G. Binnig and H. Rohrer (1999), *In touch with atoms,* Reviews of Modern Physics, Vol. 71, No. 2

The article can be accessed at https://www.researchgate.net/publication/238552666_In_Touch_with_Atoms (Click the 'Download full-text PDF' button and a download should start without having to sign up).

You can also download the Cornell notes template for this paper (which includes the same questions) as a Word Document or PDF. Teachers, feel free to download this and forward it on to your students.

This week's article focusses on *local-probe microscopy*. The authors, Binnig and Rohrer, are two of the key figures in the development of the popular nanoscale probes the scanning tunnelling microscope (STM) and the atomic force microscope (AFM). They won the 1986 Nobel Prize and what we're reading here is the Nobel acceptance paper (much like the graphene one we previously read). These techniques began life as imaging techniques and there's a beauty in their simplicity. As the techniques have evolved (particularly the STM) they have been able to do more than simply scan a surface, but can now manipulate nanoscale objects.

We're going to start with a skim read. Don't worry if it doesn't make complete sense, or if you skim some sections quicker than others as you're feeling uncomfortable with them, that's fine.

This week we'd like you to come up with about three **SKIM-READ QUESTIONS** that you felt you needed to answer to allow you to understand as much as possible on a second read through.

Why do physicists often argue that two objects never really 'touch'?

What is quantum mechanical tunnelling?

What is a wavefunction?

What are piezoelectric tubes?

Acronyms and initialisms in this paper:

AFM	Atomic Force Microscope
SNOM	Scanning Near-field Optical Microscope
STM	Scanning Tunnelling Microscope

ABSTRACT

What is the rough size of an atom?	10^{-10} m
What is the rough size of a water molecule?	Around 3×10^{-10} m
What do they mean by the term 'local probe'?	A tool that looks at a material in a particular location.
At the scale of atomic structures, what will local probes be able to sense?	Individual atoms and their arrangements.

BACK TO THE FUTURE OF MECHANICS

(P1, C1) What do the authors mean by the term ’electronics’?	The motion of electrons in and the deformation of their arrangements.
(P1, C1) What do the authors mean by the term ‘mechanics’?	The motion of the mass of atomic cores and the deformation of their arrangements.
(P1, C1) Why do the authors consider the atomic cores to be, at best, the ‘guardian of the electron’?	Because the electrons give rise to the electronic, chemical and mechanical properties of materials whereas the atomic cores’ do not affect or define the macroscopic properties of materials so strongly.
(P1, C1) Why might you argue that atomic cores are much more than the ‘guardian of the electron’?	The electronic states are caused by the interaction between the electrons and the atomic cores. Without the atomic cores, we’d simply have an electron gas which does not have the wide variety of properties as material systems.
(P1, C1) What can a Scanning Tunnelling Microscope (STM) do?	Sense and manipulate atoms/molecules/tiny objects.
(P1, C1) Analyse the individual words of the phrase *‘The STM is a mechanically positioned, electrically sensitive kind of nanofinger’* to understand what an STM is.	Mechanically positioned – it is moved externally through classical means. Electrically sensitive – it has the ability to sense the electrons of a material. Nanofinger – it is designed to be thin so that the probe is essentially atomically sharp.
(P1, C1) Looking at Figure 1, how might you improve your earlier definition of ‘local probe’?	A local probe interacts with an object in such a way that its interaction deteriorates rapidly with distance away from the probe so that the probe only feels that atom(s) closest to it whilst not affecting any of the atoms further away.
(P1, C1) What does ‘inhomogeneity’ mean?	The opposite of homogeneous (which means having the same composition throughout so that it is considered uniform). We can think of it as being non-uniform.
(P1, C1) What had been the focus of condensed matter physics?	Periodic structures – structures that are uniform and repeating such as crystals.
(P1, C1) Why do we consider an inhomogeneity to be a local phenomenon?	Because the breaking up of a uniform pattern (homogeneity) can occur in a specific place. Imagine a perfect grid of points (e.g. graph paper) – if we could rub out one small part of one of the lines, then we’ve introduced inhomogeneity and it occurs at a particular location (it is local).
(P2, C1) Why would such a small local probe (atomically thin) need a ‘high precision nanodrive’ when scanning a material?	We need to move the tip with precision to maintain close proximity to a sample. With this in mind, we need to be able to alter the position of the tip incredibly deftly, thus we need high precision motors.
(P2, C1) What are ‘continuous and reproducible displacements’?	We want to be able to alter the position smoothly not in discrete steps, to be able to be precise about the location of atoms. We

