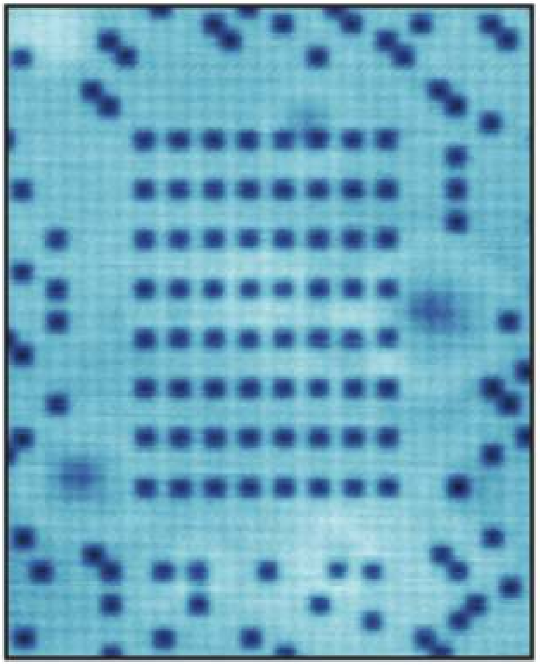
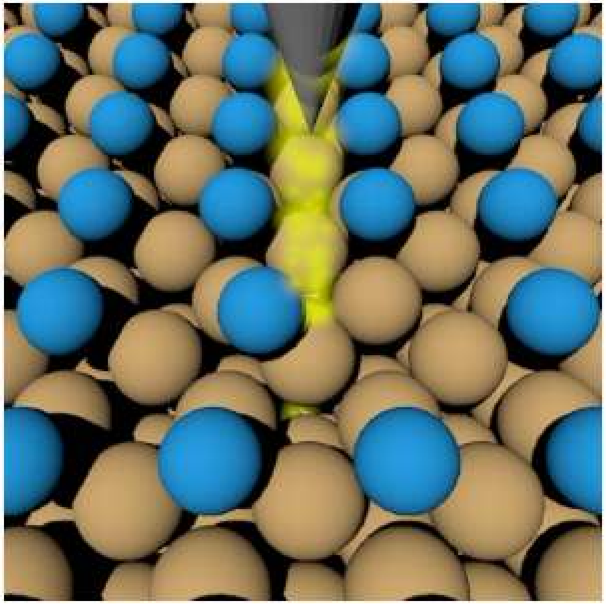
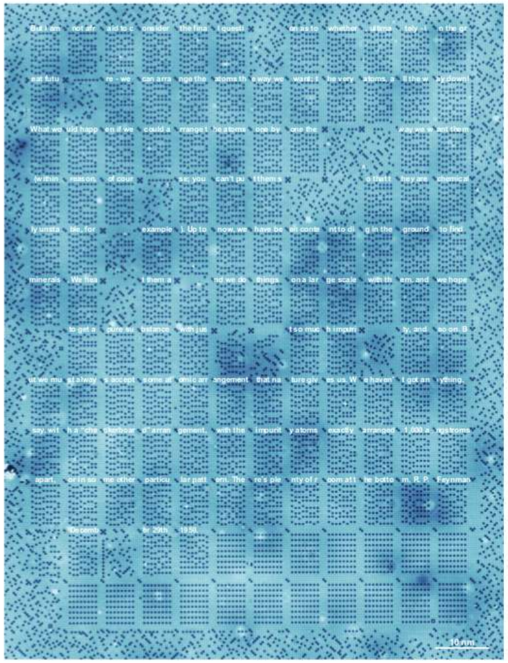
Storing information at the atomic level: a kilobyte rewritable atomic memory

J. L. Lado

International Iberian Nanotechnology Laboratory, Braga, Portugal







Nature Nanotechnology 11, 926–929 (2016)

FE Kalff, MP Rebergen, E Fahrenfort, J Girovsky, R Toskovic, JL Lado, J Fernández-Rossier, AF Otte

January 20th Alicante, Spain

About INL

International Iberian Nanotechnology Laboratory
(Braga, Portugal)

Around 120 researchers

Several areas of research
- Environment & Food
- Nanomedicine
- Nanomanipulation
- Nanoelectronics

Condensed matter theory group

Condensed matter theory group in INL

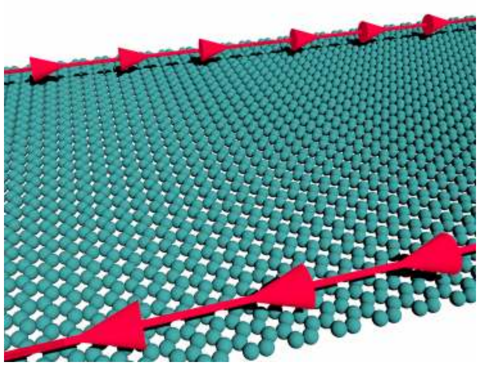
<u>Group leader</u>
J. Fernandez Rossier

N. Garcia

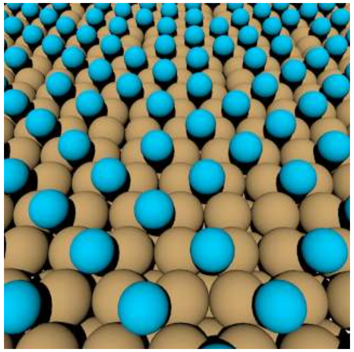
JL

Main research lines

2D materials & topological states



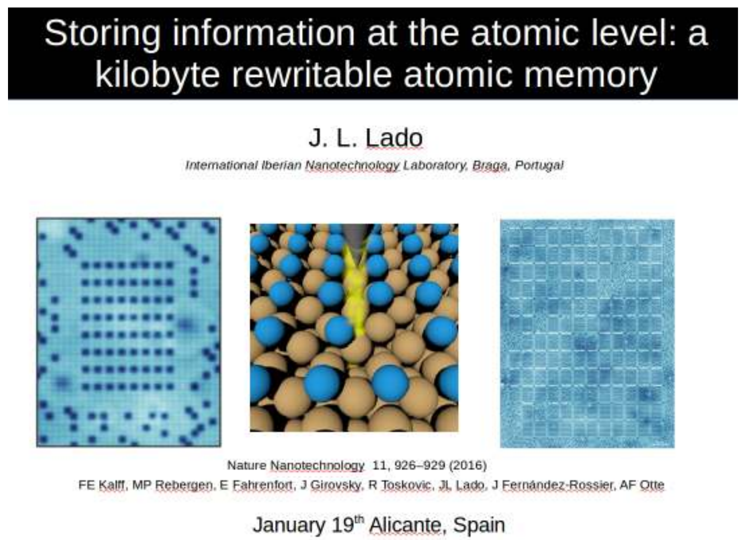
Atoms on surfaces



How much storage do we need?

Rick and Morty Season 2
8000 MB

These
slides
50 MB



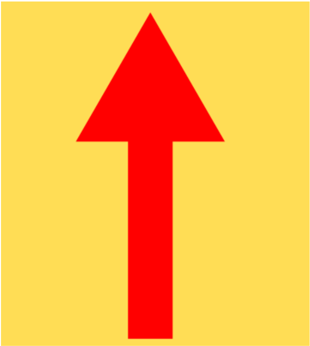
IBM 0665
(from 1985)
44 MB

Our capacity to store information **has increased dramatically** in the last 30 years

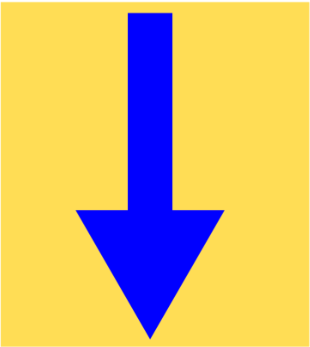
Storing information

Where to store: hard disk drive

How to store: magnetic moment



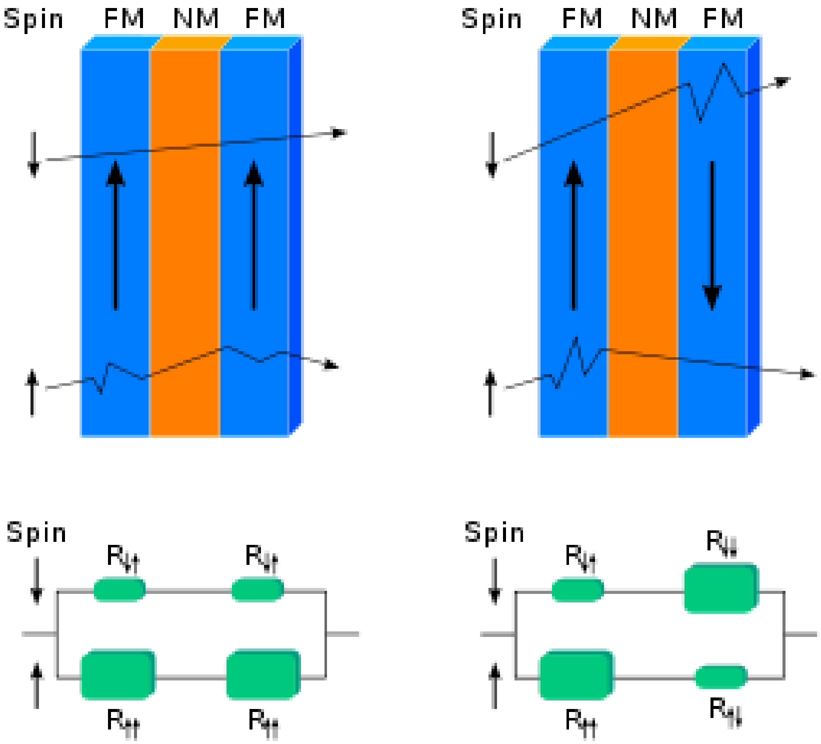
Up = “0”



Down = “1”

