERN COPERNICAN REVOLUTION

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The 100 years between the mid 1500s and mid 1600s produced a number of important new theories and surprising discoveries. Copernicus' sun-centered system, Tycho's astronomical observations, including the discovery that supernovae and comets are superlunar phenomena, Galileo's investigations with the telescope, Kepler's discovery that planetary motion could be accounted for vastly better by abandoning the old view of planetary motion as perfectly circular and uniform – these theories and discoveries, and others, would eventually lead us to a substantially different view as to the sort of universe we inhabit.

The set of changes that eventually resulted from such discoveries is often referred to as the "Copernican revolution." Although this phrase is rather imprecisely defined, there is not much doubt that the changes involved went far beyond the mere issue of whether the earth moves about the sun, or vice versa. Instead, discoveries such as those noted above led to a wide range of dramatic changes – scientific changes, conceptual changes, and technological changes, and arguably political, social, and religious changes as well, to name just a few – that could not even be imagined in the early years of the 1600s.

One of my central questions in this paper is whether we, in the early years of the 21st century, are in a similar situation to that of our predecessors in the early years of the 1600s. Roughly, are we in the beginning stages of a modern Copernican revolution?

Generally, as will emerge below, I think it likely that the answer to this question will turn out to be "yes." In the 1600s, new discoveries eventually led us to understand that we did not inhabit the sort of universe we thought we inhabited. We came to realize that the old view of the universe – the teleological, essentialistic, more or less Aristotelian sort of universe that had been accepted for 2,000 years – was the wrong *sort* of view. The universe, we realized, was nothing like the way it had been conceived to be for the past two millennia.

Instead, we eventually came to believe, we live not in a teleological universe in which natural objects behave as they do largely because of internal, goal-directed essential natures, but rather we live in a mechanistic universe, in which objects behave as they do largely because of the influence of external objects and forces. And these objects and forces could be described by precise, deterministic mathematical laws within a more or less Newtonian framework. Generally speaking, we came to believe that the universe is like a machine. Much as parts of a machine interact with one another in a push-pull sort of way, so too do objects in the universe interact with one another in this sort of machine-like, mechanistic way. We knew, or thought we knew, what sort of universe we inhabit.

In recent years, however, new discoveries have arisen that call into question this machine-like view of the universe. These discoveries are, at bottom, a combination of a relatively-recent mathematical proof, together with the outcome of a series of carefully conducted experiments. For reasons that will emerge below, these new discoveries are, I think, every bit as dramatic as, say, Galileo's discoveries with the telescope, or Kepler's discoveries about planetary orbits.

Unfortunately, these new discoveries are not nearly as widely known as the discoveries of Galileo and Kepler just mentioned (or of most of the discoveries and new theories in play in the early 1600s). Partly this is because these new discoveries involve a mathematical theorem (namely, Bell's theorem), and also because they involve one of the more difficult of modern theories (namely, quantum theory). This, too, provides part of the motivation for this paper. I think these new discoveries are fascinating and important, and deserve to be more widely known. And so, generally speaking, the goals of this paper are to present the new discoveries alluded to above in a way that is accessible to a non-technical audience, and to explore the question of whether, as with the situation in the early 1600s, these discoveries call into question the overall machine-like view of the universe we have had since the first Copernican revolution.

The structure of the paper is straightforward. My first general goal will be to explain, in a manner as accessible as possible, the new discoveries alluded to above. These discoveries are best approached by first discussing what has come to be called the *locality assumption.* This will lead to a discussion of the mathematical theorem mentioned above, generally referred to as *Bell's theorem* or *Bell's inequality*, which in turn will be followed by a discussion of the ties between the locality assumption, Bell's theorem, and quantum theory. Finally, we will turn to an explanation of certain new experimental results (which I will refer to collectively as the Aspect experiments), followed by a discussion of the implications of these discoveries. In particular, the concern of this final section will be to assess what these newly discovered facts tell us about the sort of universe we inhabit.

