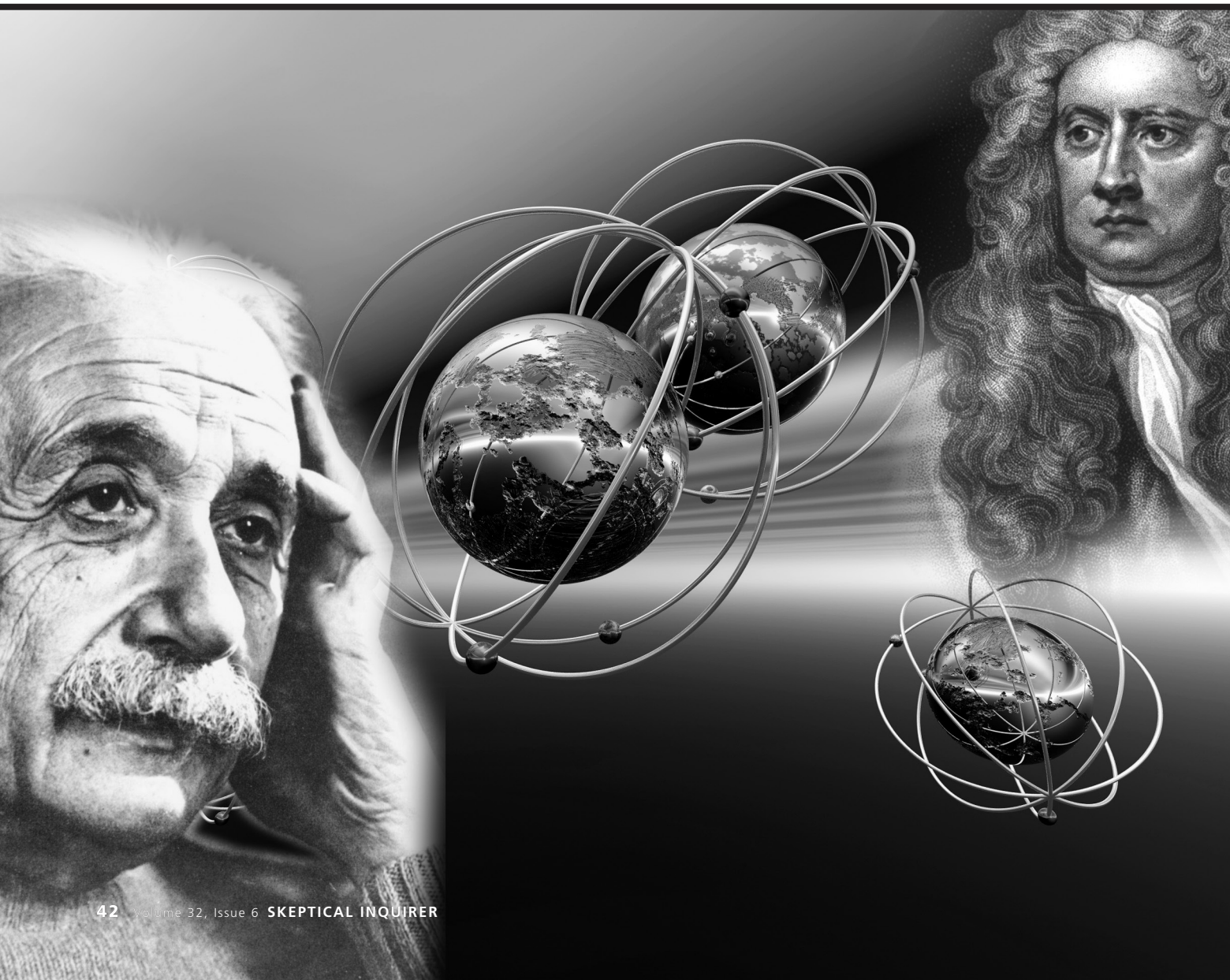
Quantum Weirdness

An Analogy from the Time of Newton

What Einstein called "spooky action-at-a-distance" in quantum physics has similarities to the "action-at-a-distance" that bothered people in Newton's time. It deserves the same fate.

PAUL QUINCEY



"Anybody who's not bothered by Newtonian gravity has to have rocks in his head."