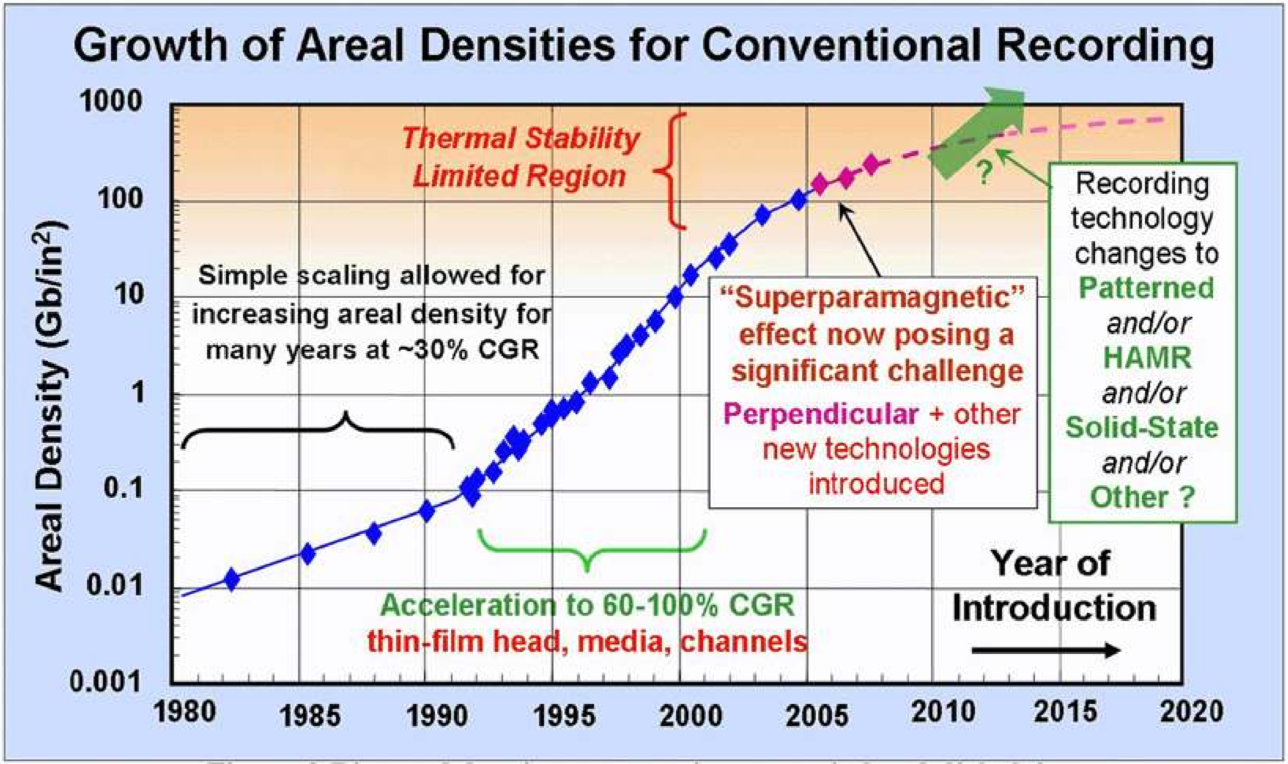
How to read: giant magnetoresistance

Low resistance High resistance



The smaller bit, the more you can have

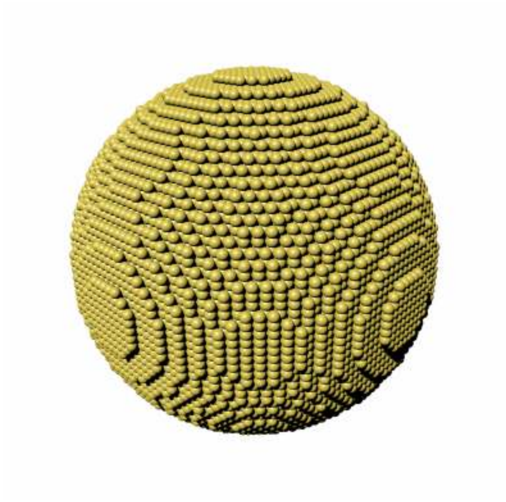
The **less space** you need to store a bit, the more you can have in a certain area



Bandic, Zvonimir Z., and Randall H. Victora. "Advances in magnetic data storage technologies." Proceedings of the IEEE 96.11 (2008): 1749-1753.

We need to go deeper

We need around 10^6 atoms to store one bit



Can we store information in single atoms?

Feynman 1959

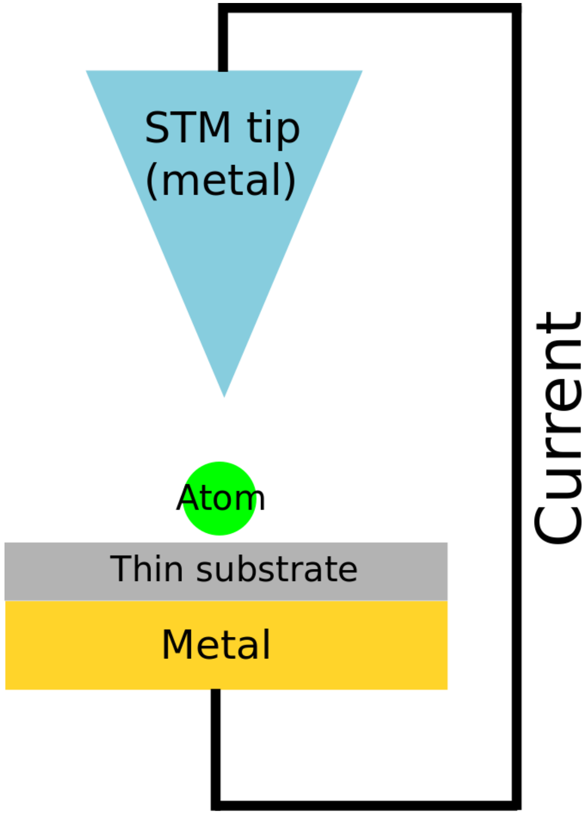
"But I am not afraid to consider the final question as to whether, ultimately, in the great future, we can arrange the atoms the way we want"

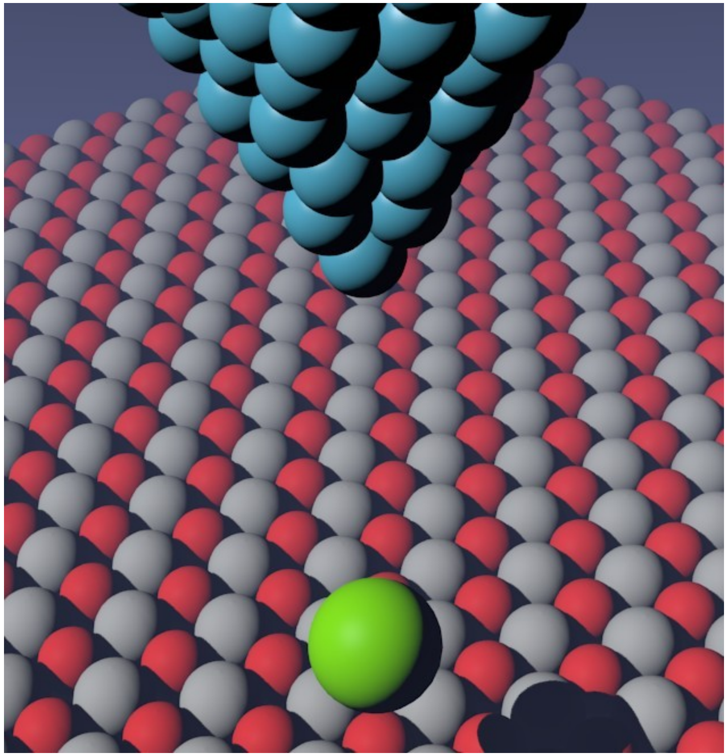
How deep can we go?

Nowadays, we can manipulate matter at the **<u>atomic level</u>**

10^{-10} m = 0.1 nm

Scanning tunnel microscope





Each sphere is an atom!

Allows to manipulate **single atoms with atomic precision**
Electrical measurement based on quantum tunneling

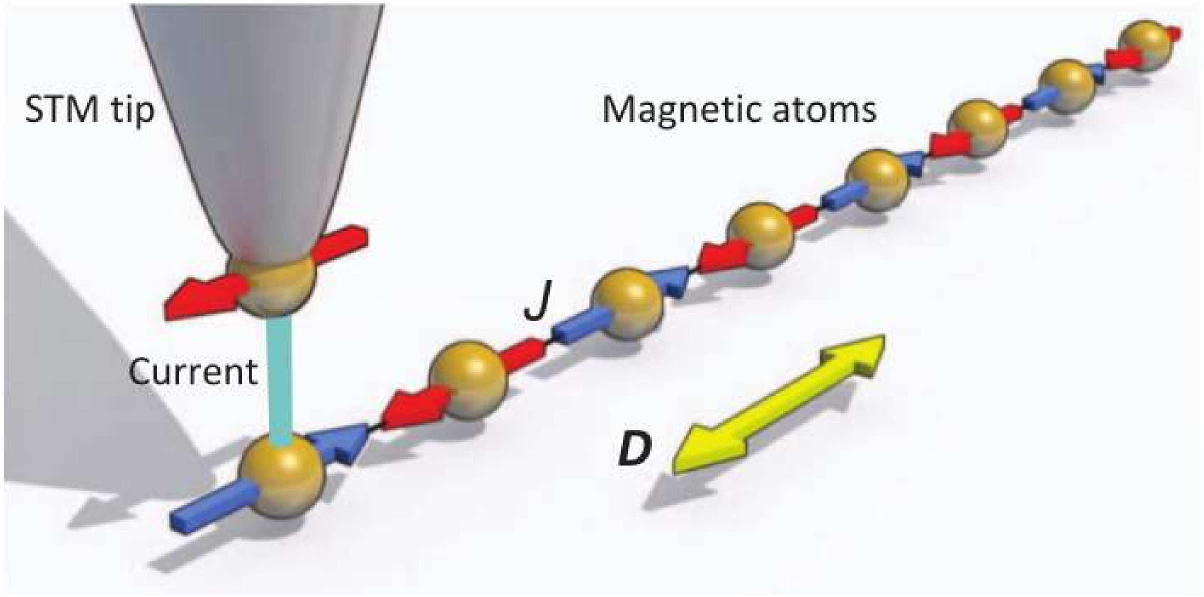
What is the degree of control with scanning tunnel microscope?