In outline, then, the major sections of the paper are as follows:

1. The Locality Assumption
2. Bell's Theorem
3. The Ties Between the Locality Assumption, Bell's Theorem, and Quantum Theory
4. The Aspect Experiments
5. Implications of Bell's Theorem and the Aspect Experiments
6. Concluding Thoughts

The Locality Assumption

Roughly speaking, the locality assumption is a somewhat updated version of the old "no action at a distance" idea, that is, that an event at one location cannot influence an event at another location unless there is some sort of connection, or contact, or communication, between the two events. For example, if there is a coin balanced on the table in front of us, we tend to think that we cannot influence the coin (say, cause it to fall over) unless there is some sort of contact or connection between us and the coin (we reach out and push it over, throw a book at it, shake the table, or ask someone else to push the coin over for us, and so on). The idea that what happens at one location cannot influence what happens at another location, unless there is some sort of connection or communication between the two locations, is a deeply-rooted belief dating at least back to the ancient Greeks. Notably, given the centrality of push-pull sorts of interactions inherent in the universe-as-machine metaphor, this belief became even more entrenched with the advent of the mechanistic, machine-like view of the universe that developed following the events of the 1600s. The phrase used above – that what happens at one location cannot influence what happens at another location unless there is some sort of connection or communication between the two locations – is one common, though somewhat rough, way of phrasing the locality assumption.

In this rough phrasing, the notion of "some sort of communication or connection" is rather imprecise. The locality assumption is typically made more precise by employing an implication of Einstein's relativity theory. From relativity, there is good reason to think that the speed of light is a sort of universal speed limit. That is, no influence can propagate faster than the speed of light.[1] Given this, if two events take place within a space of time too short for light to cover the distance between the two events, then there can be no possibility of any sort of signaling or communication or contact or connection between two events. Such events – that is, events that occur within a length of time too short for light to cover the distance between them – are said to have occurred *at a distance* or, equivalently, at *distant locations.*

This consideration leads to a more precise formulation of the locality assumption, sometimes termed *Einstein locality* (partly because of the emphasis on the speed of light stemming from Einstein's relativity, and partly because this sort of influence seemed to be the most worrisome for Einstein – this is the sort of influence he once famously referred to as "spooky action at a distance").

> *The Locality Assumption (Einstein Locality):* An event at one location cannot influence an event at a distant location.

At bottom, that is all there is to the locality assumption. As I am construing it here (that is, in terms of Einstein locality), the locality assumption is essentially the dictum "no action at a distance," somewhat modified and made more precise by employing the speed of light restrictions from relativity. With this brief description of the locality assumption finished, the next task is to consider Bell's theorem.

Bell's Theorem (An Informal Account)

As the name suggests, Bell's theorem is a mathematical theorem, first produced by John Bell in 1964.[2] As will emerge, Bell's theorem has interesting ties to both the locality assumption and to quantum theory. In what follows, I will present a quite informal, non-mathematical account of Bell's theorem. I should note that my approach owes much to what I take to be some very good informal accounts provided by Bell himself, as well as by David Mermin and Nick Herbert.[3]

Suppose we have two devices that we will simply call "A" and "B," each

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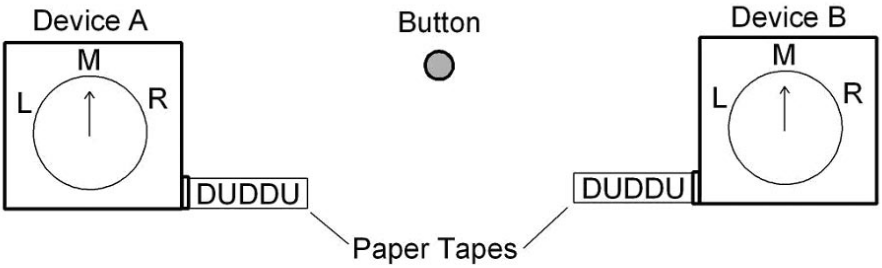
[1] See Maudlin (1994) for a careful analysis of what sorts of influences are and are not ruled out by relativity.

[2] Most of Bell's writings on the foundations of quantum theory can be found in Bell (1988).

[3] Most notably, Bell (1988), Mermin (1981) and (1985), and Herbert (1985).

having a dial with three settings, labeled "L" (left), "M" (middle), and "R" (right), and each equipped with a paper tape on which the device can print. Suppose also that we have a button, and that each time we press the button, each device records either a "D" or a "U" on its paper tape. Pictorially, this setup would look as follows:



We will use "A:M" to abbreviate that the dial on device A is set to the middle position, and likewise use "B:M" to abbreviate that the dial on device B is set to its middle position (we will likewise use "A:L" to abbreviate that A is set to its left position, and so on). Using this notation, we can compactly summarize the results of various button presses with the dials set to various positions. For example, "A:M DUDDUDUUUD" will represent the output of 10 button presses for device A when that device is set to its middle position.

