Microscopes for Science

Science

What Will be Covered?

"So what is a *microscope*?"
Some or probably a lot of you would answer that it is some kind of gadget that enlarges something by producing "enlarged" images or pictures of something small. Of course, no microscope makes things actually bigger, it just makes tiny objects *appear* magnified so they are visible to the eyes of humans. A *telescope*, on the other hand, "magnifies" big things that happen to be far away. Both implements produce pictures of something the eye can otherwise not see.
So what would you call a gadget that also produces pictures of something that the eye cannot see - even so the object "looked at" is neither too small nor too far away? Or gadgets that do not give you a *picture* but other kinds of information about small things? Maybe there is more behind the word "microscope" than meets the eye?
There is, but in this set of modules I will restrict myself to those kinds of microscopes that in the end *do* produce a picture that allows you to "see" the things of interest directly. This excludes "microscopes" like particle accelerators or X-ray machines that we use a lot for looking into the structure of extremely small things. These "microscopes" do not produce *direct* pictures of those things but "numbers", or at best rather abstract pictures that only the cocgnoscenti can interpret.
The special modules in this mini-series are entitled:

- **1. Light microscope**
- **2. Scanning electron microscope** or ***SEM***.
- **3. Transmission electron microscope** or ***TEM***.
- **4. Needle scanning microscopes** including the
  Scanning tunneling microscope or ***STM***, and
  Atomic force microscopes or ***AFM***.

A Few General Remarks to Microscopes

In a simple definition, a microscope is a gadget or machine that produces *pictures* of some specimen that allow you to see details that you cannot see just by looking at the specimen with your unaided eyes. We assume here that the things you are going to see would be visible to your eye if they just would be large enough. That's not automatically the case. A large piece of air is just as invisible to your eye as a small one, so I need to point this out.
A microscope renders details visible that the optical instrument we call "eye" cannot *resolve*. It is **resolution** that matters, not *magnification*.

All microscopes come in:

- two basic *types*,
- are run in one of two basic *modes*,
- and need three basic *ingredients*.

Let's look at the three **basic ingredients** first. In order to build a microscope, you need:

1. A *probe* that is sensitive to the things you want to see. You use it to, well, *probe* the specimen. Light rays, for example, could be such a probe.
2. A *detector* that detects changes in the probing agency caused by the specimen or changes in the specimen. For a light microscope, the detector is a photographic film, a sensor chip, or your eye. However, we may also detect changes in the *specimen* caused by the probe. That's a bit more unusual but by no means uncommon.
3. Some *information processing* by suitable hard and software. Detector signals must be converted into a "picture" that can be interpreted by the brain. Only the most simple light microscopes use only your eyes as a detector. Your brain then must suffice as the information processor. You don't get very far this way. For most other microscopes, including all "scanning" microscopes, our eyes and brains are too limited to be of any use. The detectors and the computer power needed to run more sophisticated equipment is often quite substantial and fundamental to the very existence of the microscope.

This sounds rather overblown if you think of microscopes *only* in terms of those everyday **optical microscopes** that movie "scientists" always stare into, frowning slightly at what they see. Real scientists, however, use many more types of microscopes than just the optical ones.

Now let's look at the two **basic *types*** of microscopes or the two fundamentally different ways to "probe" your specimen:

1. The **probe** interacts with the *all* of the specimen all the time.
   In other words, you illuminate all of the specimen with a spread-out "beam" of the probe and watch what happens at all the "pixels" simultaneously.

That's what you do with light in light microscopes, or electrons in transmission electron microscopes. When you look at your uniformly illuminated specimen, you perceive the changes to the probe made by every pixel of the sample *simultaneously*. You might call this *direct* or **analog imaging**.

2. The probe is very thin and only interacts with a tiny part of the specimen (a pixel) at a given time. You record the changes in the probe agency (or the specimen) for that pixel, and then move to the next pixel.
   In other words: you are *scanning* your probe across the specimen. This is the base of all **scanning microscopes**. You don't see a thing directly. A picture emerges only after you made a full scan and some program converts the recorded signals into a picture that is displayed on a screen. You might call this *scanning* or **digital imaging**.

Finally, let's look at the two basic *modes* of imaging or "looking" at your specimen:

1. You look *through* it in *transmission*. Your probe (analog or digital) enters the specimen from on one side (the "top"), and you detect what's coming out on the other side (the "bottom"). This **transmission microscopy** has the big disadvantage that it is limited to specimens that are halfway transparent to your probe. The specimen therefore need to be very thin in most cases. The big advantage of transmission microscope is that you can "see" what's *inside* the specimen.
2. You look at what is "*reflected*" or scattered off from the surface.
   This "**surface microscopy**" has the huge advantage that you can apply it to all specimens, including big and bulky ones, and the disadvantages that you "see" only the surface or whatever is close to it.

- Let's arrange the various types of microscopes in a matrix

	Analog (Full area)	**Digital** (Pixel scanning)
"Reflection" (surface)	Optical (Metallographic)	SEM STM, AFM
Transmission (Volume)	Optical (Biological, medical) TEM	STEM

Resolution

So how small are the smallest things you can "see" with some microscope?
The proper questions are: what is the **resolution** of your microscope, always given in micrometers (µm) or nanometers (nm). And what are the limiting factors? Why can't your microscope do better?
Those are not-so-easy question to answer for analog techniques but rather easy to field for the digital ones. But let's first define what I mean with resolution.