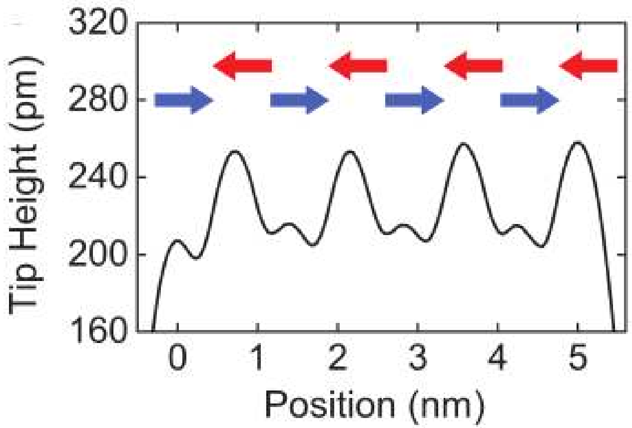
The smallest movie, IBM Almaden 2012

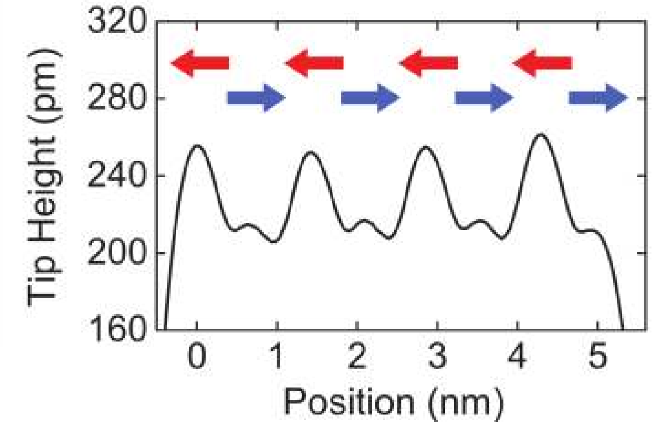
CO molecules in Copper

Storing information in antiferromagnetic chains

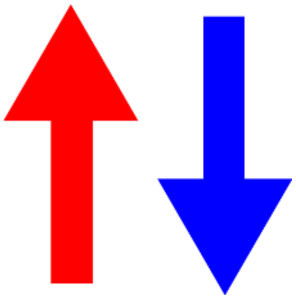
Loth, Sebastian, et al.
"Bistability in atomic-scale antiferromagnets."
Science 335.6065 (2012): 196-199.



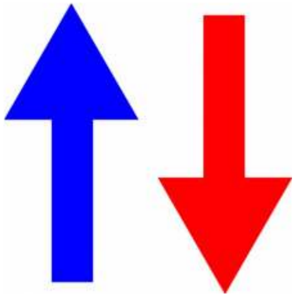




"0"

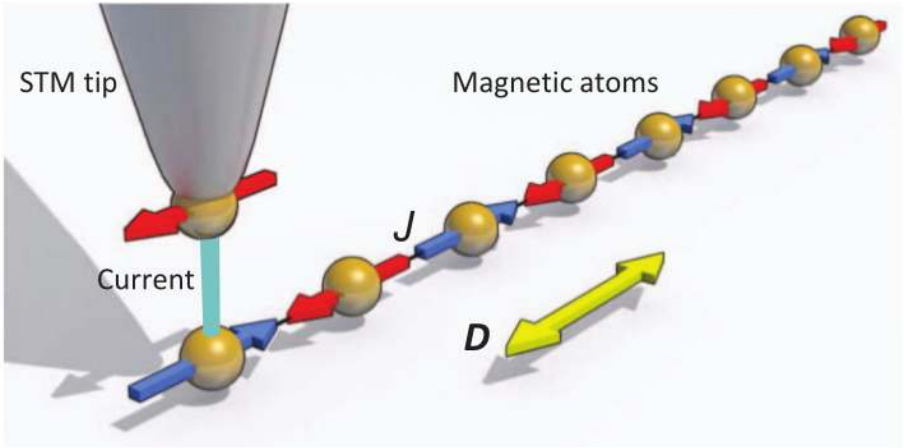


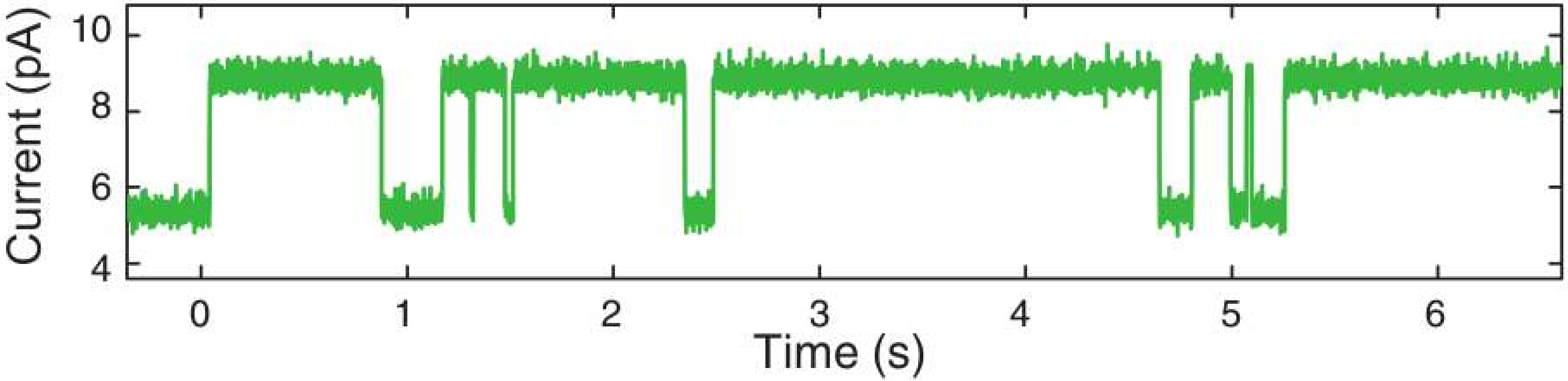
"1"



Switching between states

Loth, Sebastian, et al.
Science 335.6065 (2012): 196-199.

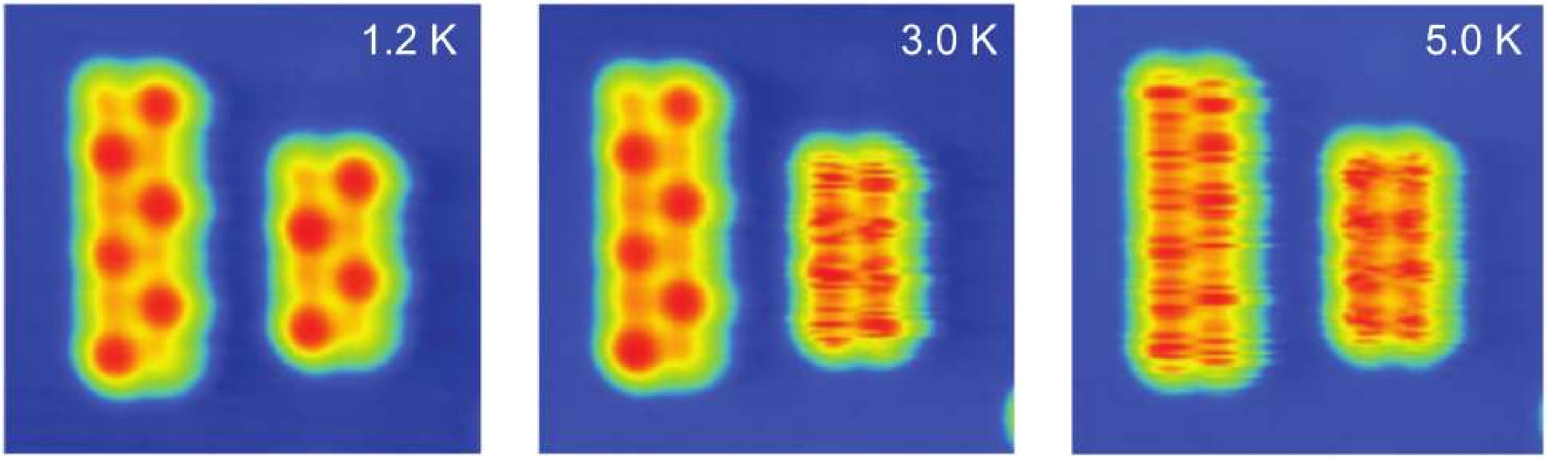




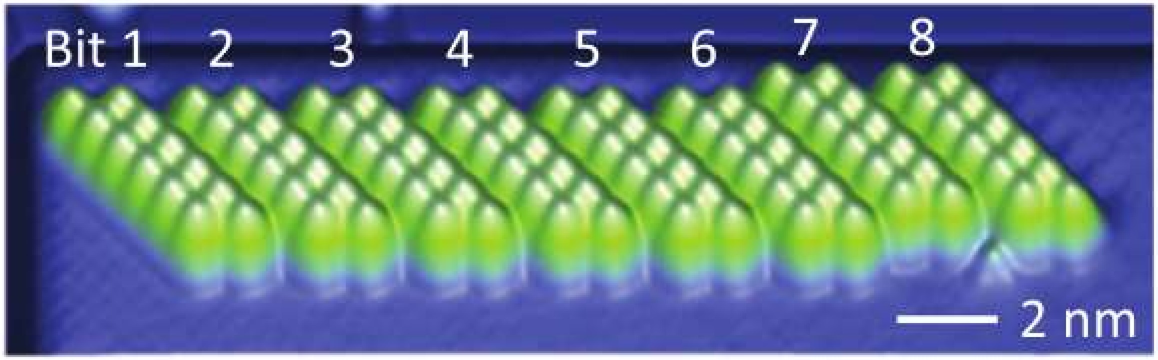
The chain switches between the “0” and “1” states

