Swartzentruber’s job is to understand the stability of surfaces on the atomic scale

- diffusion, sticking, and binding
- interactions with defects
- surface chemistry

Some key points...

Individual atoms can be imaged.

Temperature affects the motion of atoms.

Atoms can be directly manipulated and arranged on a surface.

Here is a movie of a growing crystal with ‘cube’ atoms. There are a lot of different processes going on here: atoms are deposited; they diffuse around; they stick to steps and to each other; they interact with defects; etc. We try to figure out what processes are active on a surface and to determine their relative importance.
How big is an atom?

A tennis ball is the geometric mean between the earth and an atom. That is, the size of a tennis ball is to the size of the earth, as the size of an atom is to the size of a tennis ball.

Earth

Human hair typically varies in diameter between 50 to 150 microns.

Here is an electron microscope picture of one of my gray hairs. I was curious to see if my gray hairs were different than my brown hairs, so I plucked a couple out and put them in the electron microscope... I couldn't tell any difference.

If the stick figure on the left, made from CO molecules, was 1 foot high, the image of my hair would be about 4 miles high.

Diameter of the earth ~ 1.2 \times 10^7 m
Diameter of tennis ball ~ 6.5 \times 10^{-2} m
Diameter of an atom ~ 1-5 \times 10^{-10} m

B. S. Swartzentruber

“World’s smallest picture” reprinted with permission from IBM

Swartzentruber’s gray hair

CO on platinum crystal
Why can’t I see atoms?

The wavelength of visible light is thousands of times longer than an atom.

X-rays have about the same wavelength as the size of an atom.
In order to get diffraction you have to have a large number of atoms arranged in a well-defined pattern. Each spot in the diffraction image is made by waves scattered from many atoms, so these spots are not images of individual atoms. X-rays (high energy) penetrate deeply into a material and are good for looking at the atomic or molecular order in bulk crystals. Electrons (low energy) don’t penetrate very far and are used to look at the atomic structure of crystal surfaces.

It is easy to demonstrate diffraction by shining the beam from a laser pointer through a diffraction grating or on a CD so the diffraction pattern appears on the screen. This pattern is produced by the regularly-spaced grooves or structures. (Be sure to keep the beam under control at all times.)
High electric fields exist at sharp points

Electric fields can ionize atoms and molecules.

E.g., Lightning rods

Lightning rods work because they ionize molecules in the air at their pointy ends when an electric field begins to form. Then the ions discharge the field before it gets large enough for lightning to form.
A sharp needle with a high field is put into a vacuum chamber. The chamber is filled with some helium gas, which diffuses around. When a helium atom gets close to the high field, it gets ionized and accelerated to a detector... where a spot is formed.

Take a closer look at the needle tip.
Field Ion Microscope

The pointy parts ionize the He atoms which make the spots on the detector.

Some atom locations are pointier than others.
First images of atoms were made with FIM in 1956

In the ‘old days’, before computers, scientists often made physical models of the things they were studying out of stuff that you might find at the hardware store. Then they took photographs of the models to publish in their papers. Now, everyone uses computers to illustrate fancy models and to plot graphs.

The surfaces were visualized with cork ball models…

…painted with glow-in-the-dark paint.
Electron probability extends out of surfaces

Electron probability falls off exponentially.

'Tunneling' is an effect due to quantum mechanics. In classical mechanics electrons are prohibited outside of the material, but in quantum mechanics there is a small probability to find them in the classically forbidden region. Because of quantum mechanics electrons can pass between materials that aren’t even touching – they tunnel through the forbidden region.
Scanning tunneling microscope (1980s)

Maintain tip-sample separation feedback on electron current – extremely sensitive to distance.

Raster tip over sample generating 2-d image line-by-line (typ. 1-100 sec)
Putting gold atoms on a silicon crystal rearranges the surface

Notice that the arrangement of silicon atoms in the upper left is much more ordered than the atoms that pile up along the step. The binding at the step isn’t strong enough for the atoms to find a nice ordered structure. And the temperature isn’t high enough (not enough energy) for the atoms to find more stable binding sites.

This is the arrangement of atoms on the clean silicon surface. The bumps are silicon atoms. Note the symmetry.

When gold mixes in the surface, the atoms rearrange to form rows. Extra silicon atoms line up along these rows.

Extra silicon atoms also sit along the crystal steps. Note the disorder.

When the surface is heated, the silicon atoms move along the rows.
“Atom Tracker” locks onto specific atoms

- Position tip over atom
- Vibrating tip senses atom position
- Electronics lock on to top of atom
- Tip follows diffusing atom
- Record position versus time (x,y,z)

Time resolution increased x 1000!
Following an atom’s motion

- Acquire initial 2-d image
- Locate diffusing atom
- Switch on lateral feedback
- Continuously monitor X, Y, and Z

Technically, the bumps in these STM images are not individual silicon atoms. They are pairs of silicon atoms bound together – called ‘dimers’. But they are bound together so tightly that they behave as a single entity.

The red dot in this movie shows the ‘atom-tracker’ position as a function of time. This movie is sped up. In real time the atoms hop about once every 10 s.

This movie is slowed down. In real time the atoms hop about 10 times per second. That is ~100 times faster than the colder movie.
Pd mixes in the top Cu layer, kicking out a Cu atom.

A palladium atom kicks out, and exchanges with, a copper atom because palladium ‘likes’ (i.e., bonds to) copper neighbors more than copper ‘likes’ copper neighbors. By embedding in the top-most layer, palladium increases the number of its neighbors.

How do these embedded atoms move in the surface?

This is an STM movie of a bunch of embedded palladium atoms moving around in the copper surface. The temperature is 41°C.
We measure every move of an embedded Pd atom

A slide puzzle is a great example of motion due to a vacancy. The pieces in the puzzle can move around because of the motion of a single vacancy – the missing piece.

Missing atoms in a surface allow the other atoms to move around more freely.
STM tip can be used to move atoms

Not only can the STM be used to image atoms – it can also be used to manipulate them. If the tip is close enough to an atom, it can exert a force. Then moving the tip moves the atom.

This type of manipulation has to be done at an extremely low temperature – almost absolute zero. If the surface is too warm, the atoms shake too much and the adsorbed xenon moves, which messes up the arrangement.

Xenon atoms arranged on nickel surface
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Quantum mechanics is evident at the nanoscale

In the sequence of images above, the STM is used alternately in imaging and manipulation modes. Because the same instrument is used for both processes, the scientists can’t see where the atoms are while they are being moved around. Therefore, they need to check every now and then to see where all of the atoms are.

‘Quantum corral’ traps surface electrons. Electron waves form the circular pattern.
Key Ideas

- The atoms in a crystal are arranged in a regular pattern.
- Atoms on a crystal surface can change their position. The higher the temperature, the faster the surface atoms can move around.
- Individual atoms can be imaged.
- Using electrical forces, individual atoms can be moved to particular locations on a crystal surface.

Discussion Questions

- What would it take to be able to see atoms?
  How would our bodies have to be different?
  How would the universe have to be different?
- What does ‘touching’ mean?
  Is sensing enough?
  Does moving something have to be involved?
- How does heat affect the motion of atoms?
- What is necessary to prove that atoms exist?