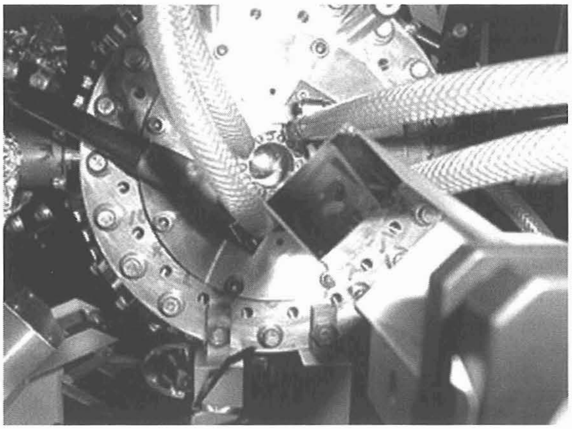
Once There Were Revolutions: Now There Are Only Surprises

IAN HACKING



We who inhabit the comfortably extended western world may think just that. Only surprise, no more revolutions. That is the way that it will be, or so we may complacently imagine. Once there was the Russian Revolution, canonizing the idea of revolution for the twentieth century. Then there was the collapse of the communist system, which we do not call a revolution at all. Nothing but a gigantic official surprise, with all the experts caught running for cover. It was, in fact, a truly radical change for several hundred million people. In the short term it was mostly for the worse, in the daily lives of most citizens of the former Soviet Union. But we do not call it a revolution. The Velvet Revolution in Prague, long after the Révolution Tranquille in Québec. We shall soon run out of gentle adjectives. Maybe even the idea of revolution will revert back to its roots, where a revolution is like a wheel that goes round, restoring what has been lost to its former glory—like the Glorious Revolution in England, 1688. But I am not talking about politics. It is the sciences that interest me.

Once upon a time, a hundred years ago, physics had revolutions as dramatic as the events in Moscow and Saint Petersburg. Kant's great *a priori* structures came toppling down. According to the eternal vision of the sage of Königsberg, they were what made human understanding possible at all. The certain knowledge of Newton's absolute space, uniform causality and determinism, Euclidean geometry itself, this was all in smithereens by 1926, a process begun with Max Planck's very modest thoughts about black bodies in 1894. Earnest young intellectuals, themselves living in turbulent times and places like Vienna, whose vast empire had just terminated, changed the way we think about knowledge itself. The sciences did not gradually accumulate and acquire a fuller, rounder, and more intricate mastery of the world. They proceeded, wrenchingly, by conjecture and refutation. Certainty and permanence, the professed twin goals of Western science ever since they had been enshrined by Plato, were over, for ever. Thus Karl Popper in 1935, stating what by then seemed obvious to like minds in Berlin, Warsaw, Lvov, Rome.

Once the idea had been fully digested, that is, by 1962, Thomas Kuhn changed refutation to revolution. (In case you think I stuck in Lvov—Lemberg—now Lviv in the Ukraine—just to show off my central European geography, Kuhn began his book by saying that he had in many ways been anticipated by a Polish epidemiologist, Ludwik Fleck, writing in Lvov in 1935.) *The Structure of Scientific Revolutions* was the work of a man trained in physics who became a historian and transmuted into a philosopher. For quite some time he was being cited as frequently as Freud and the Bible. Whatever spark he inadvertently struck turned into a firestorm. An obscure word used mostly by grammarians changed overnight into a cliché. (Kuhn used to have on his mantle a *New Yorker* cartoon, circa 1963, a Manhattan cocktail party, pompous person addressed by buxom girl, *O, Mr. so and so, you are the first man I have ever heard say that word 'paradigm.'*) Kuhn came to assert, quite explicitly, that science was impossible without revolution. Without revolution science would just die, doing the same old thing better and better until it withered away. At best it would turn into mere technology. Kuhn, like Popper and Plato before him, was ever an elitist, saying that theory, the scientific life of the mind, is what counts. Experiment, practice and technology is what engineers do. But they cannot do it without theory, and theory needs revolutions to feed on, or so Kuhn said.