The above is not a genuine quotation, but I hope you will agree that it is a fair summary of the original, made over three hundred years ago: "That one body may act upon another at a distance through a vacuum, without the mediation of anything else . . . is to me so great an absurdity, that I believe no man, who has in philosophical matters a competent faculty of thinking, can ever fall into it."

This quotation highlights the controversy that surrounded Isaac Newton's theory of gravity, put forth in his astonishing book *Principia*, published in 1687. His theory says that anything with mass exerts an attractive force on anything else with mass, depending only on the masses and their separation in a very simple way. Through virtuoso mathematics, Newton showed how this force accounts precisely for the known motions of the planets, the comets, the moon, and the sea.

His book does not attempt to explain how this "action-at-a-distance" actually works—indeed Newton makes a point in *Principia* of saying that he would not speculate on this. He used the Latin phrase "hypotheses non fingo," which can be loosely translated as "shut up and calculate."

You might think that the quotation mentioned earlier came from one of the many philosophical critics of Newtonian gravity, perhaps Newton's great German contemporary and rival Gottfried von Leibniz, but you would be wrong—the words were written by Newton himself. Newton was very bothered by the issue of how a planet could "know" about the sun's gravitational pull without something physically giving it a nudge, and he tried hard to invent a plausible mechanism. One such mechanism he proposed was a fluid that fills all space—the ether—which is somehow sucked toward the sun, tending to carry the planets with it and thus keep them in orbit instead of flying off. Needless to say, this idea does not stand up to scrutiny, which is why Newton wisely left it out of *Principia*.

In fact, Newton and Leibniz had very similar views on the plausibility of gravity as a force without a mechanical agent. As Leibniz put it: "if [gravity] transpires without any mechanism . . . then it is a senseless occult quality, which is so very occult that it can never be cleared up, even though a Spirit, not to say God himself, were endeavoring to explain it."

Why are these quaint problems from the ancient history of physics worth mentioning? There are two related reasons. First, the borderlands of scientific knowledge have always contained some ideas considered virtually supernatural at the time, and it is instructive to see with hindsight how such ideas are ultimately accepted or rejected by mainstream science. Second, there are illuminating parallels between gravity and quantum theory that may help us come to terms with the current philosophical difficulties surrounding quantum theory.

Whatever Happened to the Problem of Action-at-a-Distance?

If we accept that Newtonian gravity was considered seriously weird 300 years ago but is seen as simple and old fashioned now, what happened to change people's minds? I suggest five possibilities:

1. Gravity, in the sense of a force between distant, separate objects, was shown to be an illusion and does not really exist.
2. Gravity is both real and weird, but a conspiracy of small-minded scientists has persuaded everyone that there is nothing wrong, because they cannot bear to admit that there are phenomena they cannot explain.
3. A crucial experiment, unknown to Newton, showed how gravity works and that it all makes sense.
4. A new theoretical idea (the gravitational field, curved space-time, or gravitons, perhaps) showed that gravity acted without a problem with action-at-a-distance after all.
5. After a while, people forgot why they found the idea so weird and moved on to other things.

It is my impression that most physicists, if they thought about it at all, would subscribe to the fourth reason on the list—the idea that physics moved on in a way that solved the problem of action-at-a-distance. For instance, by the nineteenth century, the idea of space as empty was replaced by the idea that it contains, at every point, a gravitational field. And so gravity does not act mysteriously across a vacuum—there is something in the vacuum that does whatever it needs to do.

Unfortunately, the truth is not so simple. The gravitational field is something that has strength and direction at every point, determining what force affects any passing mass at that point. The field does not transmit the force like Newton's ether; it provides information about the force. But how does the field adjust correctly at every point? Instead of the object responding to distant masses, we now say that the field responds to them instead. Furthermore, there are no measurable consequences of the existence of the field that differ from the old action-at-a-distance view of gravity, which of course worked remarkably well all along. Newton and Leibniz would have seen the gravitational field for what it is—a mathematical device that has its uses but doesn't help with the underlying philosophical problem.

However, we don't have to rely on the gravitational field, because we can move on to the improved theory of gravity that replaced Newton's theory—Einstein's General Theory of Relativity, published in 1915. In this view, there is no grav-

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itational force across empty space. Matter causes space-time itself to curve: objects move in curved paths accordingly, and the problem is solved. We know that the new theory is correct because there are observable differences, like the detailed motion of the planet Mercury.

