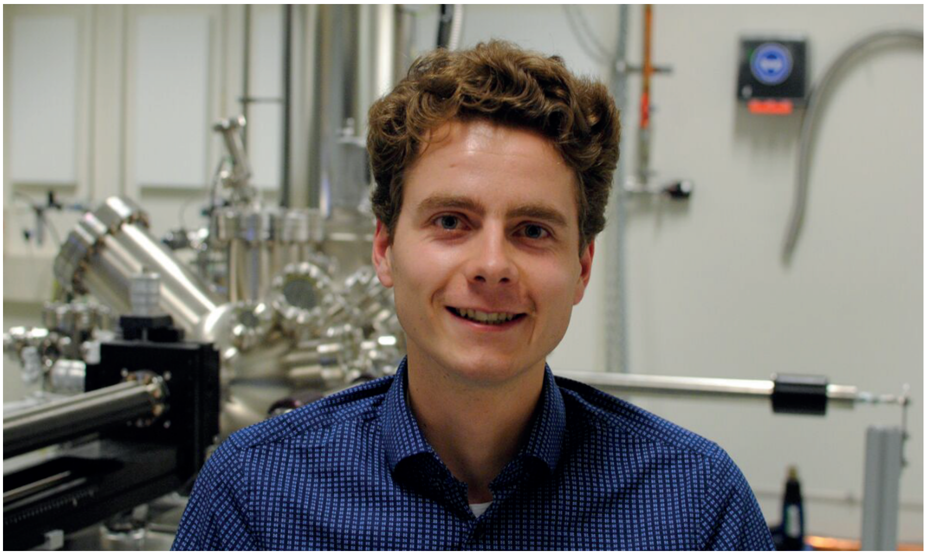
The value of the unforeseen

Straying off-course can lead to unexpected far-reaching results, says **Floris Kalff**.

In science, we often work towards an ambitious goal, proceeding on a path that might not always be clearly marked, but that has predetermined milestones along the way. Last year we were on such a path, and only when we went off-course did we discover how to store digital data in atoms, as we show on page 926.

Our original goals were to position individual atomic spins into specific arrangements and learn about quantum magnetism in the process. We were exploring various surfaces that could serve as suitable templates for building structures of deposited magnetic atoms, when we stumbled on unwanted atomic vacancies (that is, missing atoms): we had just evaporated a monolayer of chlorine atoms on a copper crystal and the number of vacancies was simply too large to make the system useful. We declared the attempt unsuccessful, but just before we pulled the sample out from the microscope to try and achieve a better coverage of chlorine atoms, we decided to play around a bit and check if we could manipulate those vacancies. After all, the manipulation of single atoms has been known for decades, so why would it not be possible to move a vacancy as well?



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Our progress was slow in the beginning. On the first day, we moved only two vacancies. The next week, we managed to move four and, after many attempts, we managed to move eight a week later. This prompted us to come up with a new exponential law, a variation to Moore's Law: the number of vacancies we could control would double every eight days. We jokingly calculated that, at this rate, we would be able to manipulate 8,000 vacancies in only 10 more weeks. At that time, 8,000 vacancies still seemed unfathomably large, and this was a small side project after all.

However, we soon realized the deep implications of this project. If we were able to master the manipulation of the vacancies' positions to such an extent that they could be aligned in ordered linear arrays, we could use the lateral displacement of a single vacancy to encode a bit of information. Gradually, our final goal shifted from manipulating spins to realizing an atomic memory based on vacancies, and we felt that our 8,000-vacancy projection could lead to a tangible milestone: a kilobyte atomic memory.

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Although it took a lot of effort to manipulate single vacancies at first, our abilities improved greatly once we got the hang of it. First, we had to gain full control over the positioning of the vacancies themselves, which is done by dipping the tip of the needle of our scanning tunnelling microscope in the surface. After tweaking the many variables such as height, voltage, time and current, we finally managed to get to the point where we could move and drag the vacancies in the right direction with over 99% reliability. Next, we focused on the automation of the movement, implementing path-finding algorithms to direct the vacancies to their designated positions. And finally, we designed the memory itself, including a marker structure to ensure proper navigation and avoiding disordered or contaminated regions of the surface where vacancy manipulation was not possible. In fact, things moved so fast that we finished the kilobyte memory three weeks before our 'exponential equation' predicted.

The interesting point to note is that we synthesized our data storage bit-by-bit by diverting and following a new path, there was no existing line of research that suggested storing data this way. By doing so, our new goal was defined and it became clear that this was the way to go.

In a way, the milestone of realizing a kilobyte atomic memory was already there. During the building process, we remembered the speech of Richard Feynman, who in 1959 wondered "what would happen if we could arrange the atoms one by one the way we want them" (R. P. Feynman, There's plenty of room at the bottom, *Eng. Sci.* **23,** 22–36; 1960). Because this sentence fitted so well with our story, we felt that this part of his speech would be the perfect data to store in our atomic memory.

Unfortunately, our version of 'Moore's Law' didn't work much longer: we should have written over a terabyte of data by now, which we haven't. But our exponential prediction can still be satisfied: we just need someone to position 6×10^{23} vacancies by summer 2017! ❐

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