Antiferromagnetic spin ladders

Spin polarized STM image of atomic ladders



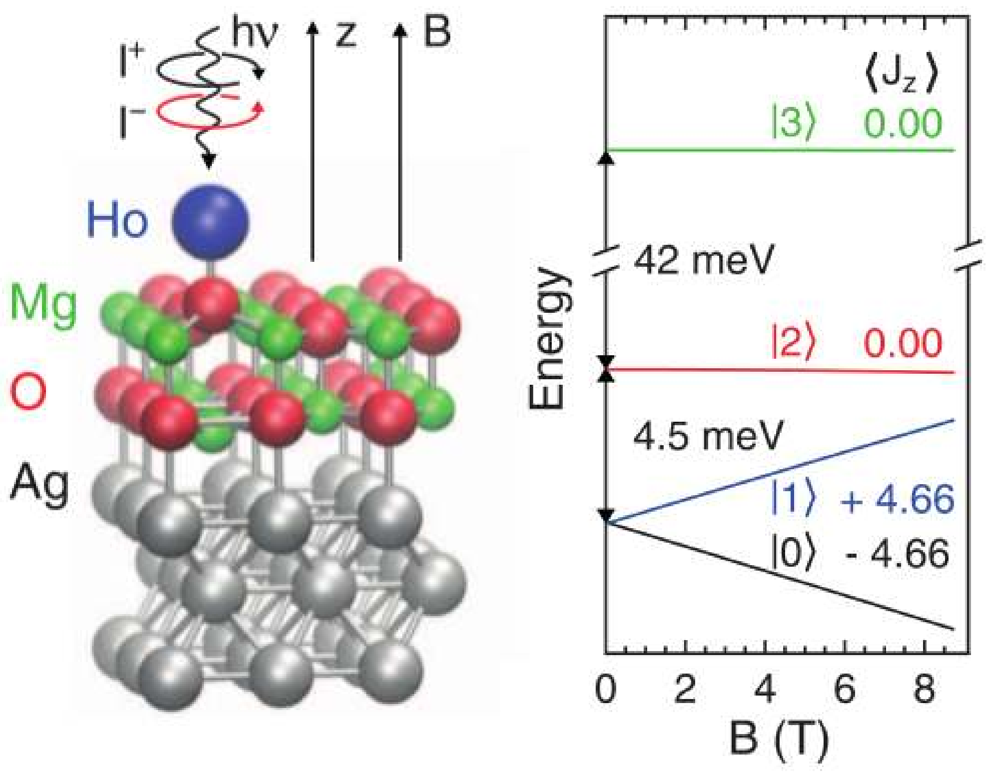
An atomic byte



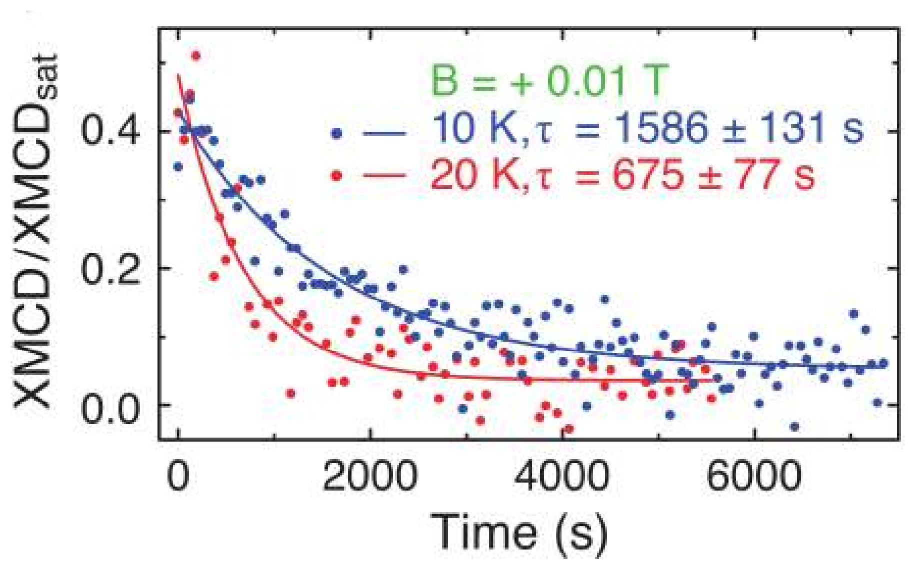
Could a bit be smaller than 12 atoms?

Single atom magnetism, Ho@MgO/Ag(111)

Single Ho atom in MgO



The atom switches every 20 min

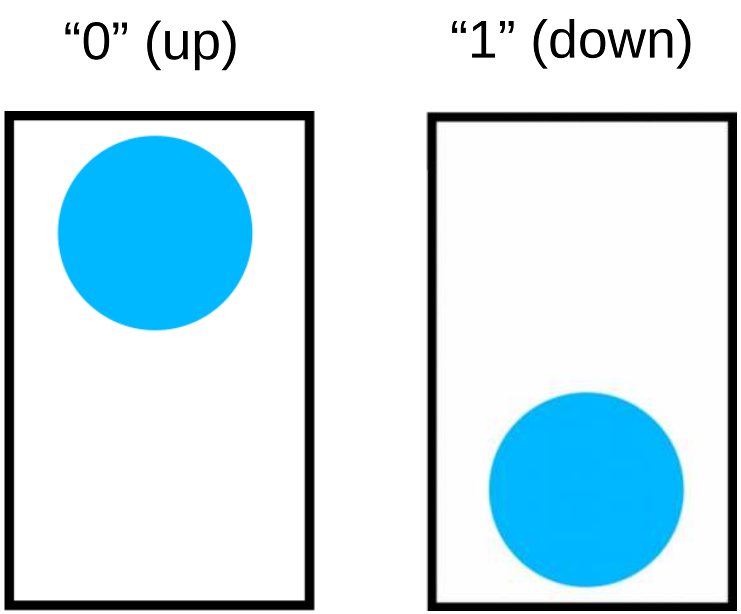


Donati, F., et al. "Magnetic remanence in single atoms." Science 352.6283 (2016): 318-321.

Alternative way to store information

Spins can easily suffer from quantum tunneling

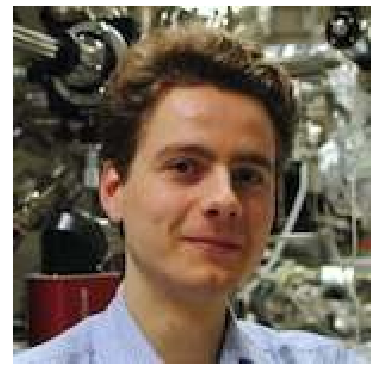
What if we try to store information on the fact of whether there is (1) or there is not (0) an a atom in a certain site?



We just have to find
the right atom
in the
right surface

A kilobyte rewritable atomic memory

Floris Kalff



Sander Otte

TU Delft — Delft University of Technology

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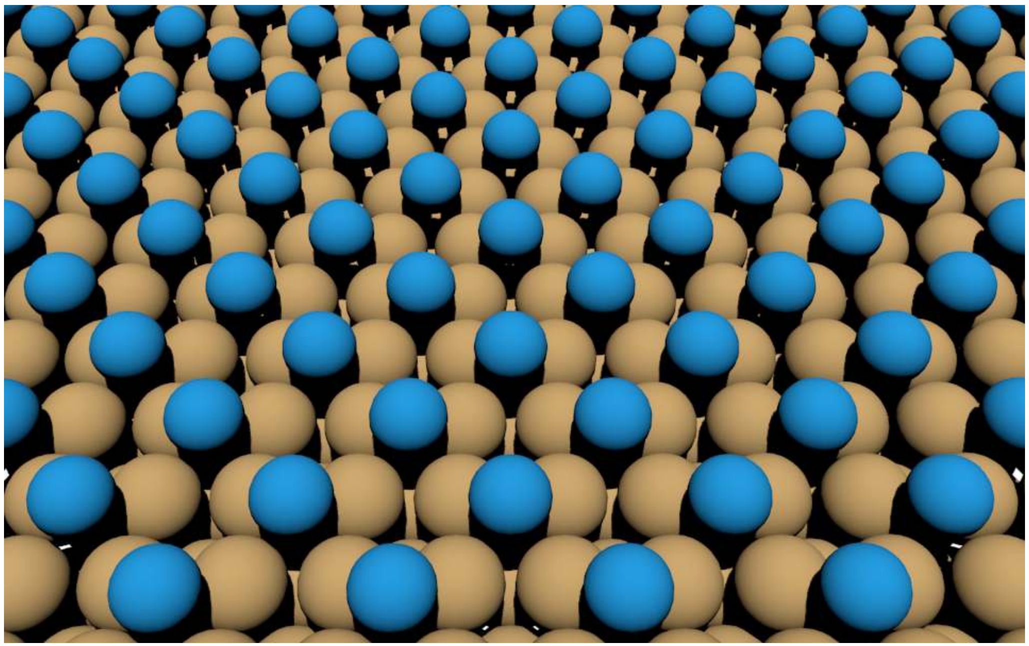
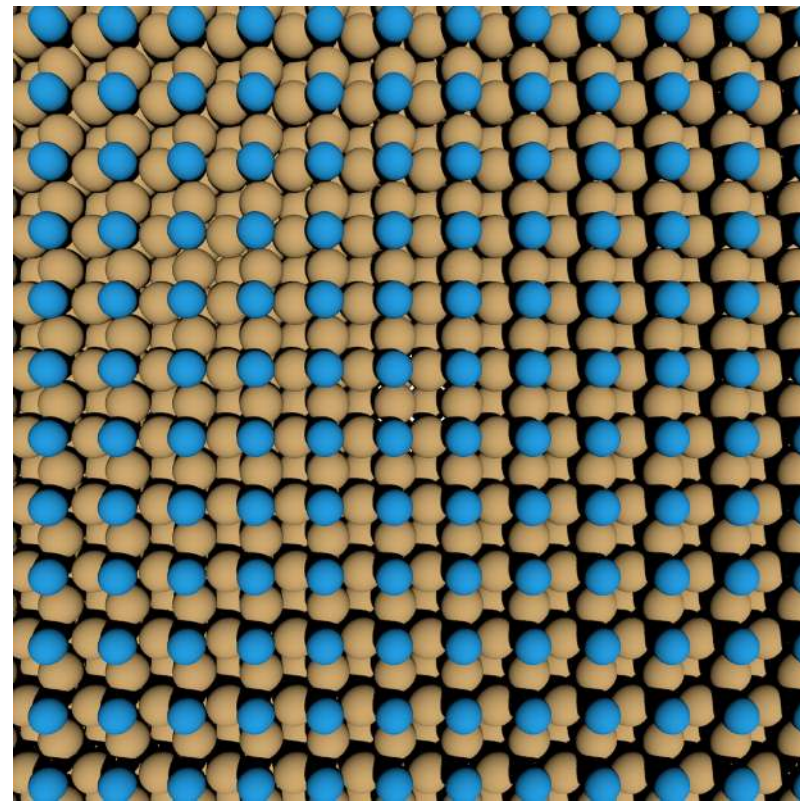
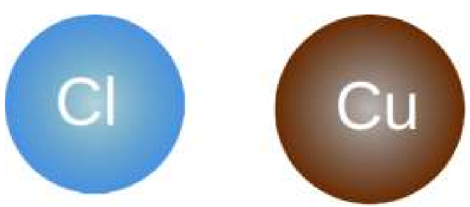
Chlorine atoms in Copper (100)