- The resolution of a microscope simply tells you what the minimal distance between two objects needs to be in order to see them separately. Take two atoms. A picture of one atoms is at best a fuzzy circular blob (what did you expect?). Two atoms close together should at least look like a dumbbell if you claim that you can see them. The resolution than needs to be at least the size of an atom or 0.3 nm.
  Magnification, often used to describe the power of a microscope, means exactly nothing. If your microscope has a resolution of "only " 1 nm, it will image one, two three and more atoms still as just *one* fuzzy blob with a diameter of about 1 nm. Increasing the magnification will just make the fuzzy blob larger.
- The limits of resolution for an *analog microscope* is a tricky topic that I won't tackle here but in the upcoming modules. In contrast, the smallest things you can see in with *scanning microscopes* (digital technique) is simply given by the size of the probe. That is easy to understand.
  Imagine your are completely blind (if you need a microscope to see things, you are pretty much blind!). So you probe your surroundings with a stick. You will simply not be able to resolve details that are smaller than the tip of your stick. And that applies to all kinds of "sticks" or beams.
- Of course the tough question now is: "how do I make the tip of my "stick" as small as possible?". Once more, I'm not going into this here but in the upcoming modules.

Probes

Now let's look at what kind of probing things we have for running a microscope. To enumerate just the important ones:

1. *Visible* light waves with wavelengths around (roughly) **0.5 µm**, or (same thing, different lingo) beams of photons with energies around **2 eV**.
2. *Invisible* light like infrared (***IR***) or ultraviolet (***UV***). We still have photon beams, just the wavelengths are somewhat smaller (UV) or larger (IR) than for visible light. Note that your eye can no longer be the detector.
3. Beams of high-energy photons called X-rays. I just mention it to point out that X-ray microscopes producing a direct picture are just coming into

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3. Beams of high-energy photons called X-rays. I just mention it to point out that X-ray microscopes producing a direct picture are just coming into their own right now. Lack of lenses for X-rays and lack of good methods for making a thin "stick" of X-rays has prevented that until recently.
4. Electron beams.
5. Beams of any other kind of particle you know and can produce (e.g. neutron beams)
6. Thin pointed sticks or wires of some material, placed real close to the specimen surface.

Basic

Link
Waves

We will forget points 3 and 5 right away, even so a lot of money is spent for X-ray and neutron imaging. For the latter you need, for example, a dedicated nuclear reactor, making neutron microscopy a bit unwieldy and not really suitable for researchers with a limited budget. This leaves us with three basic kinds of microscopes:

1. Light optical microscopes (including IR and UV versions).
Light optical microscopes are mostly analog microscopes, but scanning types are getting more prominent in recent years.
You can look at the specimen surface (working in reflection mode) or through the specimen (transmission mode) if your specimen is halfway transparent. Metal specimen, of course, are not transparent and we can only look at their surface.
The resolution is still given by the "size" of the "stick", we just use a lot of sticks simultaneously. It is the "size" of the individual photons we are talking here. There are lot of quotation marks here for obvious reasons but for our purposes the size of a photon is a useful thing and simply given by its wavelength (see below). The wavelength of visible light is somewhat less than 1 µm, so the **resolution of normal optical microscopes** is roughly 1 µm, too. Objects smaller than 1 µm you just won't see. Note that you would need about 10.000 times better resolution to be able to "see" atoms.

2. Electron microscopes
Electron microscopes come in two basic kinds and one combination:

- **Scanning electron microscope** or ***SEM***.
  An electron beam can be focussed into a tiny spot. This gives us a "stick" we can scan across a surface with a "point" that's just about 1 nm in size . Resolutions around 1 nm are thus possible **-** if you can cough up the dough (say $ 700.000). But you still see only the surface of your sample.
- **Transmission electron microscopes** (***TEM***)
  Here we look *through* (always extremely thin) samples with a resolution of about 0.1 nm = 0.0001 µm. A good TEM (plus the required infrastructure) will allow you to see atoms and will set you back at least 4 Mio $.
- **Scanning transmission electron microscopes** (***STEM***) are a combination of both. You scan a very well focussed electron beam across a very thin specimen and detect what comes out on the bottom, pixel by pixel.

3. Needle scanning microscopes.
This term, though correct, is never used. The terms used for the two basic types of "needle scanners" are:

- **Scanning tunneling microscope** or ***STM***, and
- **Atomic force microscope** or ***AFM***

The "sticks" we use for these types are true "needles", just extremely sharp, made for example from silicon or some metal. Atomic resolution around **0.1 nm** is routinely achieved.

With scanning microscopes it is also fairly easy to obtain signals that the probe *induced* in the specimen. For example, X-rays might be emitted as soon as a pixel is hit with the probe, currents might be induced that one can measure, and so on and so forth.
Using and developing new kinds of "microscopes" is an integral part of Materials Science, and new kinds of microscopes, with more or less new and often amazing features, are coming up every year.

Here are the follow-up modules once more:

- **Light microscopes**
- **Scanning electron microscope** ***SEM***
- **Transmission electron microscope** ***TEM***, ***STEM***
- **Needle scanning microscopes**
  Scanning tunneling microscope ***STM***
  Atomic force microscopes ***AFM***