Now let's consider four scenarios involving these devices.

Scenario 1: For scenario 1, we set the dial on device A to its middle position, and we likewise set the dial on B to its middle position. We push the button hundreds of times, and we notice that every time we push the button, each device records an identical output. That is, each time device A records a D on its tape, device B likewise records a D on its tape, and each time device A records a U, device B likewise records a U. Moreover, we notice that the devices produce a random mixture of D's and U's. That is, although for each button press the devices record identical outputs, 50% of the time the outputs are D's and 50% of the time the outputs are U's.

Using the notation mentioned above, we can summarize scenario 1 as follows.

Scenario 1:
A:M DUDDUDUUUDUDDUUDUDDUDUUUDUDD...
B:M DUDDUDUUUDUDDUUDUDDUDUUUDUDD...
Summary: Identical Outputs

Scenario 2: For scenario 2, we move the dial on A to its left position, and leave the dial on B in its middle position. Now when we press the button a number of times, we notice that although the devices usually record identical outputs, occasionally the outputs do not match. In particular, we notice that there is a roughly 25% difference in the output of the two devices when the dials are set in this way. To summarize:

Scenario 2:
A:L DDUDUUDUDDUUDUDUUDUDDDUDUUDU...
B:M DUUDUDDUDDUUDUUDUDUDUDUDDUUU...
Summary: 25% Difference

Scenario 3: For scenario 3, we return the dial on A to its middle position, and move the dial on B to its right position. We again push the button a number of times, and again notice that, although the outputs usually match, roughly 25% of the time they do not. In summary:

Scenario 3:
A:M UUDUDDUDUUDDDUDUUUDUDUUDDUDD...
B:R UDDUDUUDDUDUDUDDUUUUDUDDDUDD...
Summary: 25% Difference

Scenario 4: For scenario 4, we put the dial on machine A in its left position (as in scenario 2), and put the dial on machine B in its right position (as in scenario 3). But before going further, we will assume the following hold:

(i) The locality assumption (that is, Einstein locality) is correct,

and

(ii) The recording of the outputs of the two devices (A and B) occur at a distance. (In other words, each time we push the button, the event of device A recording a D or U on its tape, and the event of device B recording a D or U on its tape, are events that occur at a distance.)

If (i) and (ii) are correct, it follows that the 25% difference in scenario 2 has to be a result only from changes to device A resulting from moving its dial. And likewise, the 25% difference in scenario 3 must be the result only of changes made to B resulting from moving B's dial. These two 25% differences, then, can combine in scenario 4 to result in a maximum 50% difference between the two outputs. In short, if (i) and (ii) are correct, then in scenario 4 the maximum difference between the output of device A and the output of device B will be 50%.

This latter statement, that in scenarios such as that described above, the maximum difference in outcomes in scenario 4 is 50%, is essentially Bell's theorem (or more precisely, a somewhat restricted version of Bell's theorem). So if the 50% figure makes sense, then you understand, for our purposes, Bell's theorem.

The next task is to explain the ties between the locality assumption, Bell's theorem, and quantum theory.

The Ties Between the Locality Assumption, Bell's Theorem, and Quantum Theory

Polarization is an attribute of photons, and an attribute that is not particularly difficult to measure. Moreover, quantum theory is the theory used to make predictions involving the polarization of photons. Given this, polarization will provide a convenient way to illustrate the ties between the locality assumption, Bell's theorem, and quantum theory.

For the sake of making the discussion easier, we will make the following simplifying assumptions:

(a) When the polarization of a photon is measured, it will be measured as having either "Up" polarization or "Down" polarization,

and

(b) there is a 50/50 chance of a photon being measured as having Up polarization and a 50/50 chance of it being measured as having Down polarization.

The actual situation regarding polarization is slightly more complex than summarized in (a) and (b), but making the simplifying assumptions (a) and (b) will make the following discussion much more straightforward, and these simplifying assumptions will not change any important facts about what is to follow.