And yet the fundamental question remains more or less unchanged—how does the Sun make space-time curve by just the right amount near the Earth, 93 million miles away? In practice, there is little conceptual difference between curved space-time and the gravitational field. Nobody said at the time: "Gravity is explained by the curvature of space-time—physics is no longer weird!"

While ideas have indeed moved forward, the main reason that action-at-a-distance no longer bothers people is the fifth option. In Newton's time it was an unquestioned assumption that there could be no force without contact, partly from experience and partly because to think otherwise appeared to open the door to all kinds of "occult" forces. In these days of mobile phones and television remote controls, the idea is no longer disturbing, and we can see how such forces act without making our familiar world fall apart—indeed our world wouldn't be the same without them.

The Problem of Quantum Mechanics

Of course, 300 years is a long time in physics, and we cannot compare past intellectual problems with current ones. The twentieth century was so much more sophisticated than the seventeenth. Everybody knows that quantum mechanics really is weird, and no amount of explanation can change this simple fact—just look at the quotations:

> "Those who are not shocked when they first come across quantum theory cannot possibly have understood it."
> —Niels Bohr
>
> "Anybody who's not bothered by Bell's theorem has to have rocks in his head."—Arthur Wightman (A description of Bell's theorem, and its relevance to quantum physics, is given below.)
>
> "I think I can safely say that nobody understands quantum mechanics."—Richard Feynman

Now, quotations are useful things, but they are not what good science is about. In fact, the idea that scientific questions are settled by finding statements made by great scientists—by appealing to authority—is the opposite of science. After all, didn't Einstein say, "Unthinking respect for authority is the greatest enemy of truth," and "To punish me for my contempt for authority, fate made me an authority myself"? I rest my case.

Another problem with relying on quotations is that it is often possible to find contradictory views expressed by the same person. Niels Bohr, more than any single person, spread the idea that the interpretation of quantum mechanics was a job completed in the 1920s, causing Murray Gell-Mann to comment in 1976 that "Niels Bohr brainwashed a whole generation of physicists into believing that the problem [of the interpretation of quantum theory] had been solved fifty years ago." Bohr evidently thought that the shock of encountering quantum mechanics would soon wear off.

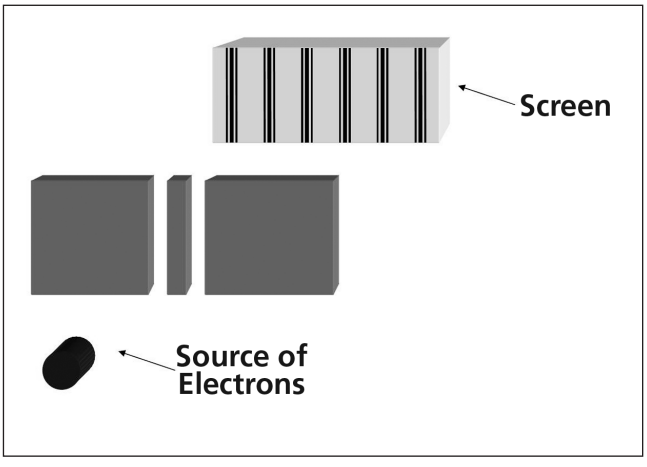
Richard Feynman, too, in his later years expressed a very different view of quantum mechanics from the one quoted above, saying in 1982: "We have always had a great deal of difficulty understanding the worldview that quantum mechanics represents. . . . You know how it always is, every new idea, it takes a generation or two until it becomes obvious that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem."

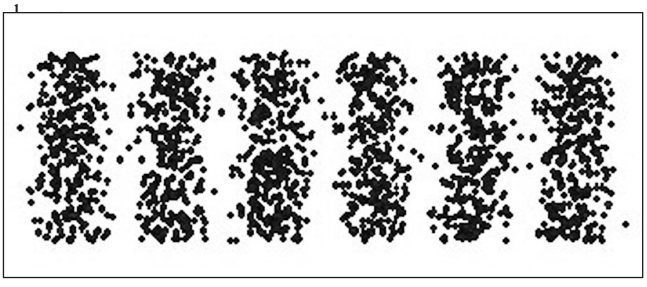
So rather than rely on a few quotations to confirm the weirdness of quantum mechanics, it is far better to concentrate on the evidence for it. And as Feynman implies, this is not a straightforward task.