	want it to be reproducible so that we can be sure that the movements of the tip correspond to features on the surface.
(P2, C1) Why is good vibration isolation necessary?	To ensure that any movement of the tip is caused by the machine itself (so that it can be recorded) and so that the tip doesn't damage the sample through non-intentional movements.
(P2, C1) Why does the concept of contact blur when we get to the nanometer level?	As we are in the range of quantum mechanics. Imagine one atom attempting to 'touch' another. The atoms themselves don't have clear boundaries – their 'edge' is a blur of the electrons that they contain (the electron cloud). When one atom comes near to another, the electron clouds overlap and repel. No subatomic particles make contact with any others.
(P2, C1) What does resolution mean in the context of creating an image?	The degree of detail that is visible.

Before you read the paragraph that begins '*In STM, the interaction can be described…*', we need to get a more basic understanding of how an STM works. Read this brief article from 'How an STM Works' now. The diagram below may also be useful. 'Describe how an STM works' will be one of our summary questions this week, so draft out an initial answer now.

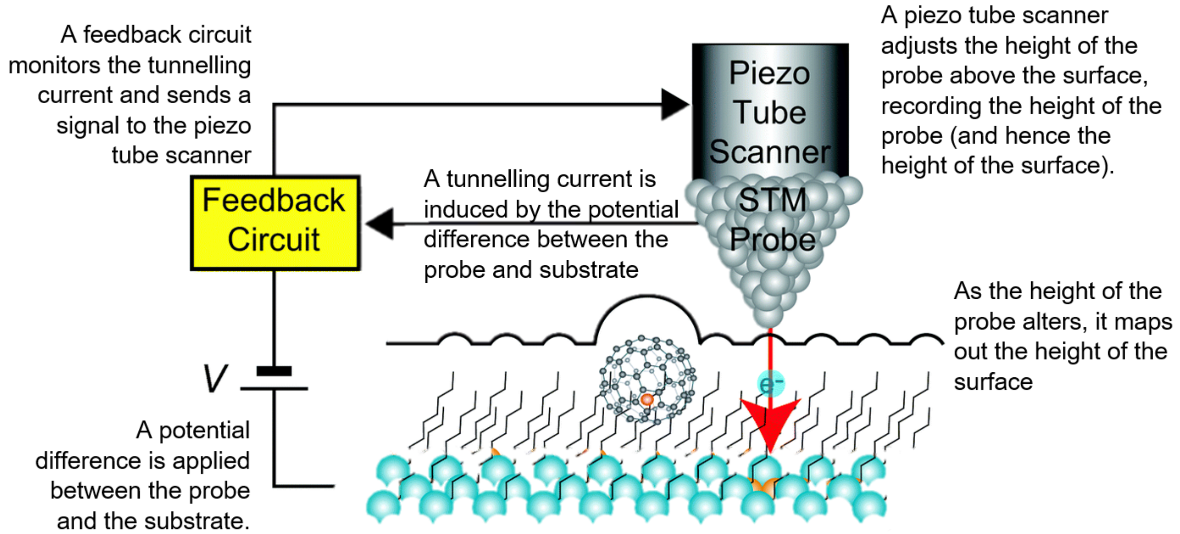


Image taken from S. Kano, T. Tada and Y. Majima (2015), *Nanoparticle characterization based on STM and STS, Chem. Soc. Rev.*, **44**, 970-987

(P2, C1) As the scanning tip (or probe) gets further from the surface of a material, what happens to the tunnelling current?	The tunnelling current decreases exponentially with increasing distance between the tip and the surface. $$I = I_0 e^{-\frac{x}{l}}$$ Where x is the tip-surface distance and I is the tunnelling current. I_0 is a constant and l is the decay length.
(P2, C1) What is the rough estimate of the decay length for most tip/sample combinations?	0.05 nm