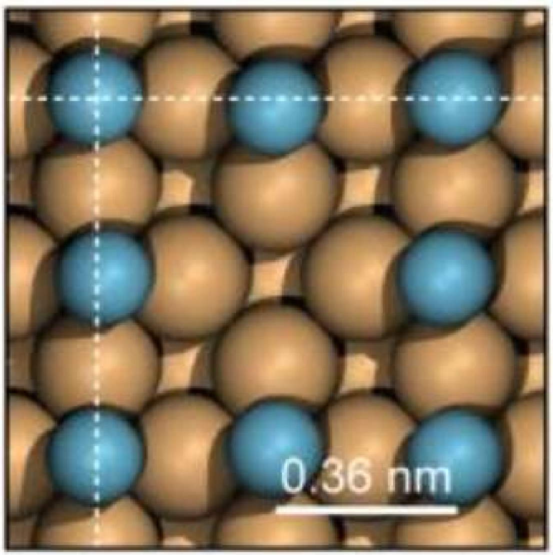


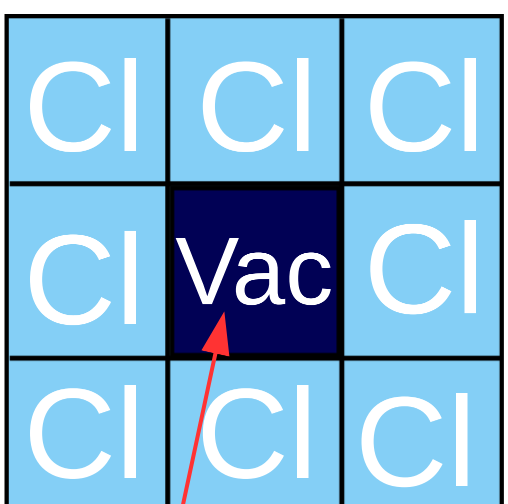




Fully covered Cu (100) surface with Cl ad-atoms

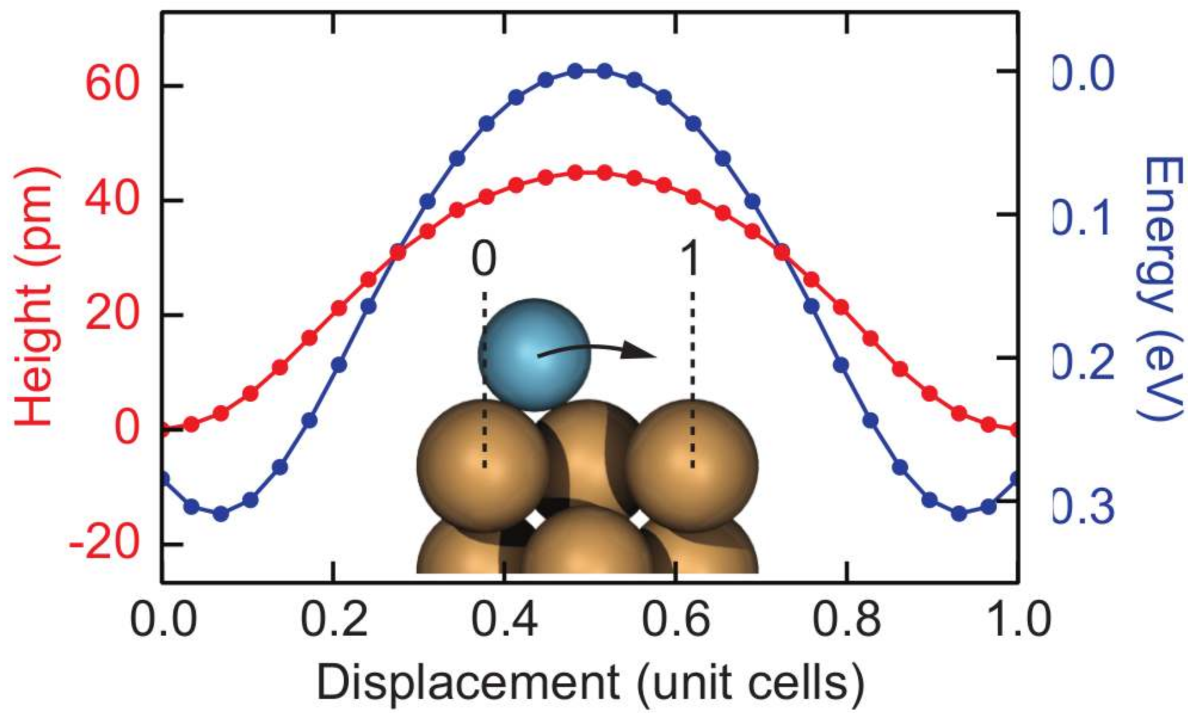
Vacancies in Cl @ Cu (100)

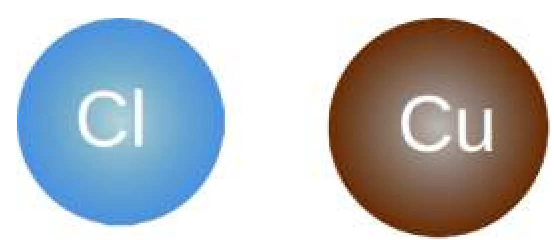




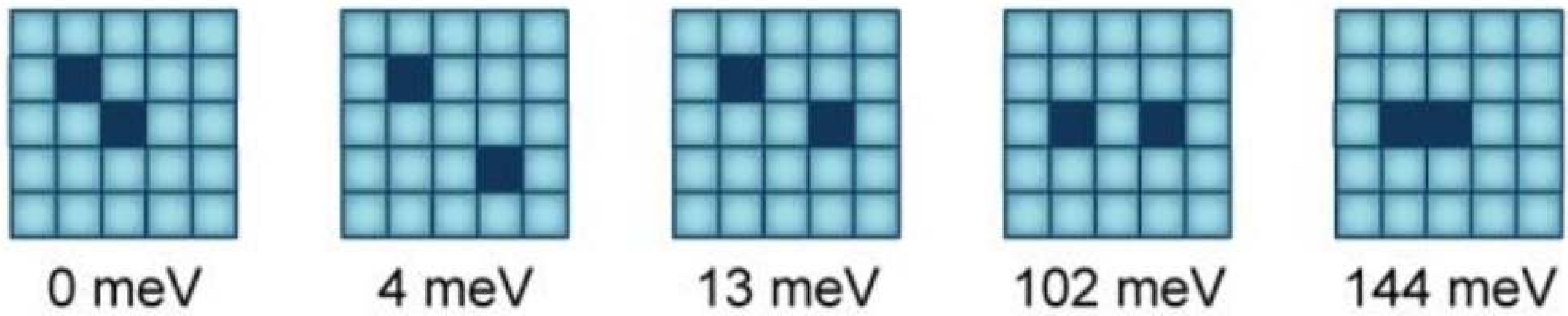
Missing Cl atom (vacancy)

300 meV barrier to jump (DFT)





Vacancy-vacancy interactions



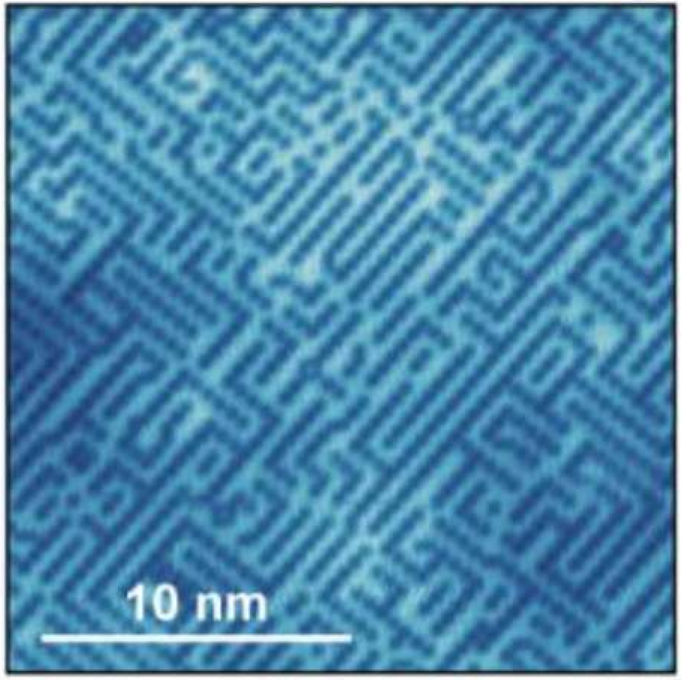
$$f(\mathbf{r}-\mathbf{r}') = \begin{cases} 0.144 & \text{if} \quad \mathbf{r}-\mathbf{r}' \in \{(1,0),(0,1),(-1,0),(0,-1)\} \\ 0.102 & \text{if} \quad \mathbf{r}-\mathbf{r}' \in \{(2,0),(0,2),(-2,0),(0,-2)\} \\ 0.013 & \text{if} \quad \mathbf{r}-\mathbf{r}' \in \{(2,1),(1,2),(-2,1),(1,-2),(2,-1), \\ & \qquad\qquad\qquad (-1,2),(-2,-1),(-1,-2)\} \\ 0.004 & \text{if} \quad \mathbf{r}-\mathbf{r}' \in \{(2,2),(2,-2),(-2,2),(-2,-2)\} \\ 0 & \text{otherwise} \end{cases}$$

Vacancies **prefer** to sit in the (11) direction

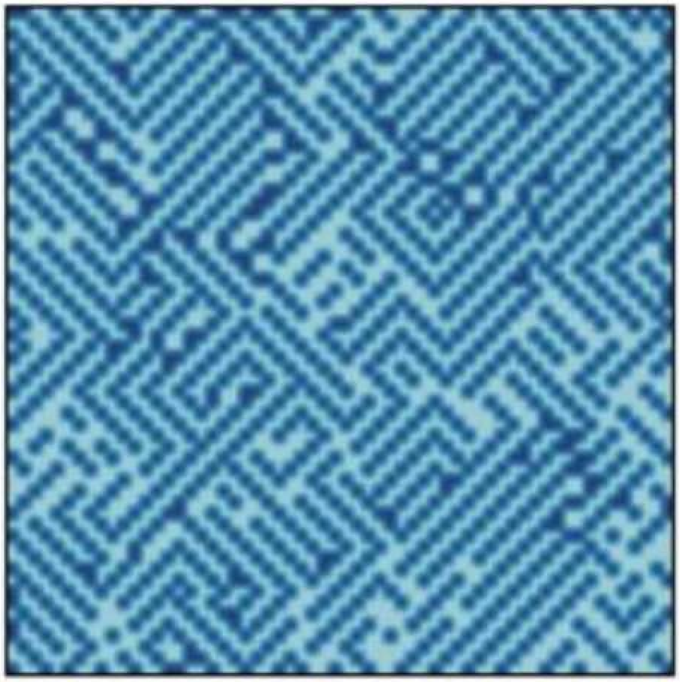
Vacancies **hate** to sit in the (10) direction