There is no single definitive example of quantum weirdness. For many years, the best example was "single particle interference," usually presented as the double-slit experiment. In recent decades, more subtle phenomena based on separate but correlated events, grouped under various banners such as Bell's theorem, EPR, and entanglement, have taken center stage. I will consider these two categories briefly, in turn.

Single Particle Interference

Richard Feynman described the double-slit experiment as the only mystery in quantum mechanics. It is well described in all good presentations of quantum mechanics—if you need a specific example, you cannot really improve upon Chapter 37 in Volume 1 of *The Feynman Lectures on Physics*. The weirdness is summarized by the illustrations below. If particles are aimed at a barrier containing two slits, in the right circumstances they will form a pattern on a screen behind the barrier, like the one





The screen in detail.

The difficulty is not in describing what you see—it is a pattern of stripes—but in explaining how they could possibly arise. The particles can be seen arriving one by one, building up the pattern randomly. How can the particles form a pattern that depends on there being two slits, when each particle can surely only be affected by one? And, if we stop worrying about that, how can large numbers of particles, separated in time, cooperate to make sure the right pattern is formed?

When the result is simple to describe but impossible to explain, chances are that we have begun our explanation in the wrong place—we must question our assumptions. One assumption that we tend to make is that every event can be predicted in advance. This is essentially a neo-fatalist assumption that all events are inevitable and that there is only one possible version of the future. This may be true, but it is far from proven, and most of us don't actually subscribe to this belief as we live our lives. The pattern is much less mysterious if we assume instead that the destination of each electron is not fixed in advance but only governed by probabilities. This covers the second question.

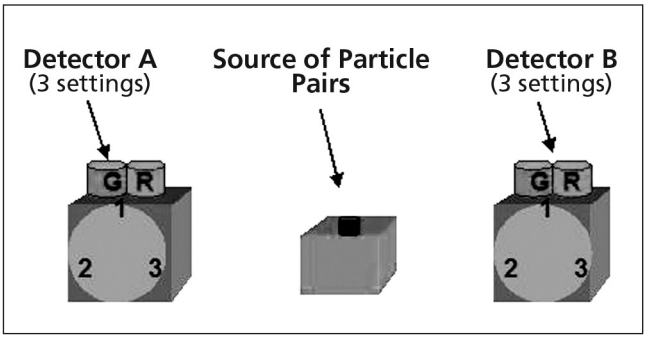
The first question is more interesting. The pattern is similar to what is seen when two waves interfere—like ripples on a pond—as if each particle changes into a wave and passes through both slits at once before hitting the screen. It is better explained as a consequence of the surveyor's wheel mechanism described in my earlier SKEPTICAL INQUIRER article (Quincey 2006). The mechanism calculates the probabilities for particles to end up at different destinations without the need for the particles to morph into waves, and it makes no distinction between situations normally labeled either "classical" or "quantum." However we choose to describe it, though, all we are really saying is that particles follow rules as they move from place to place. We may find it weird that particles (or rocks, for that matter) follow rules, but then we may just as well find it weird that the sun rises every morning.

Single particle interference is, to me, the best and clearest example of quantum behavior—simpler to describe and actually harder to explain than examples based on Bell's Theorem.

Bell's Theorem, or Quantum Sudoku

The second type of quantum weirdness was first highlighted by Albert Einstein, Boris Podolsky, and Nathan Rosen (EPR) in 1935. There is an excellent presentation of the problem in an article by David Mermin (1985), whose approach I have followed here.