Recall the two devices A and B in the discussion of Bell's theorem above. We will now take these devices to be polarization detectors, with the U and D recorded on the tape representing Up and Down polarization. As in the discussion above, the detectors will have L, M, and R settings. (The details need not concern us, but polarization detectors can indeed have the equivalent of L, M, and R settings.)

It is not difficult to generate pairs of photons in what are called the "twin state," and it is possible to separate such photons and send one to polarization detector A and one to polarization detector B. So now, in the setup described in the section above, suppose each time we push the button, it generates a pair of photons in the twin state, separates the photons, and sends one to detector A and one to detector B. Each detector subsequently measures the polarization of its respective photon, and records either a D or a U on its respective paper tape.

Photons that are in the twin state are such that, if polarization detectors A and B are set to the same position (that is, both are set to the L position, or both set to the M position, or both to the R position), then when the two detectors are used to measure the polarization of the two photons, the photons will be measured to have the same polarization. For example, suppose both detectors are set to their M position. We push the button many times, and each time we push the button, a pair of photons in the twin state are generated, separated, and sent to their respective detectors. In this situation, every time we push the button, whenever detector A measures its photon as having Up polarization, detector B will likewise measure its photon as having Up polarization. And likewise, if one of a pair of such photons is measured as having Down polarization, then the other will be Down as well.

Now consider four experimental setups, exactly analogous to the four scenarios described above in the discussion of Bell's theorem. In the first scenario, exactly as described above, we set both detectors to their M positions, and we push the button hundreds of times. The result will be exactly the pattern described in scenario 1 above, that is, whenever detector A measures a photon as having Up polarization, detector B will register its photon as also having Up polarization.

Importantly, note that this is simply an empirical fact about photons, polarization detectors, and certain experimental setups. This is not a conjecture, or theory, or thought experiment, or whatever. Rather, what is described above is simply a fact about the universe we live in. When polarization detectors are set so that both are in their M positions, and photons in the twin state are generated and separated, with one being sent to each detector, then the photons will always be measured as having the same polarization.

Now we set the detectors up as in scenario 2, that is, we move the dial on A to its L position and leave the dial on B in its M position. Again we push the button hundreds of times. Again the result will be exactly as summarized above in the discussion of Bell's theorem, that is, most of the time the two photons will be measured as having the same polarization, but about 25% of the time the polarization will differ.

Again it is important to note that this is simply an experimental fact. Set the dials on the detectors as described, and the experimental outcome will be as described.

Likewise for scenario 3. Move the dial on A back to its M position, and turn the dial on B to its R position. Push the button hundreds of times, and again the experimental outcome will be as described, that is, about 25% of the time the two polarization detectors will record different polarizations for the two photons. And again, this is simply a fact about the universe we inhabit.

Finally, scenario 4 will likewise be exactly as described in the section above on Bell's theorem. That is, set A to its L position and B to its R position. Once again we will push the button hundreds of times.

Before going further, suppose we can assure that, each time detector A and B measure the polarization of a pair of photons in the twin state, that these measurements occur at a distance. That is, the event of polarization detector A measuring the polarization of the photon sent to it, and the event of polarization detector B measuring the polarization of the photon sent to it, take place within a period of time too short for any sort of signal or communication to be sent between them. Then, exactly as in the discussion in the section above, if the locality assumption is correct, it follows from Bell's theorem that in this scenario there can be at most a 50% difference between the pattern of D's and U's on the tapes of detectors A and B.

This is where the tie to quantum theory comes in. As noted, quantum theory is the appropriate theory for making predictions about the readings of polarization detectors such as those described above. When quantum theory is used to make predictions about what will be observed in scenario 4, the prediction is that there should be an almost 75% difference between the recordings of detector A and B.

In short, Bell's theorem amounts to a discovery that predictions based on the locality assumption, on the one hand, and predictions based on quantum theory, on the other hand, conflict. So although Bell's theorem is essentially a mathematical theorem, the main importance of it (and this is what Bell was primarily interested in) is that it shows that quantum theory and the locality assumption cannot both be correct.