Cooling down the sample

Experiment



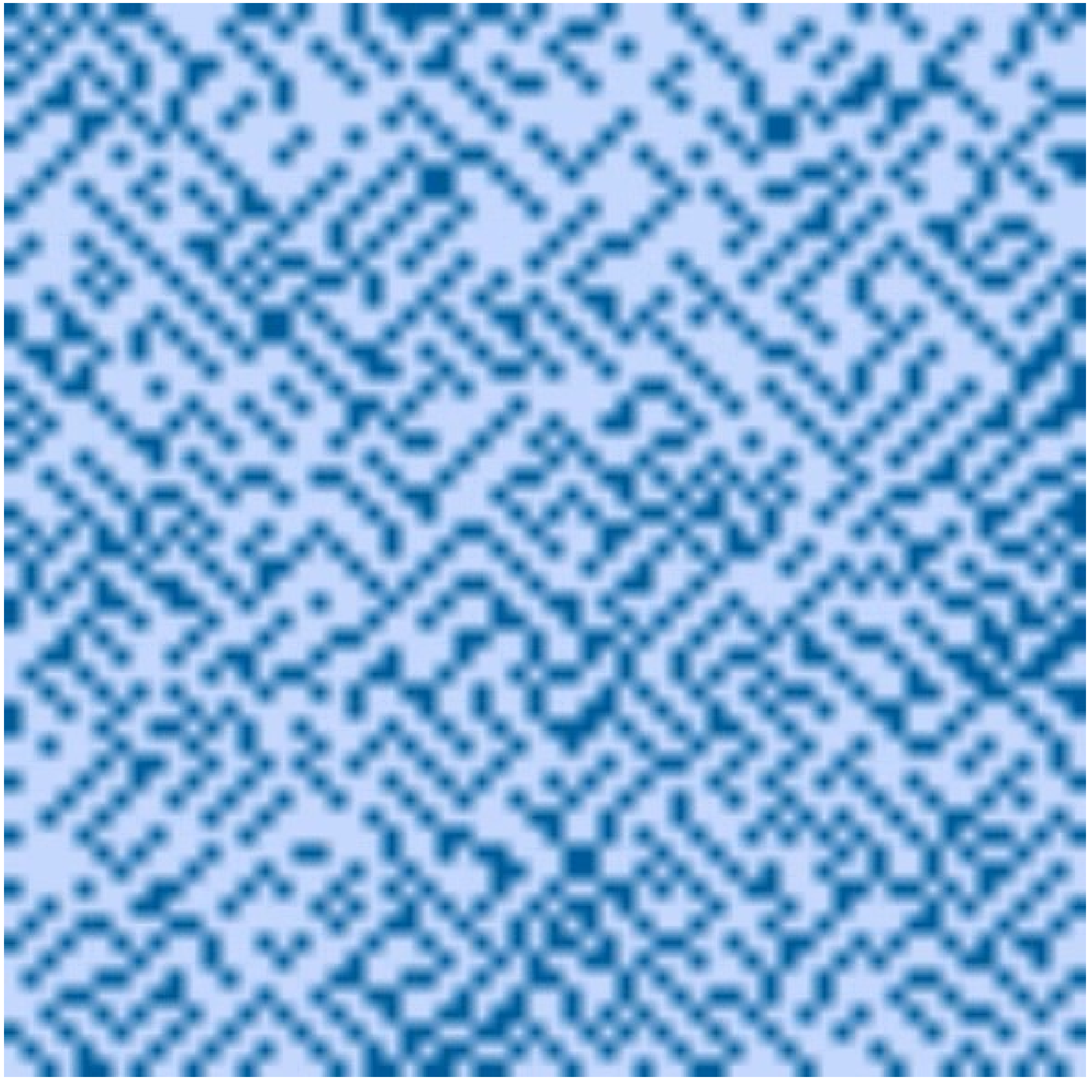
Theory



Maze-like pattern at filling 1/3, whose origin is the short range repulsive interactions

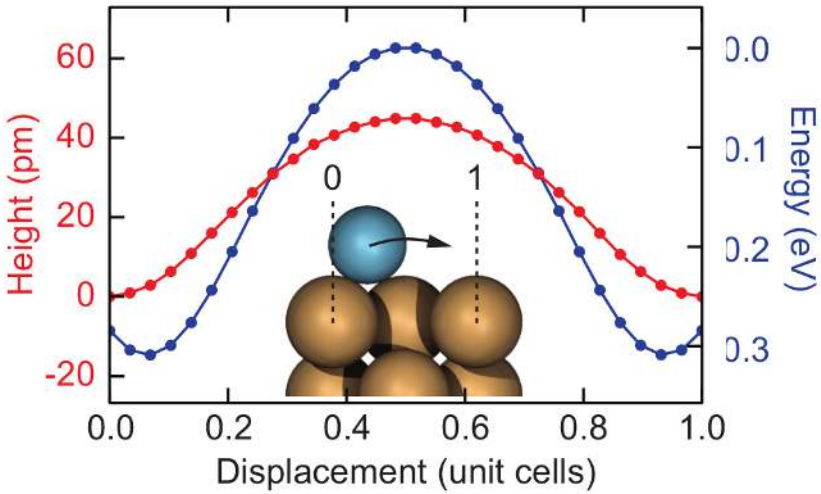
Cooling down Cl@Cu(100) atoms

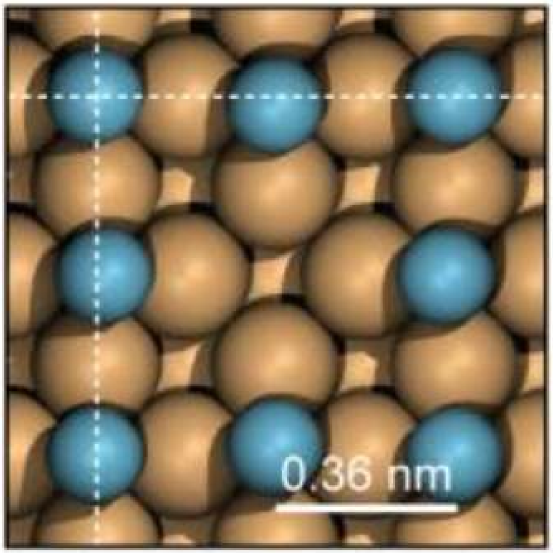
Starting from a random configuration, by cooling down the maze pattern appears



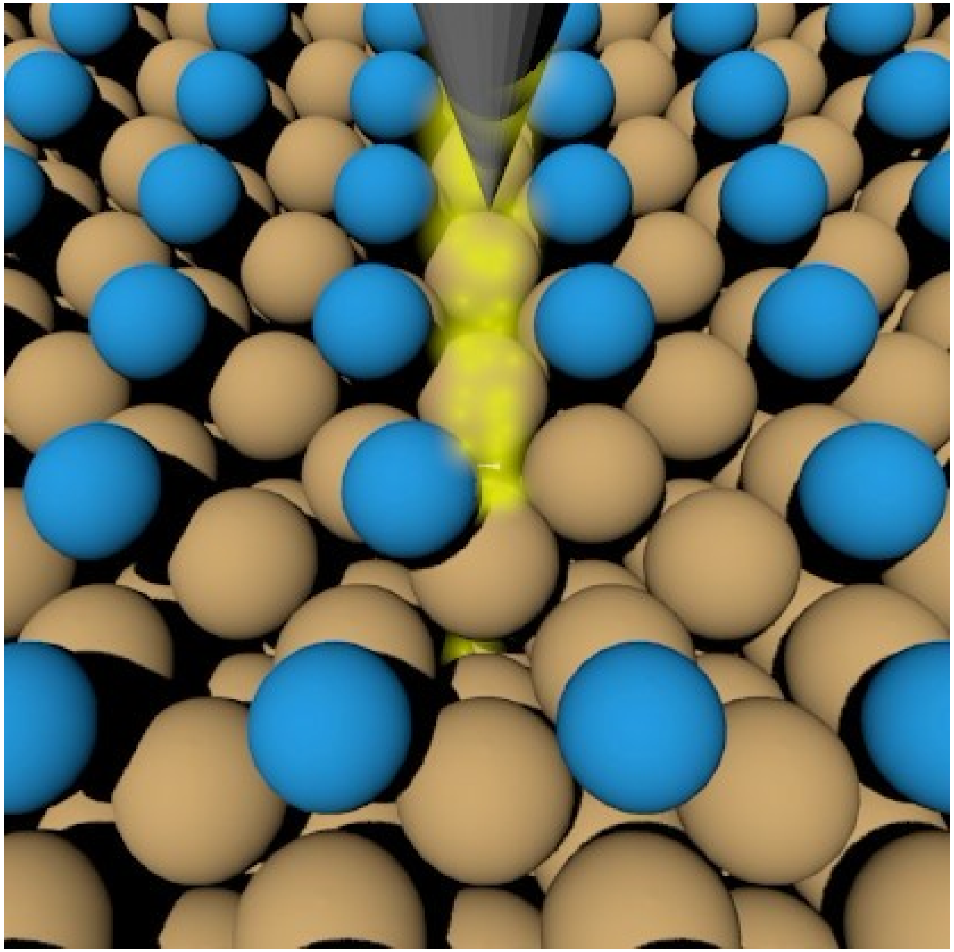
Monte Carlo simulation using the DFT vacancy-vacancy interactions