The central feature is a device (the central box in Figure 2) that creates pairs of particles, the particles of each pair flying away from each other. They head toward detectors positioned to either side, which are entirely independent of each other and can be far apart. Some property of each particle triggers one of two responses in the detector indicated by a green or a red light (G or R), so when each particle pair is created, let us say by pressing the black button in the center, one of the two lights flashes on each detector shortly afterwards. Crucially, each detector has three settings, each measuring a different property of the particle, and these settings are changed randomly and independently before each run. The results from an experiment of this type look like the tables below—a series of settings and



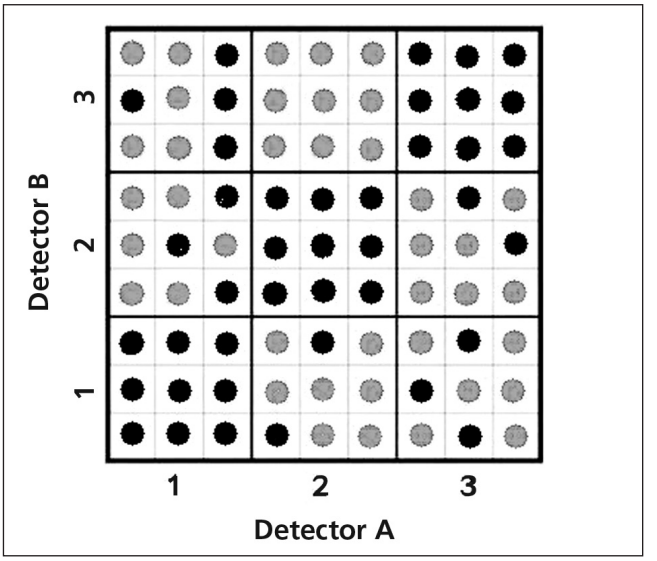
A																		
1			R			R	G	G		R				G		R		R
2	G		R	G													G	
3		R							G		R	R	G		R			

B																		
1			R								G					R		
2					G			R	R	G				R		R		

flashes from Detector A and a separate series from Detector B.

Figure 2: Schematic of an experimental test of Bell's theorem with typical results below.

So where does the weirdness come in? To see it, it is helpful to present the results in a different way. Take a three-by-three grid with a square for each of the nine ways the detectors could have been set (A on 1, B on 1; A on 1, B on 2, etc.). For each run, put a mark in the appropriate square—a dark one if the two lights flashed the same color, or a light one if they were different. Figure 3 shows an example in which the first nine runs



for each of the nine settings are recorded.

Figure 3: Bell's theorem test results presented on a convenient grid.

The results here have been invented, but they represent what happens when a carefully chosen experiment is conducted in a laboratory. They show something that is about as weird as

physics gets, although you can be forgiven for not noticing. The pattern that emerges when this experiment is repeated many times is this: when the settings on the detectors are the same, the lights always flash the same color, while in all other cases the lights only flash the same color a quarter of the time. What makes this truly weird is that if you make superficially reasonable assumptions about what must be going on, you would expect this last fraction to be around half, and certainly no less than a third of the time—definitely not a quarter of the time. The fact that there is a clear difference between results predicted by quantum physics, now confirmed to be the same as the results of real experiments, and those predicted by any theory that makes the superficially reasonable assumptions was discovered by John Bell and is called Bell's Theorem.

Should we be bothered by this? Being bothered shows we are clever enough to understand the logic,[1] but as in the case of the double slit, if an observation is impossible to explain, we are probably making the wrong assumptions.

The two assumptions that make the results mysterious are usually called "locality" and "reality." The first, in effect, says that things cannot form conspiracies without being able to send signals to one another. The second says that any properties of particles, like the ones measured by the detectors, are defined at all times, even when they are not being measured. Einstein took the reality assumption for granted, so this sort of result implied non-locality. He called this "spooky action-at-a-distance."

With hindsight, it is the restrictive idea of reality that is the root of the problem. To restate a point made earlier, if we accept that there are different possible versions of the future, any properties of particles in the future will exist only as a mixture of probabilities. So before they are measured, the properties are indeed undefined and hence not real in the sense that is needed to make the results weird. We can, if we like, see results from tests of Bell's theorem as confirming experimentally what we instinctively feel—that the future is genuinely uncertain until it happens. The choice we are presented with is not between a conspiracy and a reality that falls apart when we try to come to grips with it—it is between a conspiracy and a reality that falls into place, bit by bit, just in time. The world may not be as real as we might like it to be, but it is as real as it needs to be.[2]

This argument could be said just to transfer any weirdness into a magical process that transforms a mixture of possibilities into a single result in the moment we call the present. This is indeed magical, but it is a kind of magic that we experience all the time. We can make it seem more exotic by dressing it up as quantum physics, but the underlying magic remains the same.