The Aspect Experiments

Although Bell's theorem, and the ties to quantum theory, are reasonably straightforward, it is not so straightforward to carry out actual experiments to test the conflict between the locality assumption and quantum theory. There is no difficulty in generating photons in the twin state, or in generating other particles whose states are tied to one another in a way similar to the way the polarization of photons in the twin state are tied to one another. (Such particles are said to be *correlated*, and correlated particles are not at all uncommon.) Rather, the main difficulty is in assuring that the measurements on the photons (or other correlated particles) are such that they take place at a distance (that is, such that there is no possibility of any sort of signal or communication between the two detectors).

Following the publication of Bell's theorem, a number of labs worked on designing such experiments. Some of the most important of these experiments were carried out by Alain Aspect and his colleagues at the University of Paris in the early 1980s.[4] The design of these experiments was analogous to what was described above (though not surprisingly, the details are a bit more complicated than the setup described above). The experiments used pairs of photons whose polarization was correlated, and the photons were separated and sent to respective detectors that had settings analogous to the L, M, and R settings described above. And the measurements of the polarization of the respective photons took place at a distance, that is, the experimental setup was such that there could be no communication or connection between the detectors.[5]

The results of the Aspect experiments were very much in line with the predictions of quantum theory. Such results have been replicated numerous times by different labs, using different sorts of correlated particles, and the results are quite robust. That is, in the conflict Bell discovered between predictions based on quantum theory and predictions based on the locality assumption, the locality assumption loses.

Of course, new discoveries are not uncommon. After all, new facts are discovered often. So why are the new facts revealed by the Aspect experiments (and similar experiments) of particular interest? For this question, we turn to the next section.

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[4] See Aspect (1982).

[5] Assuring that the measurements of the photons occurred at a distance was one of the most difficult tasks to accomplish. It is not crucial for this paper, but in essence, and speaking a bit roughly, this was accomplished in Aspect's lab by waiting until the photons were separated and each heading toward their respective detectors before (quasi) randomly setting each detector to its L, M, or R setting. Baggott (1992) and Cushing (1998) contain nice discussions, thorough and accurate but still accessible to a general audience, of the Aspect experiments.

Implications of Bell's Theorem and the Aspect Experiments

In this final section, I want to consider the general question of whether we find ourselves, in the late 20th and early 21st century, in a situation similar to that of the early 1600s. As noted earlier, in the early 1600s new discoveries led to the realization that the existing general conception of the universe was mistaken. The cumulative effect of Copernicus' sun-centered theory, discoveries such as those Galileo reported from his observations with the telescope, Kepler's discovery that a sun-centered system employing elliptical orbits and varying speeds would account for the astronomical data far better than any of the alternatives, Kepler's publication of substantially superior astronomical tables based on his sun-centered system, and other new discoveries and theories, eventually led to the acceptance of the sun-centered view. And with the acceptance of a sun-centered view came the rejection of the general, roughly Aristotelian, conception of the universe. Importantly, it was not merely that this or that particular theory proved to be mistaken. Rather, it was the general Aristotelian, teleological, essentialistic conception of the universe that was wrong. That is, we turned out to be mistaken about the *sort* or universe we inhabit.

For the sake of having a convenient term, I will refer to the sort of instantaneous influences between distant events, of the sort demonstrated by the Aspect experiments, as Bell-like influences. The discovery, in recent years, that we live in a universe that allows for Bell-like influences is certainly an interesting discovery, and one that most people find quite surprising. But how similar is our situation today to that of the early 1600s? Do Bell's theorem and the Aspect experiments suggest, as was the case with the situation in the early 1600s, that we are mistaken about the sort of universe we have thought we inhabited for some time?

There is no doubt that there are differences between the situation today and that of the early 1600s. One difference is that the existence of Bell-like influences is not as widely known as were the theories and discoveries that were central in the early 1600s. For example, Galileo communicated his discoveries with the telescope in a popular and accessible manner, and as a result, his discoveries quickly became widely known. Other key works, such as that of Copernicus and Kepler, were directed more toward a narrower audience, but still, it seems safe to say that the theories and discoveries that were key in the early 1600s were more widely known than are Bell's theorem and the Aspect experiments today.

