Field notes from space-time

The importance of uncertainty

Quantum mechanics had a disordered beginning and is still developing today. Science is rarely a done deal, says **Chanda Prescod-Weinstein**

Chanda Prescod-Weinstein is an assistant professor of physics and astronomy, and a core faculty member in women's studies at the University of New Hampshire. Her research in theoretical physics focuses on cosmology, neutron stars and particles beyond the standard model

Chanda's week

What I'm reading
I'm teaching this semester from Arjun Berera and Luigi Del Debbio's new textbook Quantum Mechanics.

What I'm watching
I'm enjoying the new Sylvester Stallone series Tulsa King.

What I'm working on
Recently my team has been stuck on a sticky calculation where the computer and pen/paper disagree!

This column appears monthly. Up next week: Graham Lawton

ONE of the challenges of teaching is picking a textbook because finding one that is reasonably priced and at the right level for my students is hard. And the more advanced a topic is, the more likely it is to include areas that are the subject of current research, where thinking is changing in real time.

Textbooks are designed to teach a subject as if it is understood, to have an authority that gives students confidence in the contents. This method of learning, while useful for helping people get a sense of the ideas at hand, can also give the false impression that a subject was conceived in an orderly fashion and has been static pretty much since then.

Quantum mechanics, the technical term for what is usually known as quantum physics, is an example of a subject that had a disordered evolution in its early stages, and that is still developing. Ideas that we traditionally associate with quantum mechanics are considered by at least some researchers to be less central to it these days.

For example, I recently suggested to a friend that maybe I should have taught my spring 2023 PhD quantum mechanics course using Paul Dirac's 1930 book *The Principles of Quantum Mechanics*. In it, he introduces a mathematical framing of quantum mechanics that presents the calculational basics of the field. It is taught to nearly every professional physicist at some point.

My friend responded: "Nah, he focuses on old-school concepts such as uncertainty." I had to giggle when I read this because the uncertainty principle is considered a hallmark quantum concept: the idea that we can't simultaneously know both the precise position and velocity of a particle is one of the quantum world's oddities.

I still think there is value in understanding how people thought at the time quantum mechanics took shape. One of my favourite stories from its early period is about the Stern-Gerlach experiment. In this, Otto Stern, a theoretical physicist, and Walther Gerlach, an experimentalist, teamed up in 1922 to try to prove that Niels Bohr's ideas about the structure of the atom were wrong.

Bohr had, about a decade before, been trying to explain why atoms are stable. Consider hydrogen, with

> "I think there is value in understanding how people thought at the time that quantum mechanics took shape"

a nucleus and a single electron. In the scenario where we think of the nucleus as the sun and the electron like a planet in its orbit, there is a problem: electromagnetism teaches us that a charged particle like the electron will lose energy when it is accelerating, and constantly changing direction in orbit is a form of acceleration. The energy loss would cause the orbit to decay, meaning the electron should crash into the nucleus, destabilising the atom. Yet, hydrogen and many more massive atoms are stable. What gives?

Bohr suggested that maybe the electron could only be in discrete orbits at set distances. This spatial quantisation had big implications for other properties, such as how magnetic forces would affect the motion of an atom.

Stern hated this model and was determined to show it was wrong. He and Gerlach did an experiment which sent a beam of silver atoms through a magnetic field. The goal was to show that the atoms would land on a target with a continuous vertical distribution, reflecting a non-quantised atom. To Stern's chagrin, they found that all of the atoms landed in one of two locations – one up and one down – and not in between. There was no possible explanation for this result from classical physics. It is a fundamentally quantum result. They sent Bohr a postcard telling him that he was right.

Ironically, Bohr's model was wrong. It wasn't until the mid-1920s that people realised what Stern and Gerlach had actually shown: electrons have a quantum internal rotation that we now call "spin". This can take one of two values, but nothing in between. This property and how it interacts with magnetic fields meant that in the Stern-Gerlach experiment the atoms all either deflected a set amount up or down based on their spin value, but couldn't deflect to points in between as intermediate spin values are impossible. Today, Bohr's atom is still taught as it is considered a good approximation, but it is also known as a core piece of "old quantum theory" which we now know isn't right.

Just a few years after the spin connection was made, Dirac wrote his book pulling many pieces of quantum mechanics together into a unified framework, one we are still teaching students today. It is so elegant, it is easy to forget that isn't how it started.

I opened my course this semester by teaching the Stern-Gerlach experiment because it is instructive in a few ways. Stern, who was Jewish, had to leave Europe. Gerlach became head of nuclear research in Nazi Germany. Sometimes scientists are simultaneously right and wrong. ■