Refutation and revolution were owls of Minerva, flying, as Hegel said, at dusk, after the dust had settled and the light was dim. They really suited the times in which Popper was young. Physics *had been* revolutionary in a way that it is almost impossible for us a century later to take in. That is why I spoke less of relativity and the quantum theory than of the grander philosophical terms of human knowledge itself, causality, space, and time. Popper and then Kuhn reflected that revolutionary fact—a long time ago. Now we live in a very different world. The owl sees a very stable landscape indeed.

Physics in the second half of the twentieth century was an astounding success story. For a long time the success was headlined with the work that was showcased with the weapon that changed statecraft, namely the atomic bomb. High energy physics, ever more elementary particles, the first three minutes of the universe, grand unified theories of everything, plus incredibly costly accelerators justified by the war effort, got the headlines. The Russian un-revolution brought that war to an end. The money for vast experiments stopped, and everyone realized that quite cheap physics had been succeeding at the same pace with the same successes.

It was called solid state physics and is now called condensed matter physics. In popular science, the laser is its best known tool. Lasers do more amazing things in day-to-day laboratory work than any science fiction ever dreamt of, not to mention running your CD player on the side. Hey, we cool down individual atoms to within trillionths of a degree of absolute zero, and they become our pals, we take four or five of these lazy little things and do almost what we want with them. The amazing fact is that those revolutions at the start of the twentieth century got things just right. We could not cool down those atoms in the way at which I just hinted until 1995, but Einstein showed what would happen in 1925, in maybe his last amazing insight. He was a bit like Newton. He really was in touch with the way the world works, and we still live in a world that he and his contemporaries divined.

Hence my title. I do not think that there will be revolutions in physics in my grandchildren's lifetimes. That is all too bold a conjecture. We do have these problems. The two great achievements from the early twentieth century just do not mesh. We cannot put (relativistic) gravity together with the quantum theory. We cannot find enough mass in the universe to keep it going! These are surely what Kuhn would have called anomalies, and he would have predicted that only a revolution would sort us out. String theory plus. Well, actually only superplus would do it, and string theory minus is at present running on a serious lack of contact with the real world. But perhaps some future theory of strings or something even more challenging will prove me wrong. I certainly want to encourage every young and dreaming student to try to revolutionize physics. But we who are mere owls should look at what is around us. It is a physics that tells about the material world better than could possibly have been hoped for.

That does not mean we know it all. That is where surprise comes in. Surprise (like revolution) is a relative notion. You are surprised by something that you do not expect. Let a city person walk in a real forest. I do not mean a preserved and homogeneous wilderness area, out there in your canoe in tamed Algonquin Park or whatever. The bewildered city walker in the real wild woods will be startled from time to time. Startle is different from surprise. Surprise comes when you know what to expect, and it doesn't happen. Startle comes from having no idea what will happen. Precisely because physics is such a success, it fills us with very detailed expectations. These are not expectations that follow from the fundamental principles of a grand theory. They follow from complex models, ever simplifying. They model in detail how some isolated and highly controlled little bit of the world will behave. The big theories do not tell us much. That is why high energy physics needs so much money, to dragoon the world into acting as it says it should. And why it needs so many incredibly highly trained employees to do anything at all, hundreds of engineers, hundreds of physicists, hundreds of janitors. If high energy physics were unionized, there would be 179 different unions, at least, involved in every major experiment at CERN.

Most theorizing in physics is not like that at all. A typical lab has half a dozen people at work. The physics consists of making models of some very special arrangements, and of building arrangements that match. We call that experiment and theory. The mix of both leads to a lot of very precise expectations. The surprises come when things do not work out. And they come all the time. Experiments do not work, models are not quite right. Most of the routine failures teach nothing, except how to do something better. The real surprises are what teach us. Kuhn was wrong. Physics does not need revolutions. It needs surprises to keep it going.

Here is an example I like. Ultracold physics is hot right now. In the past twenty years we have been able to cool things down with quite astonishing success. All sorts of techniques are used. A high-class version of evaporation is at present essential. If you trap some atoms and some of the faster ones are encouraged to wander off, they take some energy with them, and the remainder get colder. But there is a wonderful short cut. Get some atoms of just one species going in one direction, and shine a laser beam of just the right frequency at those atoms. They get stopped dead in their tracks (sort of). That means they go much slower, and so are colder. It is of course more tricky than that. It is a practical version of the Doppler effect, which in this case has to do with the velocity of the laser light relative to the prepared atoms. Theoretical models of what is happening predict exactly how much cooling (energy loss) you can get in this way.