(P2, C1) Why would the STM be less effective if the decay length was longer?	As you'd be less certain that the frontmost atom of the tip was carrying the current and therefore the STM would not necessarily be probing the local area.
(P2, C1) Why do the authors state that 'atomic resolution was inevitable'?	As the required distance between the tip and surface needed to achieve a current in the measurable range was less than 1 nm. This distance is in the range of the size of an atom.
(P2, C1) Why do you think that thermal fluctuations (think of these for now as random fluctuations in the movements of atoms in the material) of atoms in a lattice can be 'averaged out'?	As the fluctuations are random, they're equally likely to occur in any direction and so the average position of an atom that is fixed within a lattice is going to be at its lattice point.
(P2, C2) What is meant by describing an STM as 'an electronic-mechanical hybrid'?	The interaction is electronic – the tunnelling of electrons from the tip to the sample. The feedback loop leads to a mechanical alteration in the position of the tip which is really what an STM is monitoring.
(P2, C2) What is the constant interaction/mechanical mode of an STM?	Where the feedback loop is designed to keep a constant tunnelling current between the tip and the surface and so adjusts the height of the tip as the tip scans over features so that the tip remains at a constant above the local surface. By relaying the height of the tip, this builds up the surface contour of the sample.
(P2, C2) How else can an STM be operated? What are the limitations?	An STM can be used in a constant height mode, where the tunnelling current changes as the surface gets closer to and further from the tip (when the surface is closer, the tunnelling current increases and vice versa). The size of the tunnelling current can be associated with the size of surface features. This mode can only be used for very smooth surfaces (where no bumps on the surface will knock into the tip) and is limited in its speed by how fast you can measure the current.

The article discusses a 'magical Si(111) 7x7 reconstruction' which was used to persuade the community that the STM was a powerful tool. This image can be seen here.

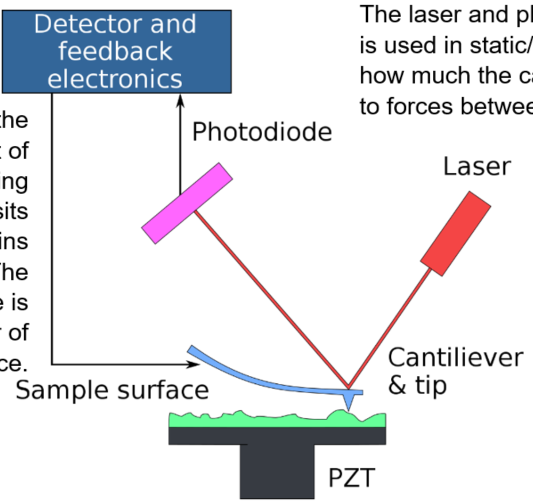
II. COLOURFUL TOUCH

(P2, C2) What do the authors mean by the term 'colourful touch'?	That local probes provide a 'rainbow of possibilities' for making contact with a surface by altering the type of interaction between a tip and surface or by altering the surrounding medium that it all takes place within.
(P3, C1) What are the two main reasons for using an STM?	To image a surface or to work with/alter a surface.

Due to the STM using a tunnelling current to ascertain where the surface is, an accurate topography of a surface relies on the electronic structure of the surface remaining constant. In the simplest case, if we imagine a hypothetical smooth surface that is in one location metallic whilst insulating in another then an STM not going to register this surface as smooth and continuous (in fact, it won't register the insulating surface at all). This property of tunnelling current – that it samples the local electronic properties of a surface – can actually be useful, though, as the authors take note of in (P3, C1)

(P3, C1) What is the downside of the slightly more recent Scanning Near-field Optical Microscope (SNOM) compared to the STM?	It doesn't have an atomic scale resolution.
(P3, C1&2) What is an advantage of the atomic force microscope (AFM) over the STM?	It can image surfaces of non-conducting samples. It provides force detection (for many different types of forces, both vertically and laterally).
(P3, C2) What are van der Waals forces? We looked at this very briefly in a previous week whilst discussing Gecko tape.	A collective term for intermolecular forces (attractive or repulsive) between atoms, molecules and surfaces that are caused by fluctuating polarisations of electric charge within the interacting molecules.

In static/contact mode, the feedback loop alters the height of the sample beneath the tip (using the piezoelectric tube that it sits on) so that the cantilever remains in a constant position. The movement of the piezo tube is then translated into the contour of the surface.



The laser and photodiode combination is used in static/contact mode to see how much the cantilever has bent (doe to forces between the sample and tip).

The atomically sharp tip is mounted onto a cantilever which bends in a predictable manner.

Image taken from Wikipedia https://en.wikipedia.org/wiki/Atomic_force_microscopy

(P3, C2) What are the two operating modes of an atomic force microscope (AFM)? Describe them briefly.	Static/contact mode where the tip is moved across the surface of a material and the deflection of the cantilever is noted (or the sample is moved to keep a constant deflection). Dynamic mode where the cantilever is oscillated, with the oscillations being driven initially by the AFM. The amplitude and frequency of these oscillations change when the tip interacts with a sample.
(P3, C2) Why is the AFM 'more mechanical in nature' than the STM?	Both the STM and AFM have a mechanical feedback loop – the position of the sample relative to the tip is altered mechanically by a piezoelectric tube.