A Posthumous Last Word from Newton

To return from spooky action-at-a-distance to the old non-spooky variety, perhaps Newton had something to say that is relevant to the conceptual difficulties with quantum mechanics. In *Principia* his final word on action-at-a-distance was this: "It is enough that gravity does really exist, and act according to the laws which we have explained, and abundantly serves to account for all the motions of the celestial bodies, and of our sea."

We could use this almost word for word as a statement about quantum mechanics:

"It is enough that quantum mechanics does really exist, and act according to the laws which we have explained, and abundantly serves to account for all the observations of elementary particles, and of our world."

Notes

1. The logic is explained very neatly in Mermin's article.

2. Any set of future possibilities will have some general constraints, for example, that the total number of some type of particle remains the same. This being the case, the future is both unreal and non-local, in the sense that an actual event at one place has immediate consequences for other places. This amounts to little more than noting that this time next week I could be in many different places, but I will only ever be in one place at a time.

References

Mermin, N. David. 1985. Is the moon there when nobody looks? Reality and the quantum theory. *Physics Today* (April) 38–47.

Quincey, Paul. 2006. Why quantum mechanics is not so weird, after all SKEPTICAL INQUIRER 30:4 (July/August) 38–43. □

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Date of filing: September 11, 2008. Title: The SKEPTICAL INQUIRER. Frequency of issue: Bimonthly. Complete mailing address of known office of publication: 3965 Rensch Rd., Amherst, NY 14228-2743; P.O. Box 703, Amherst, NY 14226-0703. Publisher: CSI (Committee for Skeptical Inquiry), Inc., 3965 Rensch Rd., Amherst, NY 14228-2743; P.O. Box 703, Amherst, NY 14226-0703. Editor: Kendrick Frazier, 944 Deer Dr. NE, Albuquerque, NM 87122-1339. Managing Editor: Benjamin T. Radford, PO Box 3016, Corrales, NM 87048-3016. Owner: CSI (Committee for Skeptical Inquiry), Inc., 3965 Rensch Rd., Amherst, NY 14228-2743; P.O. Box 703, Amherst, NY 14226-0703. Known bondholders, mortgagees, and other security holders: None. Average number of copies of each issue during the preceding 12 months: (a) Total number of copies (net press run) 48,839. (b) Paid and/or requested circulation: (1) Paid/requested outside-county mail subscriptions stated on form 3541: 24,717. (2) Paid in-county subscriptions stated on form 3541: 0. (3) Sales through dealers and carriers, street vendors, counter sales, and other non-USPS paid distribution: 9,576. (4) Other classes mailed through the USPS: 492. (c) Total paid and/or requested circulation (sum of b[1], [2], [3], [4]): 34,785. (d) Free distribution by mail (samples, complimentary, and other free): (1) Outside-county as stated on form 3541: 1,047. (2) In-county as stated on form 3541: 0. (3) Other classes mailed through the USPS: 50. (4) Free distribution outside the mail (by carriers or other means): 0. (e) Total free distribution (sum of d) 1,097. (f) Total distribution (sum of c and e) 35,882. (g) Copies not distributed: 12,957. (h) Total (sum of f and g): 48,839. Percent paid and/or requested circulation (c divided by h times 100): 96.94%. Number of copies of the single issue published nearest to filing date: (a) Total number of copies (net press run) 52,488. (b) Paid and/or requested circulation: (1) Paid/requested outside-county mail subscriptions stated on form 3541: 25,153. (2) Paid in-county subscriptions stated on form 3541: 0. (3) Sales through dealers and carriers, street vendors, counter sales, and other non-USPS paid distribution: 9,300. (4) Other classes mailed through the USPS: 32. (c) Total paid and/or requested circulation (sum of b[1], [2], [3], [4]): 34,485. (d) Free distribution by mail (samples, complimentary, and other free): (1) Outside-county as stated on form 3541: 1,615. (2) In-county as stated on form 3541: 0. (3) Other classes mailed through the USPS: 50. (4) Free distribution outside the mail (by carriers or other means): 0. (e) Total free distribution (sum of d) 1,665. (f) Total distribution (sum of c and e) 36,150. (g) Copies