Interestingly, it is not clear that Bell's theorem and the Aspect experiments are widely appreciated even within the physics community. Consider, for example, the physicist Jim Baggott's reaction to his first coming to appreciate these results:

> Here I was, proud of my scientific qualifications and with almost 10 years' experience in chemical physics research at various prestigious institutions around the world, and I had been going around with a conception of physical reality that was completely wrong! *Why hadn't somebody told me about this before?*[6]

Such reactions seem not to be particularly unusual.[7] In short, even within the relevant scientific community, these results are not as widely known as were the relevant similar results in the 1600s.

Outside the physics community, no doubt part of the reason results such as those described above are not more widely known is that we tend to work in quite specialized fields, certainly much more specialized than was the situation in the early 1600s. We each have our narrow areas of specialization, and mainly talk (and read the papers of, and so on) to others in that same narrow area. Note that this is not a difference that is relevant to how important the existence of Bell-like influences are, but it is certainly a factor in how well known are those influences. (And to repeat a point made in the introduction, this is one of my motivations for focusing on these results in this paper. That is, such results are not so technical as to be beyond the understanding of almost anyone who is interested, yet these results are not widely known. Anyone interested in what is perhaps the most basic question we have had since the time of the ancient Greeks – what sort of universe do we live in? – will be well served by becoming familiar with these results.)

Although there are certainly differences between the early 1600s and our time, there are, I think, striking similarities. Prior to the Copernican revolution of the 1600s, we were convinced we understood the sort of universe we inhabited. The universe, we believed, was a universe in which things behaved as they did because of internal, teleological, essential natures. In much the same way that an organism consists of parts that function to achieve natural goals, so too does nature consist of parts that function to achieve natural goals. The heavenly bodies move in continual perfect circles at uniform speeds because that is the internal, teleological, essential nature of the superlunar element. Natural objects in the sublunar region naturally move with straight line mo-

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[6] See Baggott (1992; p. ix). Emphasis his.

[7] An interesting discussion of this can be found in Mermin (1985), especially around page 41.

tion, with heavy objects moving out of a natural, internal "desire" to move toward the center of the universe, with light elements such as fire having a natural desire to move away from the center. In general, we thought we had a good understanding of the sort of universe we inhabit – we live in a universe in which objects behave as they do out of internal, natural, essential, goal oriented desires.

The situation in the early 1600s would eventually lead to a change in this conception of the sort of universe we inhabit. And eventually, a new general view emerged as to the sort of universe we find ourselves in. The universe, we came to believe, is a mechanistic universe, one that is like a machine. We came to view the universe as proceeding as a machine-like series of events. Objects behave as they do because of interactions with other objects and because of the influence of external forces. Central to this mechanistic concept is that interactions and influences are local interactions and influences. In a machine, gears influence only other gears in their local area, pulleys influence only other parts of the machine with which they are connected, and in general, parts influence only other parts of the machine with which they have some sort of contact or connection.

In short, the idea of local interactions is a central, core part of the mechanistic conception of the universe that has been dominant since the Copernican revolution. But Bell's theorem and the Aspect experiments show that we are simply mistaken about this core part of our general conception of the universe. The existence of Bell-like influences, demonstrated by the Aspect experiments (and other experiments of a similar sort), shows that we live in a universe with instantaneous, non-local influences between events, even events separated by substantial distances and for which there is apparently no possibility of any sort of communication or connection between them. No one knows *how* the universe can be like this, only that the universe *is* like this.[8]

In this, we are in a similar situation to that of the early 1600s. They knew that the earth moved about the sun, and eventually (from Kepler's work) that planets moved in elliptical orbits and at varying speeds at different places in their orbits. But they, like us, knew only *that* the universe was like this, with no conception of *how* it could be this way. That is, there was no broader framework, metaphorical or mathematical, into which to put these discover-

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[8] Richard Feynman (1965, p. 129), one of the top physicists of the 20th century, puts the oddness of non-local influences this way: "Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain,' into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that."

ies. There were specific, mathematically-based approaches that allowed for increasingly-accurate predictions (for example, Kepler's account of planetary motion, Galileo's work with the mechanics of falling bodies, and others), but no broader framework into which to place these findings. (Such a broader framework would eventually be discovered, culminating in Newton's physics, but not until some decades later.)

Likewise for us. We know that the universe allows for Bell-like influences, and we have quite good mathematically-based theories (mainly the mathematics of quantum theory) that result in very good predictions. But we have no broader framework, again neither metaphorical nor mathematical, into which to place these findings.