	But the interaction between the AFM tip and the sample is mechanical in its nature (contact or tapping) whereas the tip of the STM's interaction with a surface is electronic in nature.
(P3, C2) Given that the usage of the cantilever is based upon Hooke's law, discuss some of the practicalities that might be involved in choosing a cantilever.	You want to get the right cantilever for the situation you have. The spring constant of the cantilever needs to be tailored to the size of the forces you're expecting to see on a given surface (and the resolution of your optical tracking). You want to create large enough deflections in your cantilever to be easily picked up by the optical tracking, but not so large as to overbend the cantilever (past its elastic limit) and snap it.
(P3, C2) We have met this idea before, but what is microfabrication?	Answer courtesy of Alex from Week 4: Microfabrication is *"the process of making structures that are extremely small - one-millionth of a metre or even smaller. An example of when this is used in making integrated circuits or microchips"*
(P3, C2) Why is it difficult to achieve atomic resolution with an AFM?	Because the tip and sample can be deformed by their interaction such that the tip is no longer atomically sharp, so the resolution becomes smeared.
(P3, C2) Why are AFMs not typically operated in air?	As, in air, any humidity will leave a thin watery film on both the tip and sample creating a strong capillary force that brings the two together.
(P4, C1&2 and Figure 2) What does Figure 2 show? Why is it remarkable? (This will be one of our summary questions this week)	Figure 2 shows a ring of iron atoms positioned deftly on a piece of copper. What is remarkable is that the same tool that imaged them also positioned all of the atoms there in the first place. By altering the strength of the interaction between tip and surface, an STM can transition between being a tool for altering the position of atoms and a probe of the surface. The wavelike structure within the circle is also remarkable and shows how the STM is actually sampling the electronic properties of a material. The waves come from the confinement of the electrons on the surface of copper within the iron ring. This shows the wavelike properties of electrons, behaving as waves to form a standing wave pattern.

III. CHANGE AND CHALLENGE

"They are fragile individuals, whose properties and functions depend strongly on their context and which are usually quite different from those in the isolated state." This quote

will be used in one of our summary questions this week. For now, just take a few moments to really think about what the authors might mean by this.	
(P4, C2 and P5, C1) Why isn't the STM strictly non-invasive?	As by its very nature, it has to interact with the sample to image it. It calls to my mind the Heisenberg uncertainty principle, but on a larger scale. We can't make measurements without affecting the thing we are trying to measure in some way. In the case of the Heisenberg uncertainty principle it is because of the delicate balances of quantum mechanics, in the case of the STM it is because we're given the sample an electric shock (and sometimes crashing the tip straight into the surface).
(P5, C1) How has the invasive nature of STM been used to advance the technique?	By using the STM to physically manipulate atoms on a surface.
(P5, C1) How can working in a liquid environment be beneficial (or why is the liquid-solid interface thought by the authors to be the interface of the future)?	As "liquids provide a very adaptive environment for protection, process control, and modification of surfaces, they carry ionic charges and atomic and molecular species, and they remove many of the ''traffic restrictions'' typical for a two-dimensional solid surface."

Around now the authors begin to dig into some of the more advanced applications of local-probe microscopy. We won't have any questions on this part, but it would be very beneficial to carry on reading this section to see how the STM and AFM develops from a tool to look and manipulate atoms to more exotic ventures.

IV. NATURE'S WAY

(P6, C2) Why do the authors draw links between the local probe microscopy techniques and nature itself?	As nature is built on the nanoscale, using nanofunctionality to create life itself. The AFM and STM are probing systems at this scale and so there is a parallel to be drawn to nature when these techniques can sense and change systems on this nanometre scale.

SUMMARY QUESTIONS (submit these, along with your SKIM-READ answers to thomas.millichamp@warwick.ac.uk)

How does a Scanning Tunnelling Microscope (STM) work?

What does Figure 2 show? Why is it remarkable?

"*They are fragile individuals, whose properties and functions depend strongly on their context and which are usually quite different from those in the isolated state.*" This is the description of atoms, molecules and nanometer-sized objects given in III. Change and Challenge. What does this quote bring to your mind about the atomic world?

FURTHER READING

This page at IBM gives a great background on the STM and the impact it has had and continues to have on modern technology

https://www.ibm.com/ibm/history/ibm100/us/en/icons/microscope/

This page gives a good background on the AFM

https://www.nanoscience.com/techniques/atomic-force-microscopy/