The building of the models and the building of the experimental apparatus went hand in hand, in the 1980s. A team in California and a team in Paris found just what was expected. But a third team near Washington D.C., from what used to be the US Bureau of Standards—now the National Institute of Science and Technology—was skeptical. Their mission is, after all, precision measurement. They could not replicate the expected measurements. In due course it turned out that the laser technique cooled far better than could be expected. Surprise, surprise! For it is the rule that experiments always work worse than can be expected; there is always something gumming up the works. But in this case, everything worked better than could be hoped for.

The initial experiments got the expected result. Wrongly. They did not do so because they fudged their data to fit their expectations. There were several sources of systematic error. One resulted from the routine fact that when you build apparatus you do it step by step. First you get the laser to cool the prepared atoms. Then you need to measure the result. You do so by letting the atoms expand after you turn your trap off. The rate at which they expand shows how fast they are moving, how much energy they have, how cold they are. You find this out by taking photographs of a little cloud of atoms expanding. You put the detector that does this on top of the apparatus you have already built.

But it makes a difference where the detector is! That was one of the first things the NIST people noticed. Why? Normally atoms pay no attention to gravity. They are moving so fast that gravity makes no difference. But these cooled atoms are so lacking in energy that they just—fall. Like stones. Exactly like stones, as a matter of fact, just as Galileo taught. The atoms coming out of the top of the apparatus are more energetic, warmer, than the ones coming out of the bottom, which are in almost free fall. Net result: Laser cooling as measured above the apparatus underestimates the cooling. The expected results were wrong. The technique works better than it ought to.

Back to the drawing board. Something else has to be put into the model to explain what is happening. The workers in Paris who figure it out call it the Sisyphus effect. When the beams of laser light and the prepared atoms come together, the atoms experience the wave of coherent light like a washboard, or rather like a washboard road in Alberta, which seriously slows you down, atoms too. This is because all the light is vibrating at the same rate, so it looks just like what we call a wave. As it climbs up each hill in the laser light, an atom loses energy. Sisyphus: it has to keep pushing itself up every hill, and does not get it all back as it goes down into the trough. The surprise is explained. Nobel prizes all round (1997, Chu, Cohen-Tannoudji and Phillips, California, Paris, and NIST).

Kuhn offered Max Planck and the problem of black-body radiation as his most detailed example of a scientific revolution, one that began the quantum theory. A whole book's worth, read only by specialists, *Black-Body Theory and the Quantum Discontinuity, 1894-1912*. I offer the little story I have just told as a less than detailed example of what I mean by a surprise. It is a surprise only because of how much we know. It is a valuable surprise because of new things it enables us to do.

I suspect that the Nobel prize was awarded only in 1997, after laser cooling had been used, in 1995 to produce the effects on cold atoms that Einstein had predicted in 1925. (Nobel prize, Colorado and MIT, 2001.) I have been saying atoms, by the way, but the desired effect works on only one kind of isotope, one species of atom called bosons, named after the Indian physicist whose letter to Einstein in 1924, about photons of light, led Einstein to his final amazing insight. In the last couple of years it has become possible to apply similar techniques to pairs of atoms of the other species of atomic isotopes, called fermions.

These results are not revolutionary. They do not demolish any vision of how the world is, or of the human place in nature. We do not have a Kant to undo any more, but if there were one, he would be unmoved. Nevertheless, the surprise I have described helped open remarkable doors to new houses in which we shall find out a lot more about nature. Not just very cold, lazy nature, but also it may help us to understand impossibly hot, overwrought nature, for it is pairs of fermions that fuel neutron stars, and for the first time—that is *now*, not five years ago—we can treat these items as collaborators, manipulate them to see what they do and how they do it. Revolutionary, in one familiar sense, but not a scientific revolution in Kuhn's sense at all.