How to manipulate the Cl vacancies

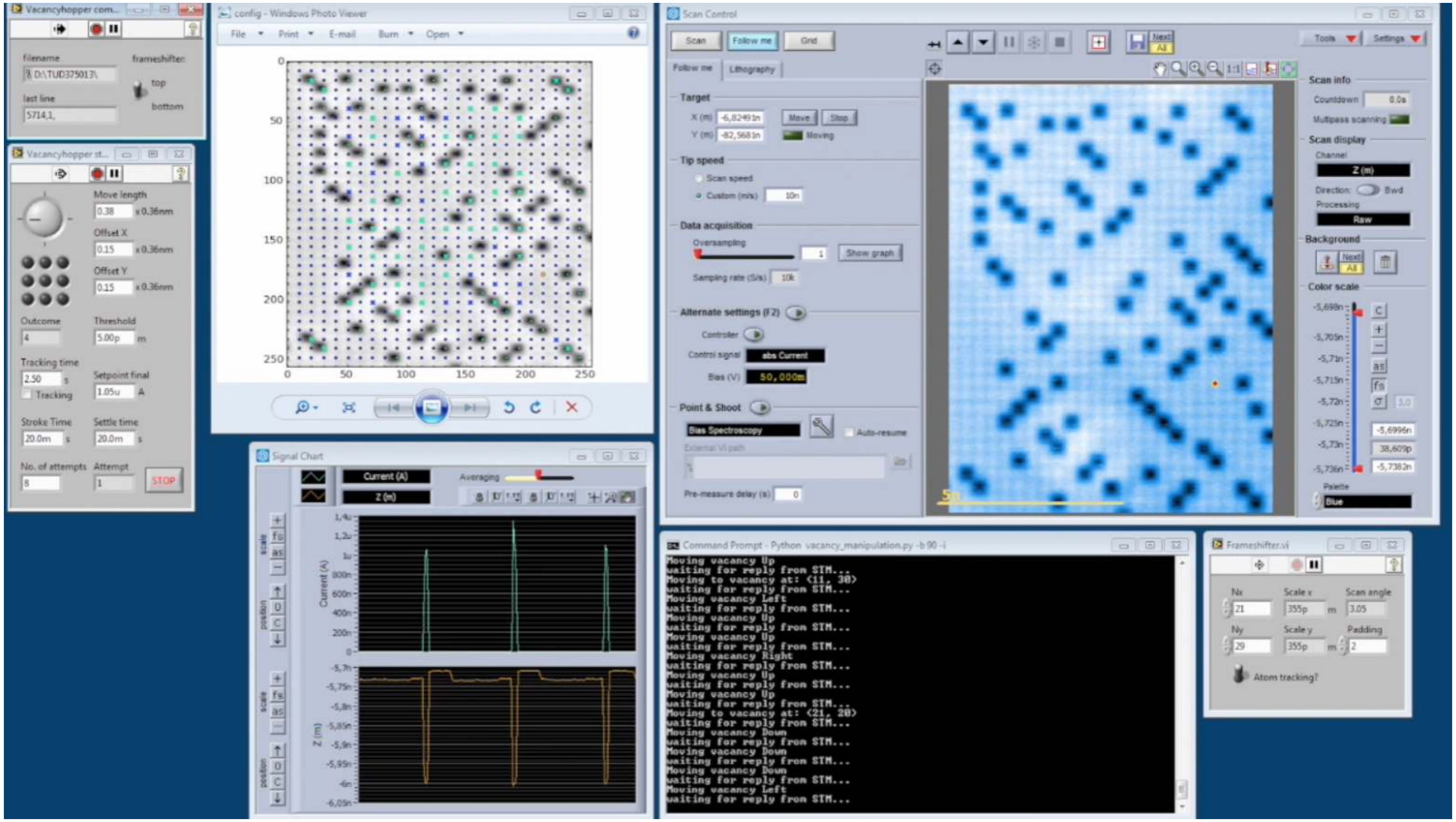




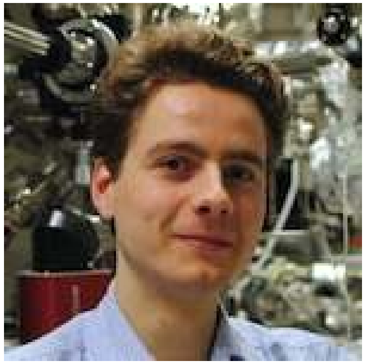
Vacancies can be manipulated with an STM current



Automated atomic manipulation

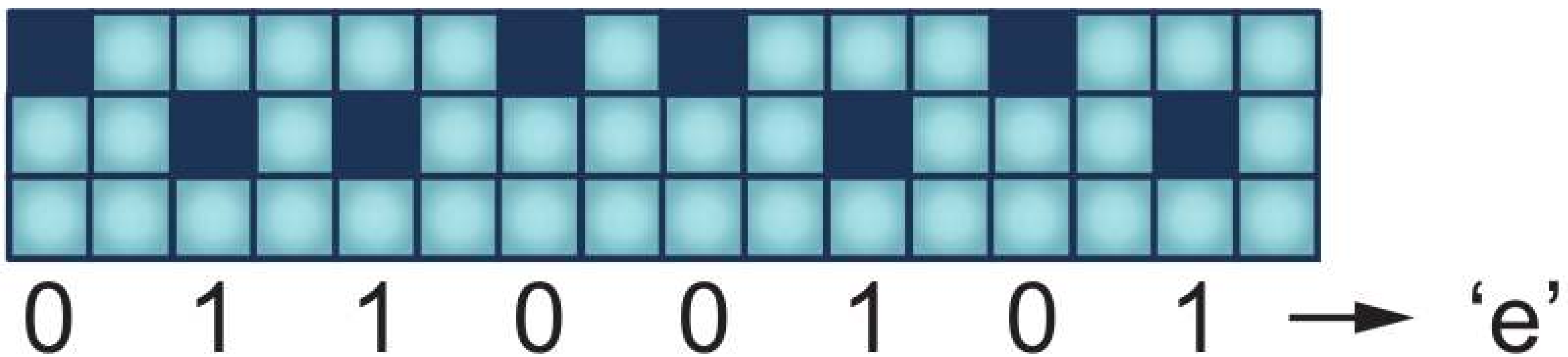


Floris Kalff

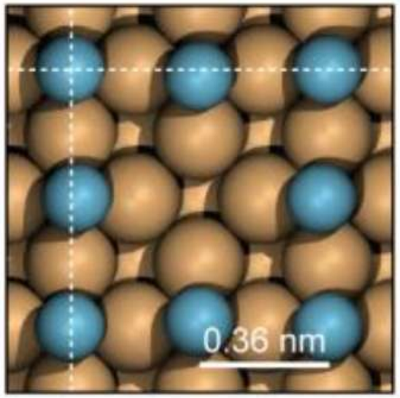


ASCII code in Cl@Cu

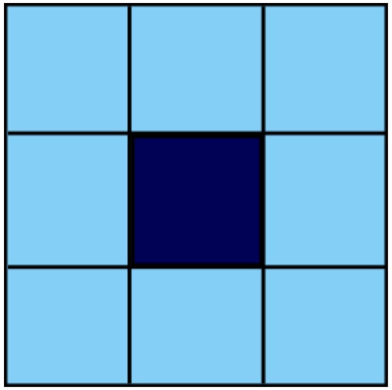
ASCII code: relates alphabetical and numerical symbols
to integer numbers from 0 to 128