I need to be careful here so as not to be misunderstood. The mathematics of quantum theory is a type of mathematics with which physicists have been well acquainted for a long time.[9] It is a widely used, well understood type of mathematics. So in this sense, the mathematics of quantum theory is not at all unique or unusual.

The sense I have in mind is that the mathematics of quantum theory does not fit well with what is generally taken as the other most important branch of modern physics, namely, relativity. Unifying relativity and quantum theory into a broader mathematical framework has been a goal for some time now, but one that thus far has eluded researchers. It is probably safe to say that most physicists are optimistic that the two will eventually be placed within a broader, unifying theory. But at this point, we are in the same situation as the early 1600s, in that we have no such broader framework.[10]

Likewise with respect to a broader, more metaphorical framework. As noted earlier, the discoveries of the early 1600s were eventually subsumed under an overall mechanistic view of the universe. But also as described above, Bell's theorem and the Aspect experiments demonstrate clearly that, whatever sort of universe we inhabit, it is at bottom not a universe for which a machine metaphor is appropriate.

In fact, no metaphor seems to fit comfortably with the existence of Bell-like influences. The sort of Bell-like influences demonstrated by the Aspect

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[9] See Gasiorowicz (2003) for a typical presentation of the mathematics of quantum theory.

[10] The prospects for reconciling the usual approach to quantum theory (for example, the way the mathematics of quantum theory is typically taught and used, where the mathematics includes a projection postulate governing the collapse or reduction of the wave function) with special relativity may be particularly problematic. See Maudlin (1994) for an analysis of some of the difficulties with reconciling the usual mathematical approach to quantum theory with the Lorentz invariance required by special relativity.

experiments are not like anything we have ever experienced. It is worth taking a moment to appreciate this. The Bell-like influences demonstrated by the Aspect experiments are influences that occur instantaneously, between objects that are separated in space and for which there is no connection of any sort between them. In the experiments carried out in Aspect's lab in the 1980s, the devices were separated by a distance of about 13 meters. But similar instantaneous influences would be expected regardless of the distance involved. That is, we live in a universe that allows for instantaneous influences even between objects and events that may be separated by any distance, even light-years.[11]

And a universe that allows for such influences is certainly not the sort of mechanistic, machine-like universe we have been comfortable with for some centuries. Nor does it seem to be a universe that is like anything we have ever experienced. In short, the fact that we inhabit a universe that allows for Bell-like influences may mean that we live in a universe that can no longer be neatly and concisely summarized by appeal to any sort of familiar metaphor.

In short, we are in a situation which in important ways is like the situation of the early 1600s, of the original Copernican revolution. The view of the universe that we have become comfortable with over the past several hundred years, the mechanistic, machine-like view, cannot be maintained in light of the discoveries discussed above. Whatever the universe is like, it is, at bottom, not like a machine.

Concluding Thoughts

As noted earlier, the discoveries of the late 1500s and early 1600s led to dramatic changes – scientific changes, conceptual changes, and technological changes, to name just a few, that could not even be imagined in the early years of the 1600s. What was clear in the early 1600s, upon the recognition that the earth did move about the sun, was that the old teleological, essentialistic view of the universe could not be maintained.

It is too early to tell where the discoveries discussed in this paper will eventually lead. But it is clear, as it was clear in the early 1600s, that the view

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[11] It is worth noting that, since the Aspect experiments of the 1980s, physicists have demonstrated Bell-like instantaneous influences between ever larger and further separated entities (including golf -ball sized collections of atoms). So it is not at all clear that this sort of oddness of quantum theory is confined only to microscopic entities, such that it cannot be brought into the macroscopic level. See DeWitt (2004), especially chapter 25, for a more thorough discussion of this.

of the universe that has been in place for some time – for us, the mechanistic, machine-like view – is no longer a viable view.

In closing, it is worth noting one final difference between our situation and the situation of the early 1600s. Because of what happened then, and because we have had the luxury of studying those developments, we are in a vastly better position to observe and chronicle the developments taking place in our time. Although the increasing specialization mentioned at the beginning of this section has some unfortunate consequences, one good consequence is that we have specialists who are experts in studying not only the changes that took place in the past, but the changes we find ourselves in the midst of. As with the early 1600s, ours is an exciting time.

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