Surprise is the way it will go, in the foreseeable future. Surprise within a stable conception of the world, immune to revolution. And of course if there is a scientific revolution that unseats the vision of the physical world that stabilized in the course of the twentieth century, it will be a surprise, but not in the sense in which I have been talking.

Surprise is very different from chance, the advertised topic of this issue of *Public*. Or it is very different from the kind of chance that was tamed during the nineteenth century. The manifesto for this issue starts by quoting Mallarmé about the throw of a die. In 1990 I ended my book, *The Taming of Chance*, by quoting the same poem as evidence that chance, which in the Enlightenment had been the superstition of the vulgar, by the 1890s had become wholly domesticated, the stuff of social science, the matter of physics, the laws of the universe, the toy of artists. That is, the chance that is described by the laws of probability, which are the laws that run the world. Mallarmé wanted to talk about the uncontrollable and free, but inexorable probability ran his show, whether he knew it or not. Chance is freedom only in the little picture, not in the big one.

But there is another sense of chance, as when we talk of chance events. Aristotle gave an example that still stands. I head out to the Saint Lawrence Market on a Saturday morning, to get the week's supply of fresh vegetables. And lo and behold, I meet an old girlfriend whom I have not seen or heard of for donkey's years. There is a perfectly good explanation of why I am standing at the stall buying apples at 8:45 on a Saturday morning. And there is a perfectly good reason why she, who usually lives in quite other parts of the world, is there beside me. Two independent causal histories intersect, and only the superstitions of the fatalist teach otherwise. It just happened that we met. We are rightly surprised: we are astonished at this chance meeting. Probabilities, the chance that was tamed, have nothing to do with it. The surprise is governed by unwitting expectations: I do not expect to see a face, at this moment, a face that was once close to mine, but which has been apart and forgotten for so many years.

And yet that tamed chance, probability, can step in here. Coincidences surprise us, but usually they too can be expected. It is not to be expected that today I meet *this* person from long ago. But it is fully to be expected that I shall have encounters from the past, especially at the St. Lawrence Market where people from my social class congregate on Saturday mornings. Probability rules even coincidence.

There is yet another kind of unexpectedness. A few years ago there was a lot of fancy talk about chaos and catastrophe theory. Aside from some clever mathematics, that was mostly a reaction against over-confident big deterministic science. People realized that tiny causes can have big consequences, and this rather obvious fact was hyped. All that talk of chaos and catastrophe was intellectual playfulness. But now occasional catastrophes may be starting to crop up more often than they used to.

We manage risk by insurance. Insurance companies manage the risks of insurance by reinsurance. There are now fairly good reasons to think that global warming is going on at such a rate that more and more radical climate change will occur. Hurricanes galore, frozen orange groves, melting glaciers, costly real estate sinks below the rising seas, the lot. Insurance companies used to get away by excluding Acts of God from risks covered. That will not wash any more. Insurance began in a coffee house in London just when the world was beginning to stabilize, and it has become more and more stabilized. Insurance companies, including pension funds, which are based on pure actuarial—probability—calculations, are the biggest accumulations of capital on earth. Climate change is beginning to make them run scared. After 400 years of increasing stability, we may be undoing it all. More and more potential catastrophes will not be covered. Reinsurance won't back the insurance.

The grand accumulations of capital are beginning to expect the unexpected. Your children will not be able to get insurance for their holiday properties because the reinsurers won't back the insurance companies to which you and I now turn. But this is not a matter of surprise. Quite the contrary. We may not know quite which hurricane or sudden freeze may hit where, but that that sort of thing is to be expected. *Is* expected, by the financiers. It is a bit like my meeting my old friend. That particular friend was not expected, but some forgotten old acquaintance, for good or ill, will cross my path quite soon.

The difference between these kinds of example, and the physics tale, is that the physical surprise is governed by extremely precise expectations. Precision engendered by models based on theories that grasp the microstructure of the world in ways that were only dreamed of by Galileo. And he did dream of them! But for a long time his dreams were not enough to give a regular round of surprises. Now they are. The Galilean dream of a mathematical structure that mirrors the (im)material world is in place. It took revolution to get us here, but from now on, it will only be surprises.