Real lattice

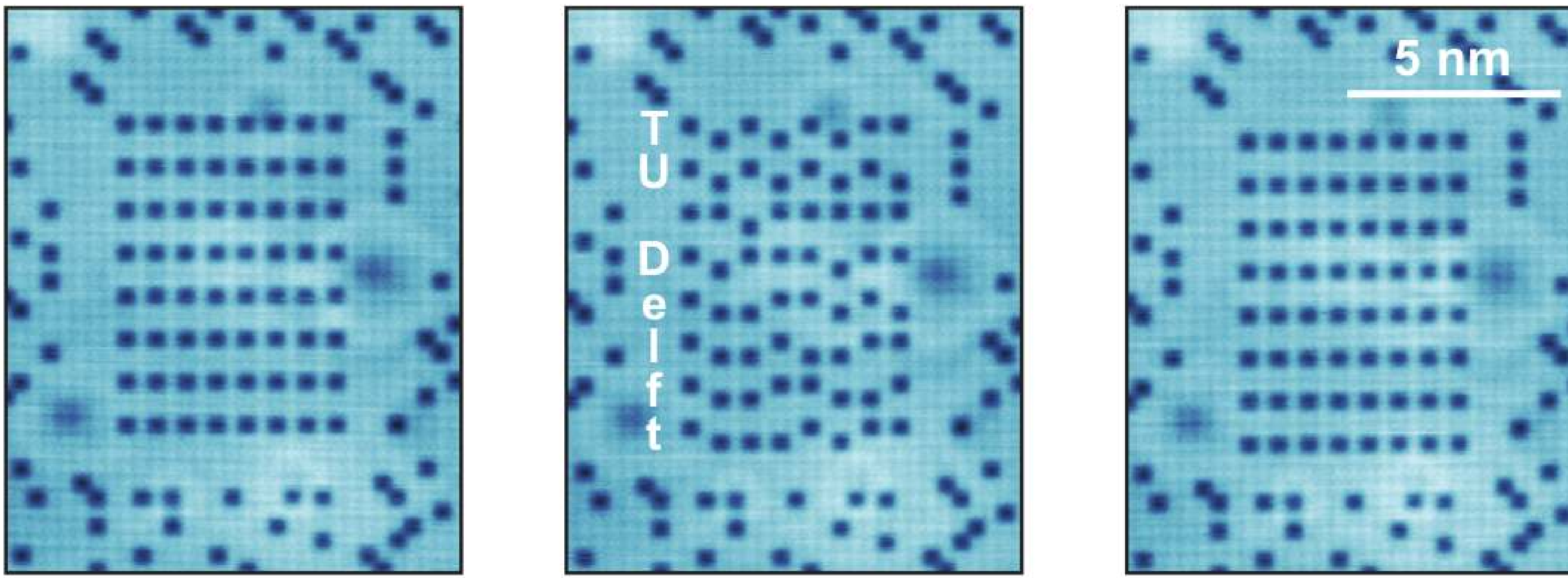


Sketch



Blank-written-blank again

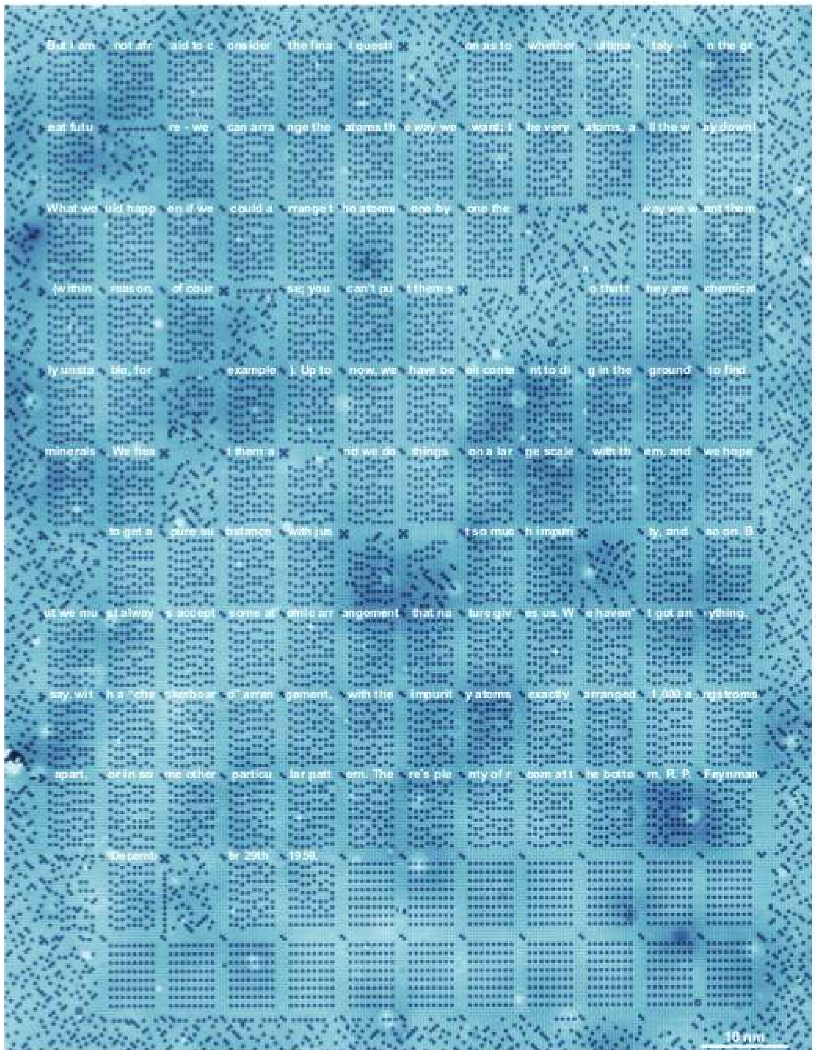
Blank page **Written page** **Blank page**



Rewritable atomic memory

Quoting Feynman, atom by atom

Feynman speech, written in Cl@Cu



Feynman 1959
There is plenty of room at the bottom

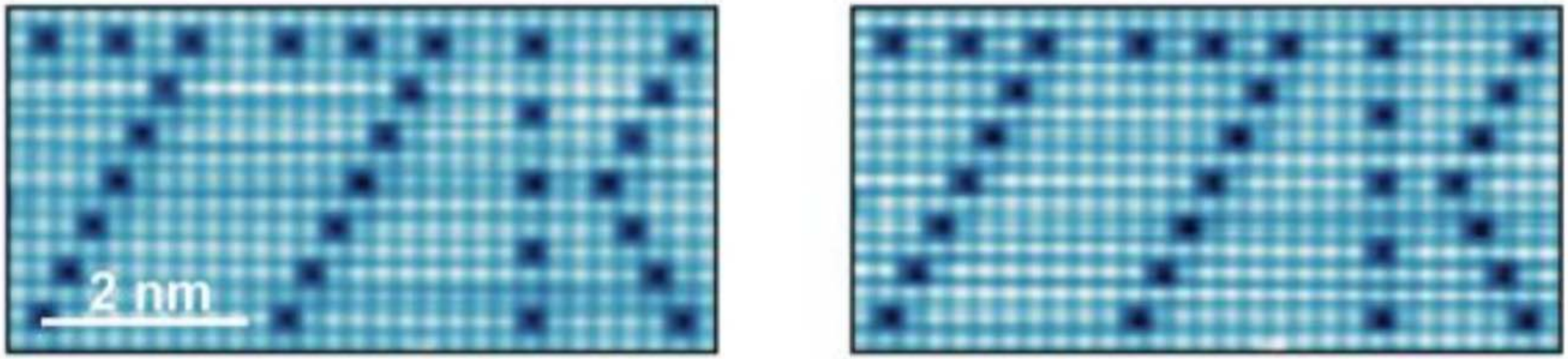
But I am not afraid to consider the final question as to whether, ultimately - in the great future - we can arrange the atoms the way we want; the very atoms, all the way down! What would happen if we could arrange the atoms one by one the way we want them (within reason, of course; you can't put them so that they are chemically unstable, for example). (...)

What could we do with layered structures with just the right layers? What would the properties of materials be if we could really arrange the atoms the way we want them? They would be very interesting to investigate theoretically. I can't see exactly what would happen, but I can hardly doubt that when we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do.

Limitations of Cl @ Cu memory

- Slow writing speed
  - 10 min for 1 block
- Stable at low temperatures
  - 77 K (liquid nitrogen)

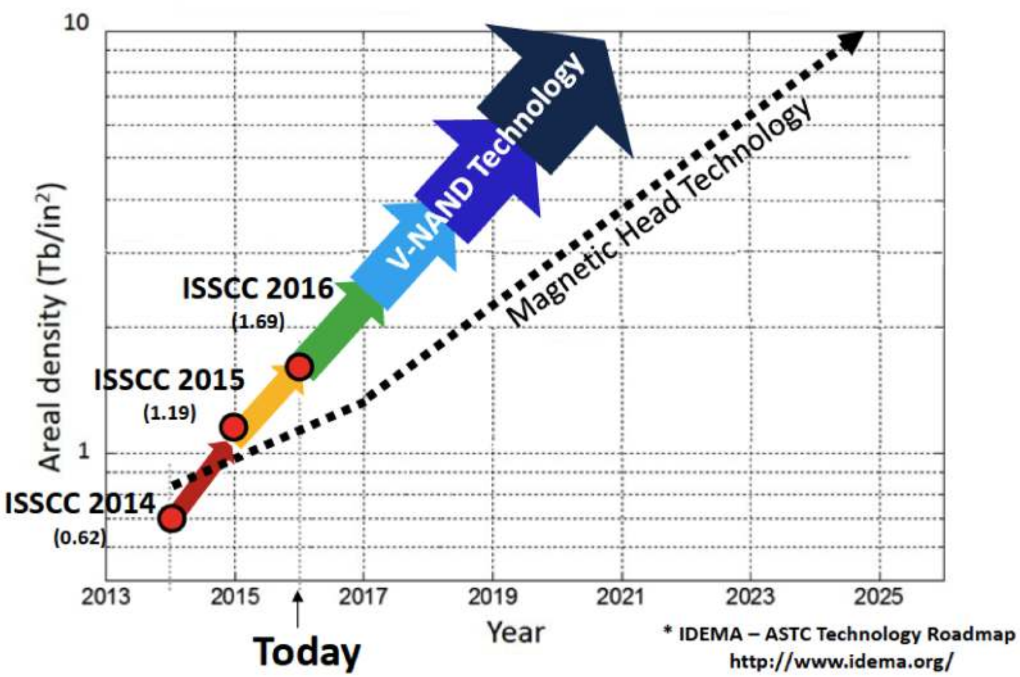
44 hours apart



How far we got

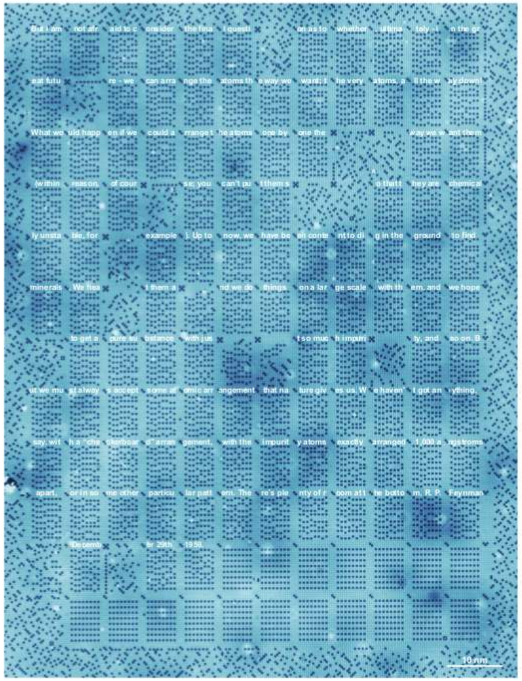
State of the art storage (2016)

1.5 Tb/in²



Cl @ Cu (100) memory (2016)

500 Tb/in²

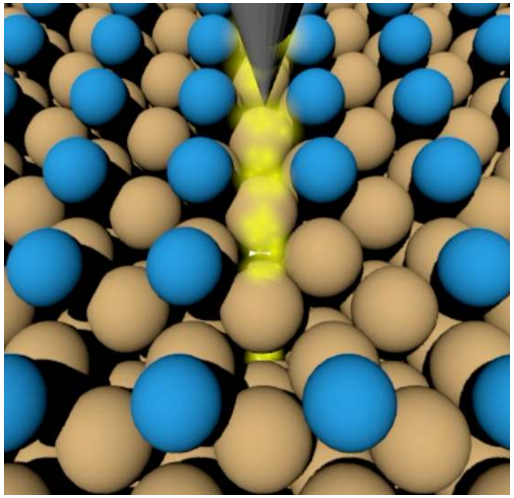


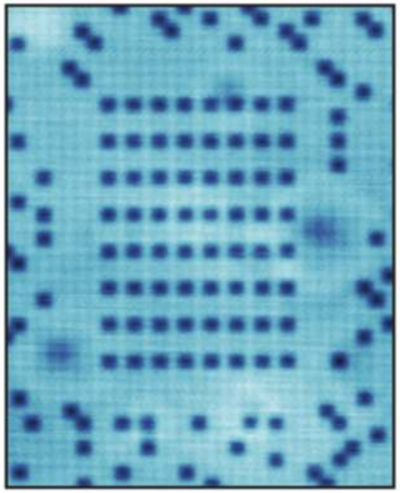
Cu @ Cl memory represents an increase in capacity of a factor 300 with respect to current technology

Take home

- Scanning tunnel microscope allows to manipulate Cl ad-atoms in copper
  - Reliably
  - At large scale

  To ultimately create **a kilobyte atomic memory**





Thank you!!

Spinograph

Spintronics in Graphene